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# Development of a Systemic Safety Improvement Plan for Two-Lane Rural Roads in Virginia

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**Final Report VTRC 21-R10**

**Standard Title Page - Report on Federally Funded Project**

| 1. Report No.: FHWA/VTRC 21-R10 | 2. Government Accession No.: | 3. Recipient's Catalog No.: |
|---|---|---|
| 4. Title and Subtitle: Development of a Systemic Safety Improvement Plan for Two-Lane Rural Roads in Virginia | | 5. Report Date: December 2020<br>6. Performing Organization Code: |
| 7. Author(s): Hyun W. Cho, Ph.D., Benjamin H. Cottrell Jr., P.E., and In-Kyu Lim, Ph.D., P.E. | | 8. Performing Organization Report No.: VTRC 21-R10 |
| 9. Performing Organization and Address: Virginia Transportation Research Council<br>530 Edgemont Road<br>Charlottesville, VA 22903 | | 10. Work Unit No. (TRAIS):<br>11. Contract or Grant No.: 115219 |
| 12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation<br>1401 E. Broad Street<br>Richmond, VA 23219 | Federal Highway Administration<br>400 North 8th Street, Room 750<br>Richmond, VA 23219-4825 | 13. Type of Report and Period Covered: Final<br>14. Sponsoring Agency Code: |
| 15. Supplementary Notes: This is an SPR-B report. | | |

16. Abstract:

About 17,500 crashes per year occur on the more than 32,800 lane-miles of undivided two-lane rural roads maintained by the Virginia Department of Transportation (VDOT), and crash numbers are increasing. Roadway departure (RD) crashes comprise about 58% of crashes on these roads. Since these crashes are widely distributed across the state, determining how and where to focus limited highway safety resources through the deployment of low-cost, high-benefit systemic countermeasures is paramount to beginning to reduce the number of crashes on these roads.

This purpose of this study was to develop a systemic safety improvement plan for RD crashes on two-lane rural roads using low-cost countermeasures. Segments that have the potential for safety improvement were selected using VDOT's RD safety performance functions. Decision tree analysis was applied to perform a systemic classification of roadway characteristics that are correlated with RD problems. A list of countermeasures to deploy to target specific segments and patterns was developed based on the literature and input from VDOT staff. The countermeasures were intended to warn of curves ahead, delineate curves, and warn of lane/road departure. Before deployment, a study of the section by VDOT district traffic engineering staff is planned in order to finalize the safety improvement plan. The output of the study will be a safety improvement plan to deploy treatments systemically to two-lane rural roads as part of VDOT's safety program.

| 17 Key Words: systemic approach, two-lane rural road roadway departure, low-cost countermeasure | | 18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161. | |
|---|---|---|---|
| 19. Security Classif. (of this report): Unclassified | 20. Security Classif. (of this page): Unclassified | 21. No. of Pages: 49 | 22. Price: |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

**FINAL REPORT**

# DEVELOPMENT OF A SYSTEMIC SAFETY IMPROVEMENT PLAN FOR TWO-LANE RURAL ROADS IN VIRGINIA


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

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

Charlottesville, Virginia

December 2020
VTRC 21-R10

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## ABSTRACT

About 17,500 crashes per year occur on the more than 32,800 lane-miles of undivided two-lane rural roads maintained by the Virginia Department of Transportation (VDOT), and crash numbers are increasing. Roadway departure (RD) crashes comprise about 58% of crashes on these roads. Since these crashes are widely distributed across the state, determining how and where to focus limited highway safety resources through the deployment of low-cost, high-benefit systemic countermeasures is paramount to beginning to reduce the number of crashes on these roads.

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## INTRODUCTION

The Virginia Department of Transportation (VDOT) maintains more than 56,600 centerline-miles of two-lane roads of which 75% (43,900 miles) are rural roads. More than 32,800 lane-miles of these undivided two-lane rural roads are maintained by VDOT; about 17,500 crashes occur annually on those roads, and crash numbers are increasing. The most common crash type on two-lane rural roads are roadway departure (RD) crashes, which represent about 58% of total crashes. Since these crashes are widely distributed across the state, determining how and where to focus limited highway safety resources through the deployment of low-cost, high-benefit systemic countermeasures is paramount to beginning to reduce the number of crashes on these roads.

Traditional site-specific network screening methods, including the potential for safety improvement (PSI) using the safety performance function (SPF) approach, focus on treating a specific location based on crash history. Although these methods are effective in detecting "hot spots" (specific locations with a more than expected number of crashes), they have limitations in developing safety improvement projects in rural areas, where those hot spots are widely dispersed or when the focus of projects is to reduce only severe crashes (e.g., fatalities and serious injuries). The systemic approach reflects the fact that crash frequency or rates at specific locations alone are not always sufficient to develop a comprehensive safety improvement plan to address similar safety concerns found across widely distributed but homogeneous roadways. The systemic implementation of safety countermeasures helps to address the primary crash types on the entire road system, not just at specific high-crash locations.

The systemic safety approach represents a two-pronged effort to reduce crashes and serious injuries on roadways. This approach offers a means to do the following:

1. Identify crash types (e.g., fixed-object RD, deer/animal, head on, and sideswipe) and the location-related factors (e.g., grade, curvature, and volume) that contribute to the highest number of fatal and serious injury crashes of each type from a system-wide data-driven analysis.

2. Widely implement low-cost countermeasures over several locations with similar crash characteristics and/or similar roadway features.

Typically, systemic safety improvements are low cost, require little maintenance, are associated with documented crash reductions, and address specific crash types or crash risk factors.

The systemic approach looks at crash history on an aggregate basis to identify high-risk roadway characteristics rather than specific hot spots (Federal Highway Administration [FHWA], 2019). The systemic approach considers multiple locations with similar risk characteristics. When the system is investigated as a whole, a particular roadway element may have a high crash experience, so it may be more cost-effective to correct the problem on a system-wide basis rather than by individual high-crash locations. In other words, with the systemic approach, improvements would be made at two-lane rural roads that might not have a demonstrated crash problem but had characteristics similar to those of two-lane rural roads that did have a crash problem.

The application of the systemic safety approach offers the following benefits:

- Systemic safety improvements can reduce overall fatal and severe crashes of certain types within a district/jurisdiction more effectively than safety improvements at a small number of hot-spot locations.

- The approach allows agencies to adapt for all levels of data availability and can help them prioritize data collection needs.

- Countermeasures implemented systemically are typically low-cost improvements.

- Systemic safety improvements help agencies broaden their safety efforts and consider risk factors in addition to crash history when identifying locations for potential safety improvement.

- Systemic safety improvements can be incorporated into planning, design, and maintenance policies; defended in tort liability cases; and used to develop a multiyear program of projects.

- The approach can bolster public confidence because it allows agencies to implement a proactive safety program.

Systemic safety improvements can be promoted for future use through a written policy or plan; implemented through explicit roadway safety improvement projects; and included in capital projects and ongoing maintenance activities.

## PURPOSE AND SCOPE

The purpose of this study was to develop a systemic safety improvement plan for RD crashes on two-lane rural roads using low-cost countermeasures. This includes developing a systemic network screening method to identify two-lane roadway features/characteristics with a high risk of RD crashes and developing a plan to implement low-cost countermeasures to maximize benefits from limited safety funding.

The scope of this study was limited to RD crashes on two-lane rural roads in Virginia. Virginia's two-lane rural road crashes were assessed over a 5-year period (2014-2018) to determine predominant crash trends and crash types. From the preliminary analysis, the majority of crashes on undivided two-lane rural roads were RD crashes. In addition, RD crashes comprise the only crash type that has VDOT SPFs, which enables the identification of segments that have the potential for safety improvement. Focusing on RD crashes, this study developed a list of systemic countermeasures that can be deployed to target roadway segments that are identified through data analysis.

## METHODS

Five tasks were performed to achieve the study objectives:

1. Identify and review the literature related to the systemic safety approach and undivided two-lane rural roads.

2. Collect and prepare crash data.

3. Analyze crash data to identify RD crashes and location-related factors for undivided two-lane rural roads using VDOT databases.

4. Identify low-cost countermeasures for undivided two-lane rural roads.

5. Develop a plan to deploy treatments systemically.

### Literature Review

The literature was reviewed to identify information related to two-lane rural road safety improvements and countermeasures for RD crashes. Relevant search engines, such as the Transportation Research International Documentation (TRID) and Transport database, were used.

### Data Collection and Preparation

Five years (2014-2018) of crash data on two-lane rural roads were collected. The data included information on collision type and severity and other crash condition factors such as light/darkness and speeding. For roadway network data, data from the 2018 VDOT Roadway

Inventory for undivided two-lane rural roads were collected from VDOT's database. This inventory included information on administrative elements (district, route name or ID, maintenance jurisdiction, ownership, functional class, mile point, etc.); facility characteristics (lane width, pavement surface type, curb type, shoulder width, etc.); and traffic data (annual average daily traffic [AADT], speed limit) for each segment. Those two datasets were compiled using the mile points of the crash data and the start and endpoint of the individual segments; they were then combined into a dataset for further detailed analysis.

## Data Analysis

This step analyzed the prepared data for two-lane rural roads by crash type and location-specific factors. Using VDOT's technical definition (Figure 1) of an RD crash, certain collision types and conditions were selected to identify which crashes were classified as RD crashes (Kweon and Lim, 2019).

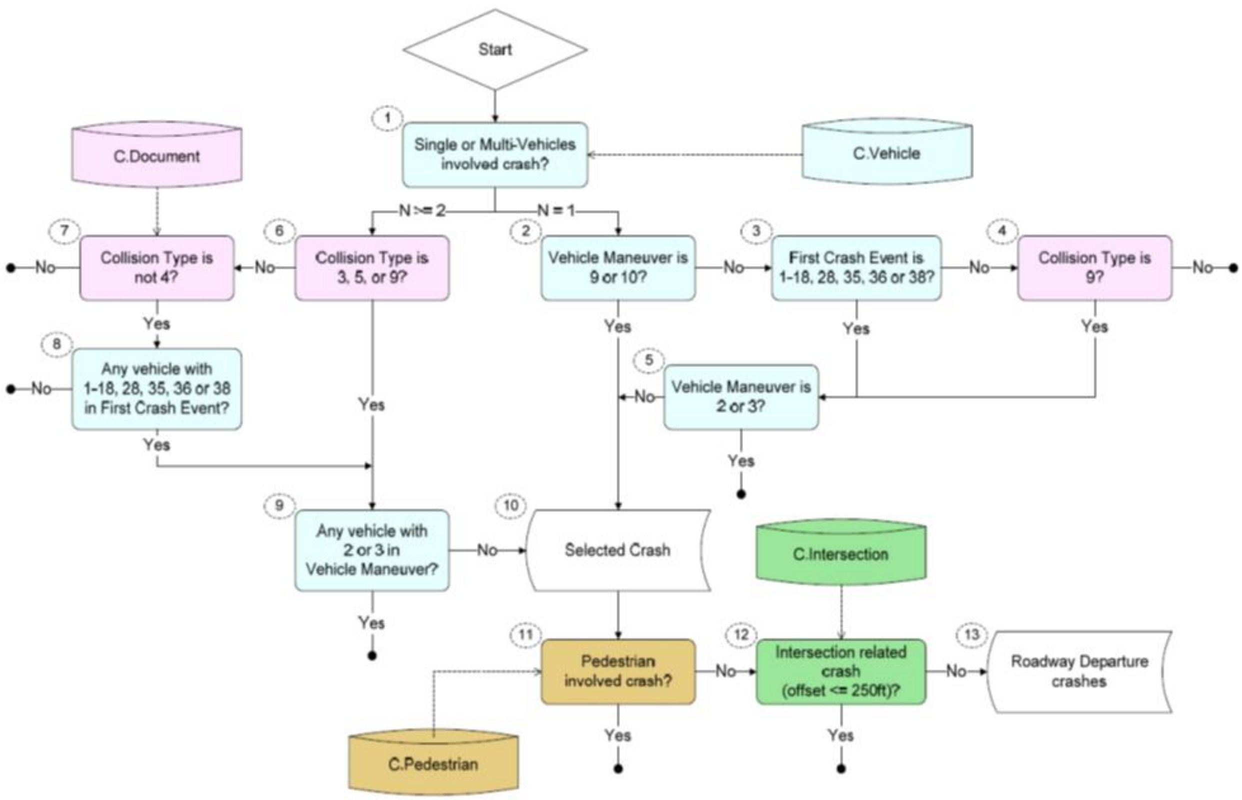


**Figure 1. Flow Diagram for Identifying RD Crashes (Kweon and Lim, 2019). RD = roadway departure; C.XXX = XXX Table of Crash Database.**

Two methods were used to perform roadway screening during this task, and they are discussed in detail in the following sections. First, VDOT's Virginia-specific SPFs for RDs on rural two-lane segments (Kweon and Lim, 2019) were used to select segments. Second, machine learning techniques, such as decision tree analysis, were used to classify road characteristics that were correlated with RD crashes.

**Network Screening of Roadway Departures Using SPFs (RD-SPFs)**

The *Highway Safety Manual* (AASHTO, 2010) defined a network screening as "a process for reviewing a transportation network to identify and rank sites from most likely to least likely to realize a reduction in crash frequency with the implementation of countermeasures." This study adopted the SPF and PSI method in the *Highway Safety Manual* to identify sites for the RD crash reduction. Specific steps were as follows.

*Step 1. Apply the RD-SPF to each segment.*

The RD-SPF produces the expected annual number of crashes on the segment. This study used the RD-SPF shown in Equation 1, which is "Site Type 101-Rural 2-lane segments Model 1" from Kweon and Lim (2019)

$$\mathrm{N_{RD-SPF}} = \exp[-5.570 + 0.621 \cdot \ln(\mathrm{AADT}) + \ln(\mathrm{Length})] \quad \text{[Eq. 1]}$$

where $\mathrm{N_{SPF}}$ is the annual number of all RD crashes for a segment; AADT is the annual average daily traffic (number of vehicles per day); and Length is the segment length (miles). The negative binomial (NB) dispersion (i.e., overdispersion) factor for the empirical Bayes (EB) method is 1.425 for this model.

*Step 2. Compute RD_PSI for each segment.*

PSI is an important criterion that measures the difference between the expected (EB adjusted) number of crashes ($n_{Exp.}$) and the predicted number of crashes ($n_{Pred.}$) using an SPF. PSI is defined as follows:

$$\mathrm{PSI} = n_{Exp.} - n_{Pred.} \quad \text{[Eq. 2]}$$

It should be noted that $n_{Pred.}$ is calculated for a 5-year period. Since most undivided two-lane rural roads generally have low AADTs, most of the annual AADTs are collected and updated every 6 years in the Roadway Network System of VDOT, so the $\mathrm{N_{RD-SPF}}$ is the same for the periods when AADT does not change. The $n_{Pred.}$ over the observed 5-year period (2014-2018) was calculated by applying 2018 AADTs and segment length on the RD-SPF and multiplying the 2018 value by 5.

The expected (EB adjusted) number of crashes ($n_{Exp.}$) is determined using (1) the predicted number of crashes ($n_{Pred.}$) from the SPF using AADT and segment length, (2) the observed number of crashes ($n_{Obs.}$), and (3) the EB weight (w) calculated using the predicted crash calibration value for the 5-year period ($C_y$ =1.68) and the NB dispersion parameter (*k*) as shown in Equations 3, 4, and 5. It should also be noted that as $n_{Pred.}$ was calculated for the 5-year period; $n_{Obs.}$ and $n_{Exp.}$ are also determined for the same 5-year period.

$$n_{Exp.} = \mathrm{w} \times (n_{Pred.} \times \mathrm{C_y}) + (1 - \mathrm{w}) \times n_{Obs.} \quad \text{[Eq. 3]}$$

$$w = \frac{1}{1+(k \times n_{Pred.} \times C_y)} \quad \text{[Eq. 4]}$$

$$C = \frac{\sum n_{Obs.\_Allsites\_5\,Yrs.}}{\sum n_{Pred.\_\,Allsites\_5\,Yrs.}} \quad \text{[Eq. 5]}$$

Equation 2 produces the sum of the 5-year period PSI value of the segment. As this study investigated the potential for crash reduction, the total PSI rather than an annual PSI was of interest.

*Step 3. Select segments for RD PSI > 0.*

After the RD-PSI was calculated for the entire network of the rural undivided two-lane segments, segments with the value of RD-PSI greater than zero were selected for further analysis, as those segments had a higher probability than others for improved safety and reduced crashes.

**Chi-square Automatic Interaction Detection (CHAID) Decision Tree Analysis**

A decision tree was used to identify groups of two-lane rural roads based on AADT and location-specific factors that are associated with positive or negative RD crash PSI. Decision tree analysis is known to be one of the most popular machine learning algorithms because of its intelligibility and ease of interpretation (Madeh and El-Diraby, 2020). In addition, from previous research (Cottrell and Lim, 2018), the decision tree analysis has been proven to be a simple but powerful method for multivariable analysis.

Decision tree algorithms produce a classifier tree by successive segmentation of the dataset into subgroups based on the relationships between independent variables and a dependent (target) variable to improve the prediction or classification of a dataset. The algorithm starts from the root node with selecting the most informative attribute, such as AADT and location-specific factors in this study, and then splits the data using the attribute; hence, at least two branches stem out of the root node. Then, the nodes in each branch split again based on their informativeness. Splitting stops when the node is ideally pure; this node is called a terminal node, and it belongs to a particular group. The terminal node indicates which attributes (independent variables) are most strongly related to the group (target variable).

CHAID is an unsupervised decision tree algorithm based on the chi-square ($\chi^2$) test that performs well with various types of variables, including categorical and continuous data, and produces output that is visual and intuitive. It operates by choosing the independent (predictor) variable that has the strongest interaction with the dependent variable at each split; categories of each predictor are merged if they are not significantly different with respect to the dependent variable. It is known that CHAID output has the added benefit of being straightforward to explain and to implement, and unlike regression analysis, it does not require the data to be normally distributed. Classification and regression trees comprise another popular decision tree algorithm; this is a supervised model that needs a sample of the population withheld. The model divides the data using binary splitting until a terminal node is homogeneously pure with respect to the dependent variable. The classification and regression tree model is frequently used in predictive analysis, whereas CHAID is widely used for descriptive analysis, as it can produce multiple branches of a single root/parent node. The IBM SPSS Decision Trees 26.0 classification method was used for CHAID. The maximum value of the tree level was set as 4, and the significance levels for splitting nodes and merging categories were set as 0.05 for this study. The output of the CHAID analysis identified the characteristics of two-lane rural roads where RD PSI showed positive values.

## List of Low-Cost Countermeasures

A list of potential countermeasures to address observed crash groups was developed along with measures of performance. There are many conventional or well-established countermeasures and some newer ones based on VDOT's experience and the literature. Examples of low-cost countermeasures may include but are not limited to the following:

*Signing:*

- curve warning signs
- curve warning signs with fluorescent yellow sheeting
- retroreflective strips on signposts
- chevron signs
- delineators
- other signs.

*Pavement markings:*

- raised pavement markers
- edge line markings
- centerline markings
- wider pavement markings
- centerline and edge line markings
- edge line rumble strips and centerline rumble strips (CLRS)
- pavement marking messages such as the curve symbol, SLOW, speed limit, etc.

*Others:*

- SafetyEdge
- clear zone
- road safety hardware such as guardrail
- innovative LED post-mounted delineators (PMDs).

## Development of Plan to Deploy Treatments Systemically

Based on the crash analysis and recommended grouping of undivided two-lane rural roads by categorized high-risk roadway characteristics and high-crash experience, potential combinations of countermeasures were developed to address the observed issues. The estimated cost and service life of the countermeasures were determined using VDOT and other data sources (described in more detail later). CMFs were considered in the selection of countermeasures using data from information sources including the Crash Modification Factor [CMF] Clearinghouse (n.d.) and the *Virginia State Preferred CMF List* (VDOT, 2019). High-level benefit/cost (B/C) estimates were developed using the CMFs as an example or case study. The benefit was estimated using the CMFs for the countermeasures to determine the potential reduction in the number of crashes. VDOT's Highway Safety Improvement Program's (HSIP) proposal form B/C spreadsheet was used to calculate present value benefits and costs using a 3% discount rate.

## RESULTS AND DISCUSSION

### Literature Review

In recent years, the Virginia Transportation Research Council (VTRC) has published several reports on RD crashes on rural roads and the systemic approach to identify priority locations based on risk factors. In 2019, Kweon and Lim developed RD-SPFs for 16 types of sites, including rural two-lane roads (Kweon and Lim, 2019). In their study, three SPF models were presented: SPFs with AADT and length of segment (1) in a logarithmic functional form; (2) in a customized functional form; and (3) with other predictors such as lane width, shoulder width, median shoulder width, pavement roughness value, pavement condition, surface type, and curb and gutter presence in customized functional forms. This study adopted SPFs of model 1, which is currently used by VDOT's Traffic Engineering Division (TED) as the network screening method.

VTRC also published a study that developed safety improvement plans using systemic low-cost countermeasures for unsignalized intersections in Virginia (Cottrell and Lim, 2018). The study applied CHAID decision tree analysis, which was also adopted in this study, to perform a systemic analysis to identify groups of high-risk intersections based on independent variables (roadway inventory and traffic count variables) that were most strongly related to the focus collision types. Four focus collision types with the highest frequency of crashes and the greatest potential reduction in crashes were identified from the data, including road inventory data: 3-leg angle, 3-leg fixed object off road, 4-leg angle, and 4-leg rear-end. For example, from the CHAID decision tree analysis it was found that the characteristics of a 3-leg unsignalized intersection with a high percentage of angle collisions were as follows:

- intersection entering volume > 15,000

- functional classification of major and minor roads of Primary Arterial–Collector, Minor Arterial–Minor Arterial, Minor Arterial–Collector, and Local–Local.

After the crash assessment was performed, case studies of selected intersections in each group were reviewed to assess the factors that might influence the four focus collision types. A tiered list of countermeasures to deploy was developed based on the literature and input from VDOT staff. The countermeasures were intended to warn of the stop ahead, to make the stop sign and stop location more visible on the minor street, and to warn of the intersection ahead on the major street. The PSI was used to prioritize the candidate treatment intersections. Before deployment, a study of the intersections conducted by VDOT district traffic engineering staff was planned in order to finalize the safety improvement plan. The output of the study was a safety improvement plan to deploy treatments systemically to unsignalized intersections as part of the safety program. This plan was included in VDOT's systemic safety plan in 2019.

In 2020, VTRC published a report by Appiah and Zhao (2020). who examined features correlated with RD crashes on rural roads. Using statistical analysis, the authors found a significant correlation between the frequency of RD crashes and AADT, shoulder width, and speed limit. The number of RD crashes increased as the AADT and speed limit increased and decreased as the shoulder width was increased. Further analysis using more granular data from two data sources, SCRIM and iVision, showed promise for further insights into factors influencing RD crashes. In particular, the results showed that these crashes were significantly influenced by roadway geometry (curvature and cross slope) and pavement condition (skid resistance and roughness). This study also provided a synthesis of the literature on RD crash influencing factors and countermeasures. Since a recent literature review was conducted on this topic, the following section will introduce only recent two-lane rural road RD crash studies and countermeasures that the prior VTRC-published study (Appiah and Zhao, 2020) did not include.

**Recent Two-Lane Rural Road RD Crash and Countermeasure Studies**

Recently, Wood and Donnell (2020) conducted an EB before-after study of the effect on RD crashes of deploying horizontal curve warning pavement markings on two-lane rural highways in Pennsylvania. They concluded that the horizontal curve pavement warning markings were effective at reducing total crashes along horizontal curves and should be considered a low-cost safety improvement for horizontal curves on two-lane rural roadways. The CMFs developed for total and nighttime crashes were 0.652 and 0.708, respectively.

Das et al. (2020) developed a safety prediction model for RD crashes on rural two-lane highways by analyzing 7 years (2010-2016) of RD crash data in Louisiana. An NB model and three separate machine learning models (random forest, support vector machine, and Cubist) were applied; all three machine learning models outperformed the NB model. Those modes had about a 23% smaller root mean square error, and the Cubist model showed higher accuracy than the other two machine learning models in estimating RD crashes on rural two-lane roadways. The variables used in this study were length, shoulder width, pavement width, AADT, and total crashes.

Islam and Pande (2020) studied the identification and quantification of the factors affecting injury-severity outcomes for single-vehicle RD crashes on rural curved segments in Minnesota. Using 5 years (2010-2014) of crash data and a mixed logit model, they identified some estimated marginal effects including the following:

- A sports utility vehicle involved in a rollover was more likely to result in severe and minor injury than other vehicle types following an RD crash on curved rural road segments, with an average marginal effect of 0.02 and 0.068, respectively.

- Drivers under 30 years of age were less likely to be involved in severe and minor-injury crashes (average marginal effect of −0.004 and −0.015, respectively) and more likely to be involved in no-injury crashes, with an average marginal effect of 0.019.

- RD crashes on rural two-lane undivided curved roadways resulted in an increased likelihood of minor injury, with an average marginal effect of 0.046.

- Rural roads with traffic volumes less than 5,000 veh/day (bidirectional) had, on average, a higher likelihood of severe injury crashes, with an average marginal effect of 0.0362.

- Dark conditions at curved segments in the rural section resulted in an increased likelihood of severe and no-injury crashes.

Hallmark et al. (2020) evaluated 18 sites in seven states (Colorado, Iowa, Missouri, Montana, Texas, Washington, and Wisconsin) where sequential dynamic chevron warning systems were implemented to reduce RD crashes on rural two-lane roadways. The EB method was applied to estimate total crashes and injury crashes, and the study developed CMFs for these systems. The resulting CMFs were 0.34 for total crashes (non-intersection) and 0.49 for injury crashes.

Hamilton et al. (2019) explored the effects of design speed and superelevation rate on the CMFs for 889 horizontal curves on rural two-lane highways in Indiana and Pennsylvania. Using an NB regression modeling approach, they developed RD CMFs for horizontal curve radius and side friction demand on rural two-lane highways. The study found that RD crashes are expected to increase for decreasing curve radius, increasing posted speed limit, and decreasing superelevation rate.

Donnell et al. (2019) identified and evaluated several RD crash countermeasures that had not been previously examined using a rigorous safety evaluation. Three evaluations were conducted: (1) an observational before-after study of curve ahead warning pavement markings; (2) a cross-sectional study of delineators on guiderail along horizontal curves; and (3) a cross-sectional study of the safety effects of geometric design consistency. The results of these evaluations indicated that the expected number of RD crashes were associated with the horizontal curve radius, radii of adjacent horizontal curves, and the tangent lengths between curves. Further, the expected number of RD crashes was associated with side friction demand on horizontal curves. Guardrail with delineators improved safety, with estimated CMFs of 0.976 for total crashes, 0.871 for fatal plus injury crashes, 0.845 for run-off-road (ROR) crashes, and 0.622 for nighttime crashes along horizontal curves that are 4 degrees or sharper. Horizontal curve warning pavement markings were associated with fewer expected total (CMF = 0.652), fatal plus injury (CMF = 0.693), ROR (CMF = 0.769), nighttime (CMF = 0.708), nighttime ROR (CMF = 0.745), and nighttime fatal plus injury (CMF = 0.771) crashes on two-lane rural highways.

Gibbons et al. (2018) examined the effectiveness of a variety of active and passive curve warning and curve delineation systems on two-lane rural roads to determine which was the most effective at reducing vehicle speeds and assisting lane-keeping. Using a human factors study and an observational study, they found mixed results, with every tested system leading to some reductions in speed or encroachments at some parts of the curve while also leading to increases in the same values at other parts of the curve. No clear difference was found between passive and active systems or between delineation and warning systems.

McGee (2018) identified and documented the practices of state departments of transportation in implementing engineering countermeasures for RD crashes. Reducing RD crashes is included as a goal in the strategic highway safety plans of many states. States are using alternative approaches for identifying locations for implementation of RD countermeasures, including traditional high-crash (hot spot), systematic, and systemic approaches. There are numerous (more than 20) effective engineering measures (e.g., traffic control devices, geometric design enhancements, pavement treatments, and safety hardware) being used to counter the occurrence of RD crashes and reduce crash severity. Some countermeasures, particularly the use of rumble strips, SafetyEdge, and high friction surface treatments, have been integrated into state design policies, with guidelines established for when they should be used.

Albin et al. (2016) updated a previous report published by the FHWA, *Low-Cost Treatments for Horizontal Curve Safety*. The primary audience for this publication is local transportation agencies. The information can be used to evaluate problems and identify appropriate countermeasures for problem curve sections. The authors stated that applying these countermeasures would help agencies reduce RD crashes and resulting injuries and fatalities. The countermeasures were presented in five groups: (1) markings, (2) signs, (3) pavement countermeasures, (4) roadside improvements, and (5) intersections in curves.

Hallmark et al. (2013) developed a toolbox to assist agencies in addressing crashes at rural curves. The main objective of this toolbox was to summarize the effectiveness of various known curve countermeasures. For 14 countermeasures, the toolbox included the following information: description, application, effectiveness, advantages, and disadvantages.

## Ongoing Research in Virginia

Gibbons et al. are currently conducting a study for VTRC entitled "Guidance for and Effectiveness of Low Cost Delineation Treatments" (VTRC, n.d.). The objectives of this study include evaluating the safety effects of different low-cost delineation and marking strategies for preventing RD crashes. Life-cycle costs of different effective countermeasures identified under the first objective will also be determined. Low-cost measures to be considered for evaluation include edge lines with different widths and materials, PMDs with different materials and spacing, and pavement markers. In addition to compiling CMFs for various countermeasures based on the literature, the project will focus on evaluating dynamic chevrons and flashing beacons on curve warning signs. That study will be a strong complement to this study in that its focus on the safety effectiveness of countermeasures supports this study's emphasis on a data-driven systemic analysis to identify candidate sites for treatment and a process to facilitate the implementation of countermeasures.

## Data Preparation

This section summarizes how the undivided two-lane rural road network and crash data were combined for analysis. Figure 2 explains the subset relations of the data used. In the figure, "U" represents a union set, which includes all two-lane rural undivided road data that are directly pulled from the 2018 Roadway Network Inventory database. Subset A ($A \subset U$) shows segments where a crash was observed from 2014-2018. These were combined with roadway network data by matching the mile marker. The Subset B of A ($B \subset A$) represents segments with at least one RD crash observed among total crash observed data. Subset C ($C \subset B$) comprises segments with RD PSI > 0.

This section also presents descriptive statistics of selected variables from the roadway inventory information used in the data analysis. A total of 36,686 two-lane rural road segments had at least one crash during the study period (2014-2018) (Table 1). As shown in the table, the mean total crash and RD crash were 2.38 and 1.14, respectively. The mean value of AADT was 2,107 veh/day, and the standard deviation was 2,679 veh/day. The average length of the segments was 0.48 miles. A data group (1,790 in total) with missing values for functional class and shoulder width was excluded from the analysis, and 55 mph was assigned to missing speed limits. Because 55 mph is the statutory speed limit, this assumption appeared conservative and more reasonable than the assignment of 45 mph as the average speed limit. Moreover, it was acknowledged that leaving the speed limit cells blank provided analysis results similar to assigning a 55 mph speed limit to blank cells. Figures 3 and 4 show the histograms of AADT and the length of segments of Set A. Both graphs show right-skewed (positive skewness), where the median value is smaller than the mean value.

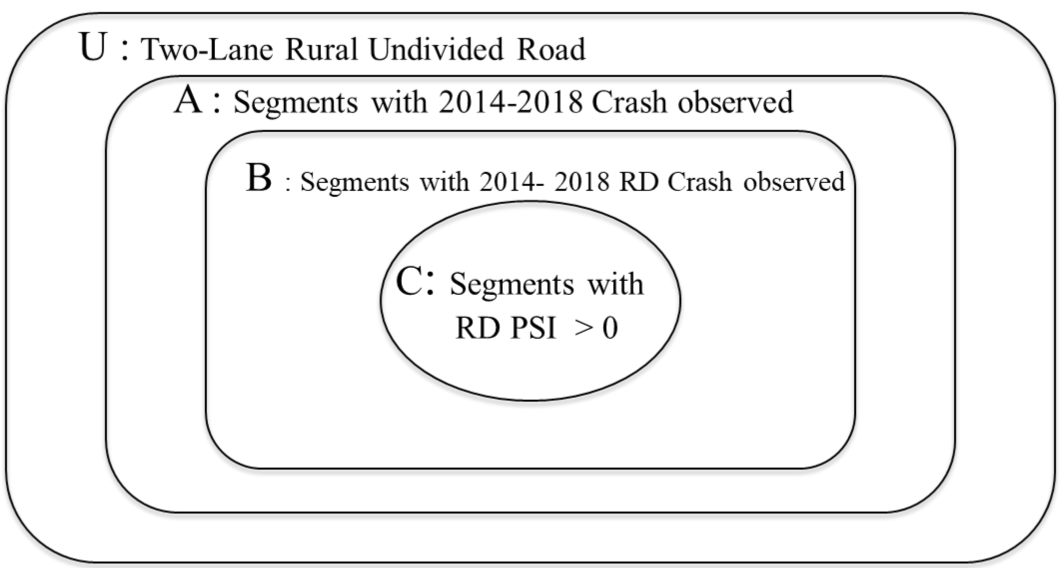


**Figure 2. Venn Diagram of Subsets of Roadway Network Data. RD = roadway departure; PSI = potential for safety improvement.**

Table 2 shows the detailed characteristics of subsets. The table includes the total number of segments, total and average length of segments, total and average vehicle miles traveled per day (in million vehicle-miles) on study segments per year and AADT, and total crash and RD crash numbers for the entire 5 years (2014-2018). It was found that Subset C contains 14.7% of all two-lane rural road segments, and it includes 24.3% of the mileage of these segments. It also includes 77.1% of the 5-year total count of RD crashes.

Table 3 presents descriptive statistics of Set C, where 15,810 two-lane rural road segments had at least one RD crash during the study period. Compared to Set A, the mean values of total crashes (2.71) and RD crashes (2.05) were greater and AADT was smaller (1,365). Figures 5 and 6 also show histograms of the AADT and length distributions of segments in Set C. Both graphs also show a right-skewed tendency.

**Table 1. Descriptive Statistics of Variables for Set A**

| Descriptive Statistics | | Total Crash | Total RD Crash | AADT | Length (miles) | Functional Class | Surface Width (ft) | Shoulder Width (ft) | Speed Limit (mph) |
|---|---|---|---|---|---|---|---|---|---|
| N | Valid | 36,686 | 36,686 | 36,686 | 36,686 | 36,447 | 36,686 | 35,037 | 20,693 |
| | Missing | 0 | 0 | 0 | 0 | 239 | 0 | 1,649 | 15,993 |
| Mean | | 2.38 | 1.14 | 2,107 | 0.48 | N/A | 9.92 | 3.80 | 45 |
| Standard deviation | | 2.50 | 1.58 | 2,679 | 0.48 | N/A | 1.74 | 1.76 | 9.35 |

RD = roadway departure; AADT = annual average daily traffic; N/A = not available.

**Table 2. Summary of Data Used**

| Dataset | Total No. of Segments | Total Length (miles) | Avg. Length of Segments (miles) | Total VMT (million veh-miles) | Avg. AADT | Total RD Crash | Total Crash |
|---|---|---|---|---|---|---|---|
| All segments (U) | 110,024 (100%) | 32,796 (100%) | 0.30 | 31.5 | 1,307 | 41,969 (100%) | 87,407 (100%) |
| Crash occurred segments (A) | 36,686 (33.3%) | 17,518 (53.4%) | 0.48 | 23.6 | 2,106 | 41,969 (100%) | 87,407 (100%) |
| RD crash occurred segments (B) | 22,507 (20.5%) | 13,740 (41.9%) | 0.61 | 17.5 | 1,768 | 41,969 (100%) | 63,771 (73.0%) |
| Total RD crash PSI > 0 segments (C) | 15,810 (14.7%) | 7,955 (24.3%) | 0.50 | 7.6 | 1,365 | 32,372 (77.1%) | 42,910 (49.1%) |

VMT = vehicle miles traveled; AADT = annual average daily traffic; RD = road departure; PSI = potential for safety improvement.

**Table 3. Descriptive Statistics of Variables of Subset C**

| Descriptive Statistic | | Total Crash | Total RD Crash | AADT | Length (miles) | Functional Class | Surface Width (ft) | Shoulder Width (ft) | Speed Limit (mph) |
|---|---|---|---|---|---|---|---|---|---|
| N | Valid | 15,810 | 15,810 | 15,810 | 15,810 | 15,763 | 15,810 | 15,468 | 7,936 |
| | Missing | 0 | 0 | 0 | 0 | 47 | 0 | 342 | 7,874 |
| Mean | | 2.71 | 2.05 | 1,365 | 0.50 | N/A | 9.48 | 3.47 | 44 |
| Standard deviation | | 2.79 | 1.85 | 1,947 | 0.43 | N/A | 1.55 | 1.6 | 8.8 |

RD = roadway departure; AADT = annual average daily traffic; N/A = not available.

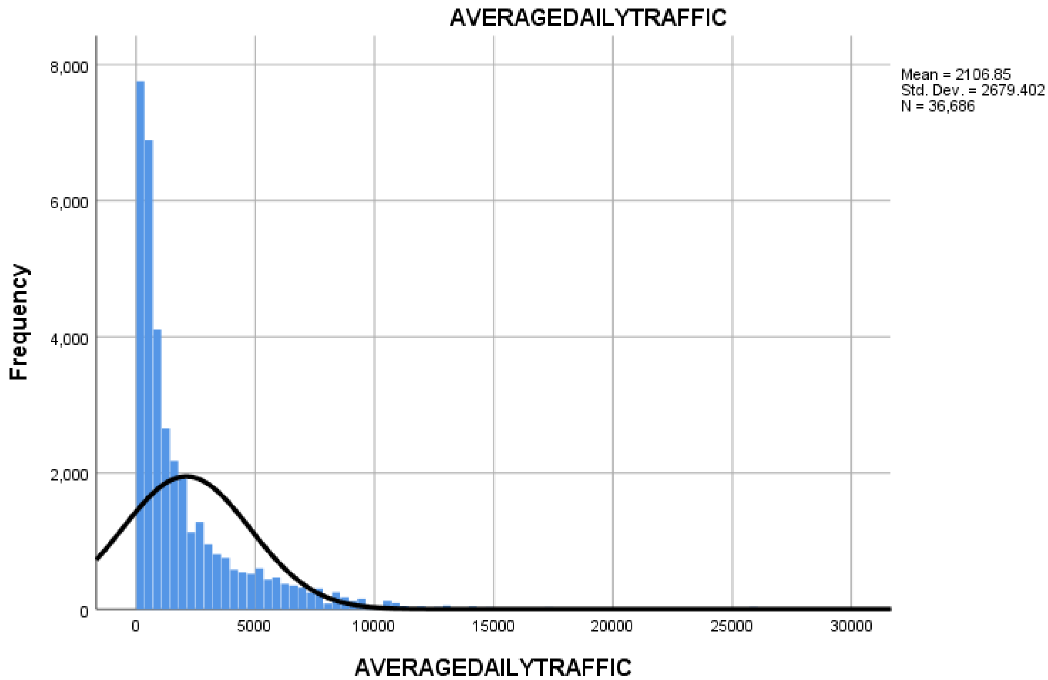


**Figure 3. Frequency (*y*-axis) Histogram of AADT (*x*-axis, veh/day) of Set A. AADT = annual average daily traffic.**

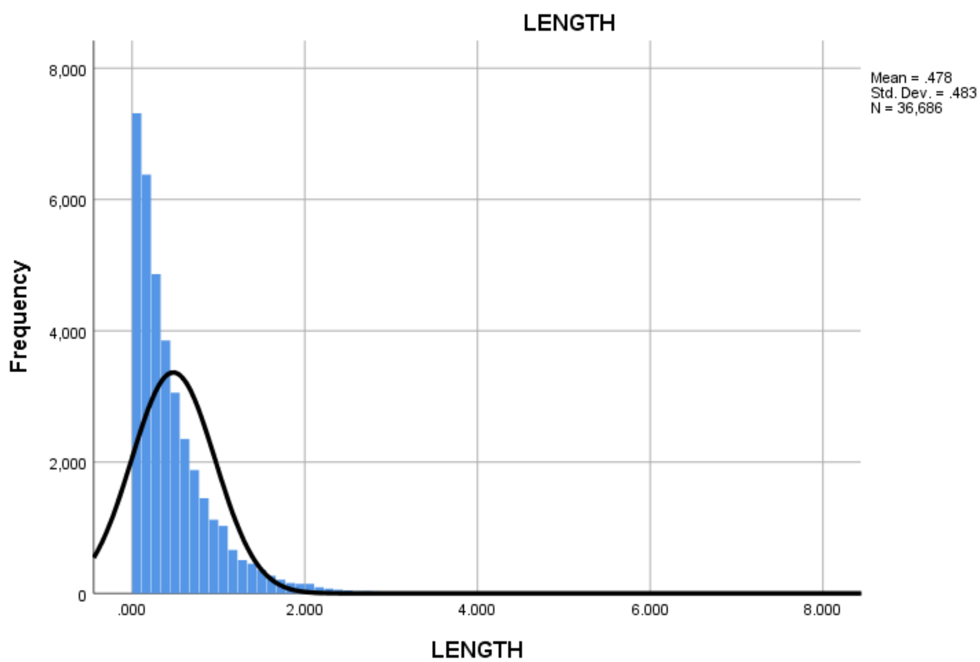


**Figure 4. Frequency (*y*-axis) Histogram of Segment Length (*x*-axis, miles) of Set A**

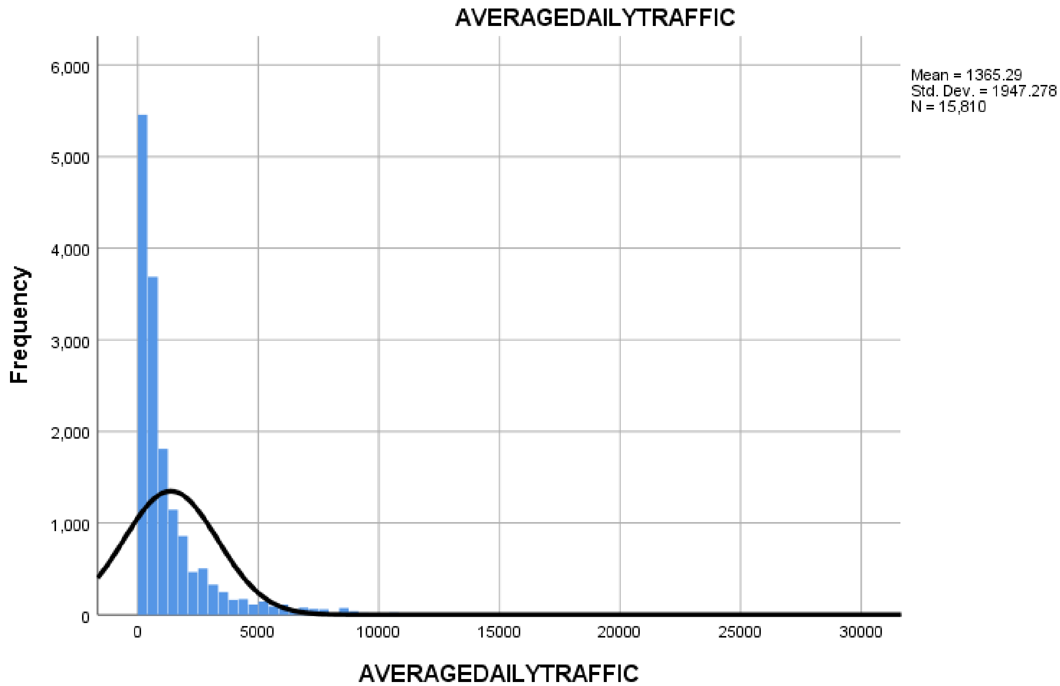


**Figure 5. Frequency (*y*-axis) Histogram of AADT (*x*-axis, veh/day) of Set C. AADT = annual average daily traffic.**

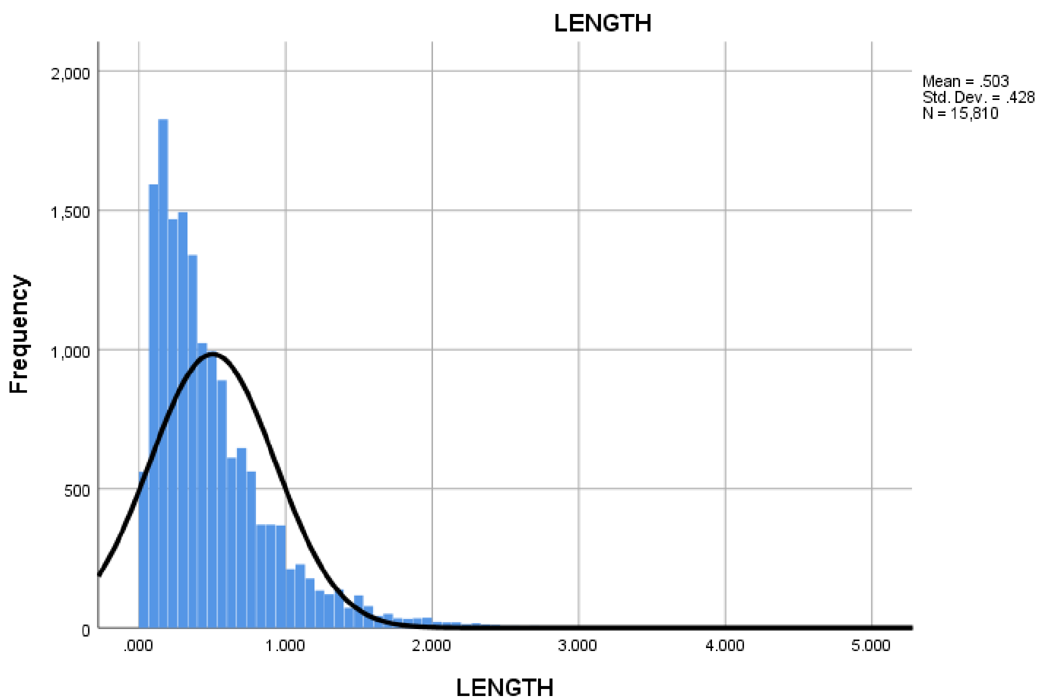


**Figure 6. Frequency (*y*-axis) Histogram of Segment Length (*x*-axis, miles) of Set C**

Table 4 presents the five undivided two-lane rural road features and their corresponding bands that were defined for each segment for the decision tree analysis. Among the categorized independent variables, bands of AADT and shoulder width were determined based on the distribution of both AADTs and RD crash frequencies; other variables' bands were simply categorized from their original classification codes. These features and bands were used as categorical independent variables of decision tree classification analysis.

**Table 4. Categorization of Independent Variables for Decision Tree Analysis**

| Undivided Two-Lane Rural Road Features | Band |
|---|---|
| AADT (veh/day) | 1. ≤ 1,000<br>2. 1,001-3,000<br>3. 3,001-7,000<br>4. 7,001-10,000<br>5. ≥ 10,001 |
| Sum of Shoulder Width (ft) | 1. ≤ 2<br>2. 3-4<br>3. 5-6<br>4. 7-8<br>5. 9-10<br>6. 11-12<br>7. ≥ 13 |
| Sum of Surface Width (ft) | 1. ≤ 18.0<br>2. 18.1-20.0<br>3. 20.1-22.0<br>4. 22.1–24.0<br>5. ≥ 24.1 |
| Speed Limit (mph) | 1. ≤ 25<br>2. 26-35<br>3. 36-45<br>4. 46-55<br>5. ≥ 56 |
| Functional Classification | 2. Rural Principal Arterial<br>3. Rural Minor Arterial<br>4. Rural Major Collector<br>5. Rural Minor Collector<br>6. Rural Local |

AADT = annual average daily traffic.

## Data Analysis

This section presents the results of the CHAID decision tree analysis for all RD crashes, RD crashes during darkness, and RD crashes involving speeding.

### All RD Crashes for Two-Lane Rural Roads

Figure 7 shows the CHAID decision tree constructed for all RD crashes on undivided two-lane rural roads. The final dataset included 34,906 segments (17,198.9 miles); segments from Set A with missing values were excluded. Each segment is classified as being either above or below the mean percentage of RD crashes based on all segment configurations. This categorization is placed at the top of the tree and is termed the "root node." At the root node (Node 0) it is shown that 15,442 segments (44.2%, 7,863.1 miles) have a PSI greater than 0, which shows that those segments have an RD problem. The remaining 19,464 (55.8%; 9,335.8 miles) segments have a PSI less than 0, so they do not have an RD problem.

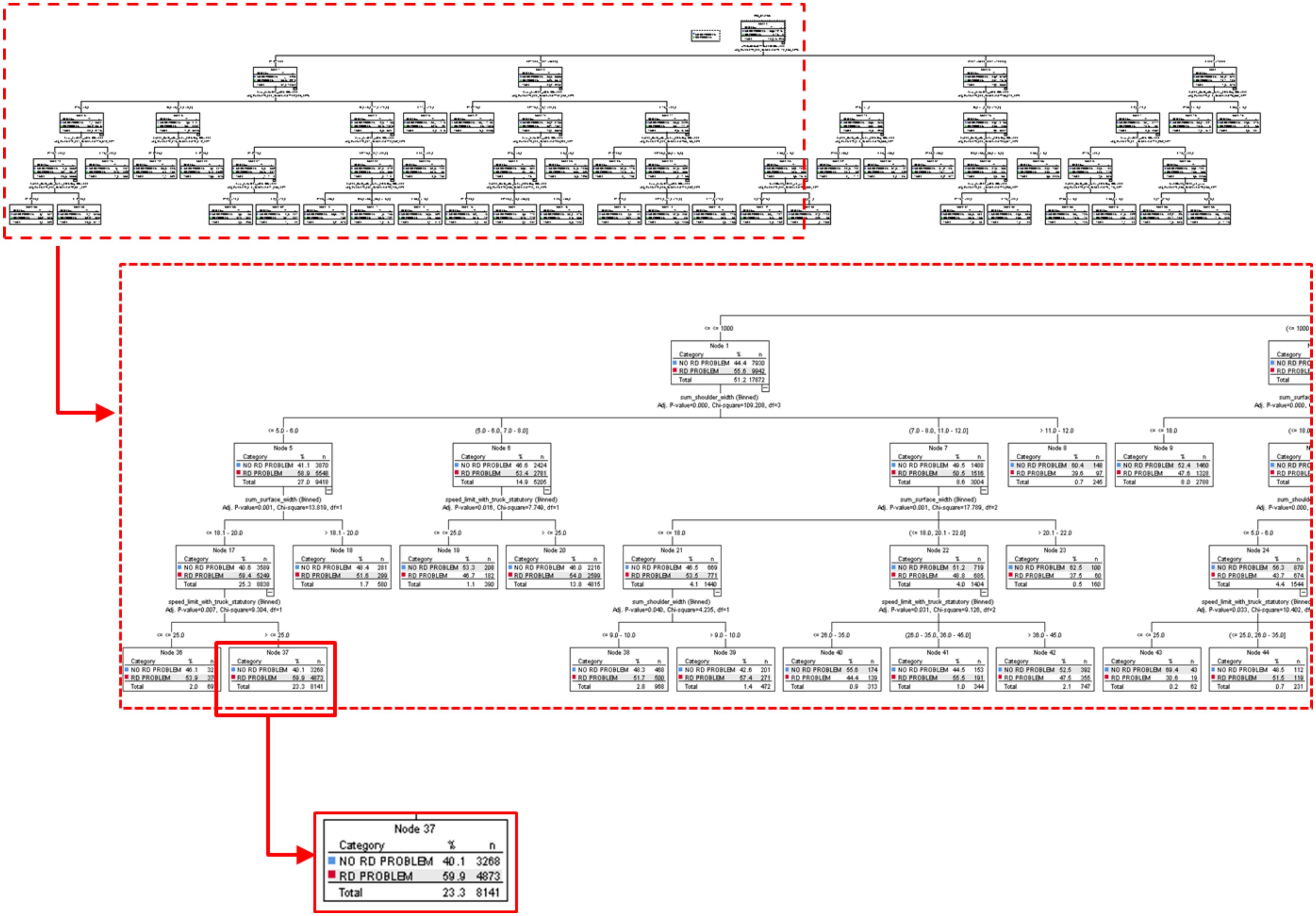


**Figure 7. Overall RD Decision Tree Analysis Result. RD = roadway departure.**

The first split of the tree (at the root node) is the variable "AADT," which is clustered by five different entering volume bands. The four splitting nodes are then split by the sum of shoulder width (Nodes 1 and 3), the sum of surface width (Node 2), and speed limit (Node 4) so that segments are assigned to subgroups defined by these splits. These nodes are then split, and the process is recursively repeated. When the tree construction is completed, 35 terminal nodes (i.e., nodes that do not get split into further subgroups) are generated, each of which has a proportion of either "RD Problem" or "No RD Problem" greater than the overall mean. Of these 35 terminal nodes, Node 37 has the highest percentage of segments with a greater than zero RD-PSI (59.9%, or 4,873, of 8,141 segments; 23.3% of total segments). This indicates that segments matching the conditions in this node might be more likely to benefit from treatments addressing RD crashes. The second and third highest percentages of segments with greater than zero RD-PSI nodes were for Node 46 (57.7%, 30 of 52 segments; 0.2% of total segments) and Node 39 (57.4%, 271 of 472 segments; 1.8% of total segments).

An index percentage was calculated to represent the probability of a group containing relatively more segments with greater than zero RD-PSI versus the overall group/population [(Percent yes for Node x / Percent yes for Node 0) ×100)]. If the index percentage is greater than 100%, the desired target category of the node has a better chance of finding characteristics of the segment group that contains more segments with values greater than the threshold of the target RD crash. The node does not offer strong classification power when it has an index value below 100%. For Node 37, the index percentage is 135.3% (59.9% / 44.2% × 100). Therefore, the identified group of Node 37 has more potential of segments with greater than the zero PSI of RD crashes than the random sample. Consideration was given to choosing multiple nodes with high classification power. However, only the best terminal node was chosen to control the number of segments. As a result of the tree analysis, the characteristics of a two-lane rural roads with a high percentage of RD crashes were as follows:

- AADT ≤ 1,000 AND
- Sum of shoulder widths ≤ 6.0 ft AND
- Sum of surface widths ≤ 20.0 ft AND
- Speed limit > 25 mph.

As shoulder widths and surface widths were treated as the sum of two lanes, those thresholds were divided by two (shoulder widths ≤ 3.0 ft, sum of surface widths ≤ 10.0 ft) for selecting the target road. Table 5 shows the total length (5,461 miles) and total and RD crashes of corresponding target roads among Set A. The percentage of RD crash for target roads was 68.4%, and that for PSI > 0 target road segments was 85.4%. The last column of the table shows 5-year RD crash density per mile; the average RD crash density for RD PSI > 0 segments is about 5 times greater than that for RD PSI < 0 segments.

**Table 5. Overall RD Target Roads**

| Dataset | | Length (miles) | 2014-2018 Total Crash | 2014-2018 RD Crash | % RD Crash | 5-Yr RD Crash/Mile |
|---|---|---|---|---|---|---|
| Target roads | | 5,461 | 14,677 | 10,044 | 68.4 | 1.84 |
| | RD PSI > 0 | 3,015 | 10,198 | 8,704 | 85.4 | 2.89 |
| | RD PSI ≤ 0 | 2,446 | 4,479 | 1,340 | 29.9 | 0.55 |
| Others | | 11,738 | 68,557 | 31,033 | 45.3 | 2.64 |
| Total | | 17,199 | 83,234 | 41,077 | 49.4 | 2.39 |

RD = road departure.

## RD Crash During Darkness

The same decision tree analysis process was performed for RD crash during darkness using Set C, which has an RD PSI greater than zero, as shown in Figure 8. About 53% of the segments at the root node have a PSI greater than 0 for the RD crashes during darkness. Through recursive tree splitting using the five feature variables, a tree consisting of 12 terminal nodes was constructed. Among those, the index percentage of Node 4 was the highest: 140.7% (74.3% / 52.8% × 100). Therefore, the characteristic of two-lane rural roads with a high percentage of RD crash during darkness was AADT > 10,000.

As previously mentioned, the sample for this analysis was Set C, which is different from the overall RD analysis that used Set A. Therefore, the target road feature of the RD crashes under darkness was "AADT > 10,000" of Set C (RD PSI > 0 segments). The bottom row of Table 6 shows the features of the target road segments. In the table, 5-year RD crash under darkness density (crash/mile) of the target road segments is more than 4 times that of others. The higher AADT is likely a factor in the higher crash density; the total miles for this group is small at 25.5.

**Table 6. Target Roads of RD Under Darkness**

| Dataset | | Length (miles) | 2014-2018 RD Crash | 2014-2018 RD Under Darkness Crash | % RD Darkness | RD Darkness Crash Density (crash/mile) |
|---|---|---|---|---|---|---|
| RD PSI > 0 | | 7,863 | 32,372 | 11,611 | 35.9 | 1.48 |
| | RD PSI > 0 only | 7,838 | 31,896 | 11,444 | 35.9 | 1.46 |
| | RD PSI > 0 AND RD under darkness target segments | 25.5 | 476 | 167 | 35.1 | 6.55 |

RD = roadway departure.

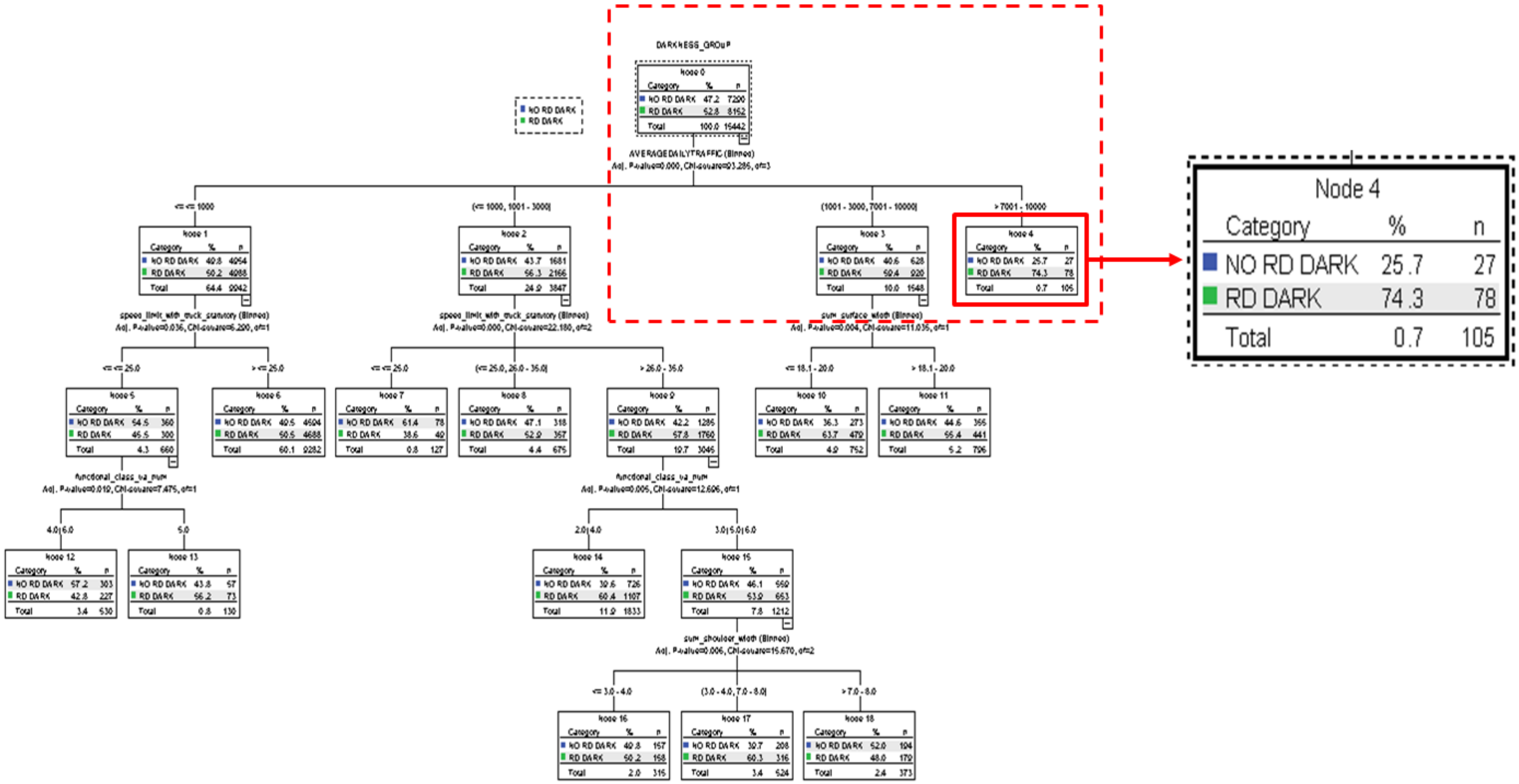


**Figure 8. RD Crash Under Darkness Decision Tree Analysis Result. RD = roadway departure.**

**RD Crashes With Speeding**

Similar to the previous section, a decision tree analysis of RD crash with speeding present was conducted using Set C where the RD PSI is greater than zero. The results are shown in Figure 9. In the figure, the Root Node 1 shows 8,075 (52.3%) segments that have an RD crash with speeding among segments with RD PSI greater than zero. Terminal Node 7 was identified as having the highest index percentage (124.1%) as compared to the other 10 terminal nodes. The intersection features that satisfied the group of Node 7 categories were as follows:

- AADT ≤ 7,000, AND
- Principal Arterial.

The bottom row of Table 7 presents the features of the target road segments. The percentage of RD crash under speeding of target road segments is nearly double that of others, and the 5-year RD crash under speeding (crash/mile) of the target road segments is more than 3 times that of others.

**Table 7. Target Roads of RD With Speeding**

| Dataset | | Length (miles) | 2014-2018 RD Crash | 2014-2018 RD Under Speeding Crash | % RD Speeding | RD Speeding Crash Density (crash/mile) |
|---|---|---|---|---|---|---|
| RD PSI > 0 | | 7,863 | 32,372 | 12,122 | 37.4 | 1.54 |
| | RD PSI > 0 only | 7,802 | 32,045 | 11,904 | 37.1 | 1.52 |
| | RD PSI > 0 AND RD under Speeding Target segments | 61 | 327 | 218 | 66.7 | 3.57 |

RD = roadway departure.

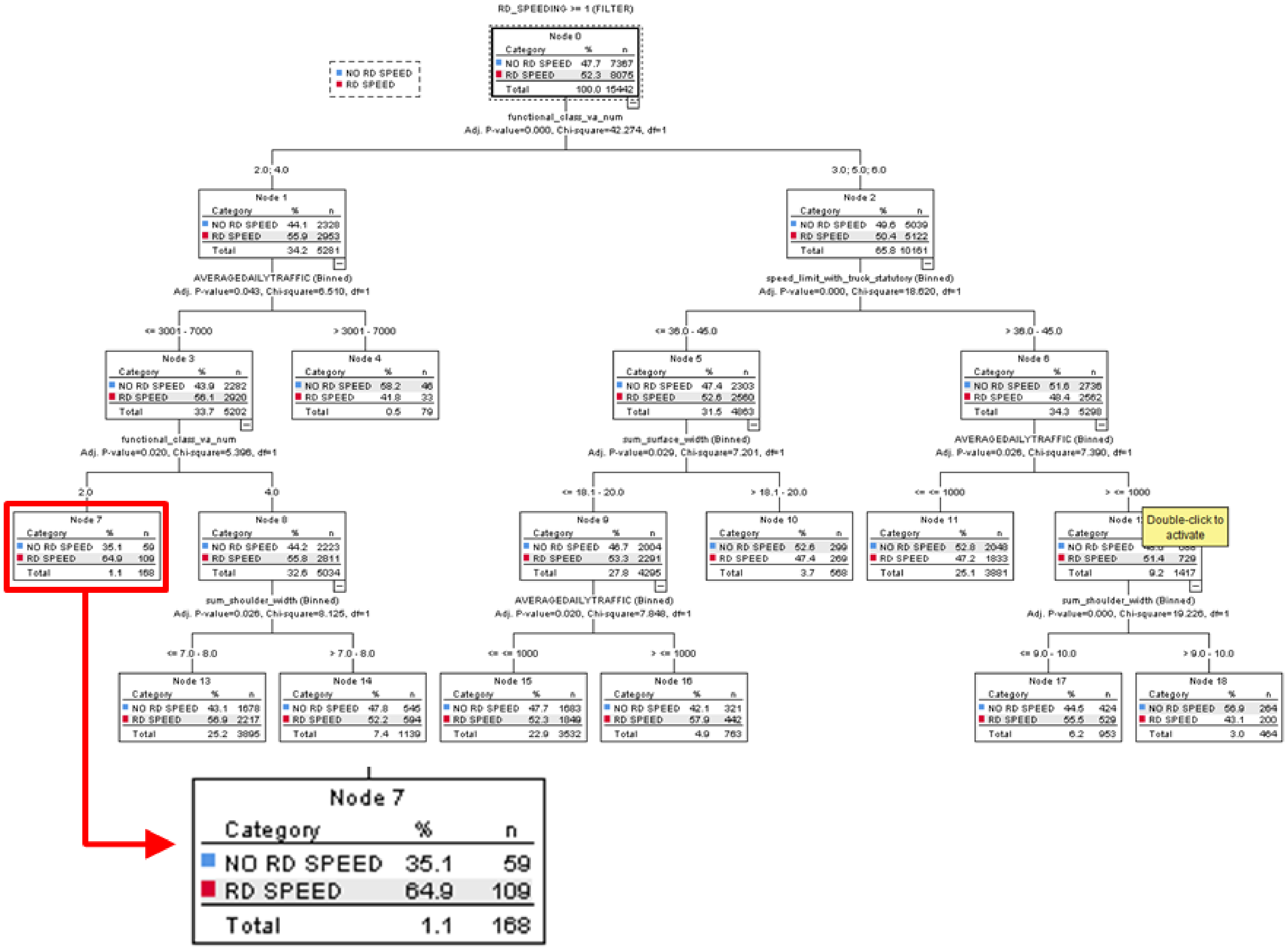


**Figure 9. RD Under Speeding Decision Tree Analysis Result. RD = roadway departure.**

## Statewide Route Review

The RD crash history of the three targeted groups (overall RD crash, RD darkness, and RD speeding) identified in the crash and route analysis was reviewed to gain insight into typical crash patterns at these types of segments. In the study, segments were combined based on routes, and those routes were analyzed again in terms of the percentage of RD PSI > 0 lengths to the total length and number of RD crashes to total crashes. From these, rankings of corridors with a high priority for safety improvement by VDOT district were generated and are provided in the Appendix. This study also produced GIS maps (Figure 10) of (1) ranked corridors of RD crash, (2) RD PSI > 0 segments, (3) RD during speeding segments, and (4) RD during darkness segments, all of which are available from the authors upon request.

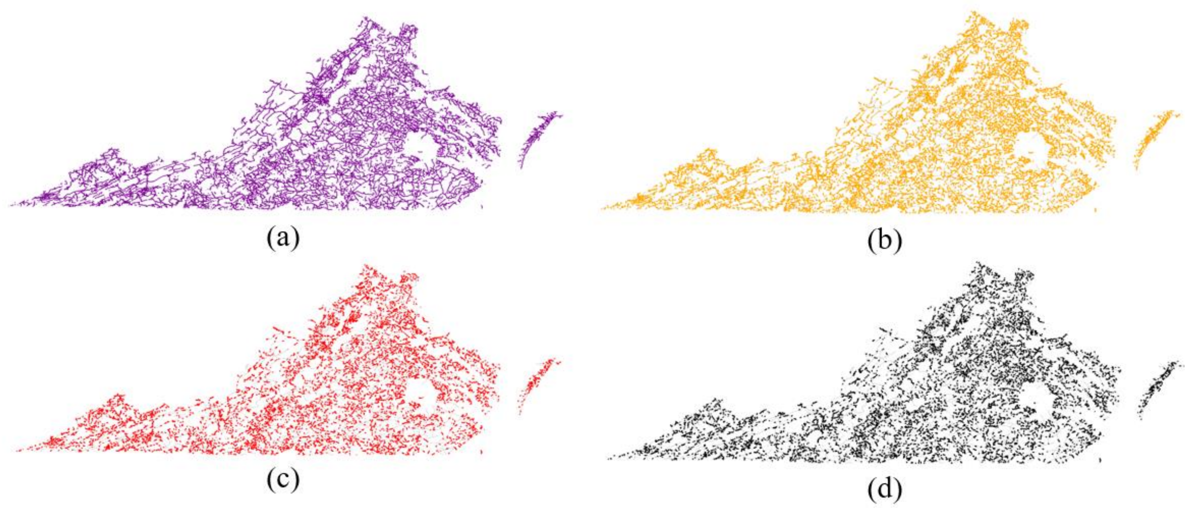


**Figure 10. Statewide Systemic Two-Lane Rural Road RD Screening Result Map: (a) ranked corridors of RD crashes; (b) RD PSI > 0 segments; (c) RD during speeding; (d) RD during darkness. RD = roadway departure.**

# Low-Cost Countermeasures

## RD Countermeasures

For each potential countermeasure, the estimated installation cost, service life, and CMF (if available) are presented in Table 8. Cost can vary from district to district depending on the size of the project and whether state forces or contract labor is used. Most of the estimated (installed) costs were provided by the traffic engineering section of VDOT's Fredericksburg District. Costs indicated in bold type are from VDOT's HSIP (VDOT, unpublished data, 2019), and CMFs indicated in bold type are from the *Virginia State Preferred CMF List* (VDOT, 2019). For CMFs not from the list but instead from the CMF Clearinghouse (n.d.), the standard error and source are identified. Where information including CMFs are not available, it is up to the engineer to determine a value.

**Table 8. Systemic Two-Lane Road Countermeasures With Cost, Service Life, and CMF**

| Countermeasure | Estimated Cost | Estimated Service Life (yr) | CMF | Std. Error | Source |
|---|---|---|---|---|---|
| Curve warning sign (includes sign, advisory speed placard and post/base) | $1,200 | 12 | | | |
| Chevron (includes 2 signs on same post, post, and base) | $800 | 12 | **0.75** | | |
| One-direction large arrow (W1-6) (1 sign, post, base) | $900 | 12 | | | |
| Fluorescent yellow curve warning sign | $1,200 | 12 | 0.82 | 0.084 | (Srinivasan et al., 2009) CMF ID 2432 |
| Fluorescent yellow chevron | $800 | 12 | | | |
| Large curve warning sign (includes 48x48 sign, advisory speed placard, post, base) | $1,500 | 12 | . | | |
| Large chevron (includes two 24x30 chevrons on 1 post/base) | $950 | 12 | 0.946 | 0.136 | (Lyon et al., 2017) CMF ID 8977 |
| Post-mounted delineators (12x36 single panel, post, base) | $700 | 12 | | | |
| Retroreflective posts | $40[a] | 12 | | | |
| Flashing beacons on warning signs | | 12 | | | |
| Flashing LED chevrons | | 12 | | | |
| Dual mounted warning signs (includes 2 standard signs on 1 post/base) | $1,500 | 12 | | | |
| Edge lines Type A paint | $ 0.06 per lf | 2 | 0.921 | NA | (Tsyganov et al., 2009) CMF ID 1937 |
| Wider (6 in) edge lines Type A paint | $0.08 per lf | 2 | **0.635** | | |
| Brighter edge lines Thermoplastic | $0.28 per lf | 2 | **0.81** | | |
| Wider and brighter edge lines Thermoplastic | $0.34 per lf | 2 | | | |
| Centerlines Type A paint | $0.06 per lf | 2 | 0.99 | 0.04 | (Elvik et al., 2004) CMF ID 87 |
| Edge lines and centerlines Type A paint | | | 0.76 | 0.06 | (Elvik et al., 2004) CMF ID 101 |
| Wider centerlines Type A paint | $0.08 per lf | 2 | | | |
| Brighter centerlines Thermoplastic | $0.28 per lf | 2 | **0.81** | | |
| Wider and brighter centerlines Thermoplastic | $0.34 per lf | 2 | | | |
| Curve symbol marking Thermoplastic | $700 | 2 | 0.616 | 0.092 | CMF ID 9167 |
| CURVE or SLOW marking | $1,400 | 2 | | | |
| Roadway lighting (LED, solar powered, motion activated/managed lighting) | | 20 | **0.68** | | |
| Plastic inlaid markers | $43 each[b] | 2 | **0.81** | | |
| Centerline rumble strips | **0.65 per lf** | 15 | **0.55** | | |
| Edge line rumble strips | **0.65 per lf** | 15 | **0.83** | | |
| Transverse rumble strips | $1230[a] | 15 | | | |
| Prohibit passing zones Type A paint | $0.28 per lf | 2 | | | |
| SafetyEdge | **0.40 per lf** | 15 | **0.79** | | |
| Paved shoulder (3-ft trench widening resulting in a 2-ft shoulder) | $20 per lf | 20 | 0.97 | 0.0811 | (Torbic et al., 2009) CMF ID 3622 |
| Clear zone/tree removal (clear zone: a fairly large area; tree removal N/A) | $60,000 per acre | | **0.62** | | |
| Improve sight distance | | | | | |
| Maintain sign visibility (trim vegetation) | | 2 | | | |
| Speed advisory plaques | | | | | |
| Dynamic speed feedback sign | $10,000[c] | | **0.95** | | |
| Dynamic curve warning sign | $10,000[c] | | | | |
| High Friction SurfaceTreatment | | | **0.759** | | |
| Add chevron signs, curve warning signs, and sequential flashing beacons | See above | | **0.592** | | |

| | | | | | |
|---|---|---|---|---|---|
| Upgrade chevrons with fluorescent sheeting | See above | | **0.65** | | |
| Add chevron signs and curve warning signs | See above | | 0.592 | 0.01 | (Lyon et al., 2015) CMF ID 1905 |

*Source:* VDOT's Fredericksburg District unless otherwise noted.
CMF = crash modification factor; N/A = not available. Costs in bold type: VDOT's HSIP (VDOT, unpublished data, 2019). CMFs in bold type: VDOT (2019). CMFs not in bold type: Gibbons et al. (unpublished data) (see VTRC, n.d.) with original source noted.
[a] Cottrell and Lim (2018).
[b] VDOT Traffic Engineering Division, bid tracker for paving contracts, April 2020.
[c] Zineddin et al. (2016).

## Countermeasures by Crash Type

Based on the crash data analysis, countermeasures were divided into three groups by crash type:

1. *RD general:* all countermeasures

2. *RD darkness:* countermeasures that add or improve delineation, such as brighter (more retroreflective) wider markings, larger brighter signing, or delineators

3. *RD speeding:* countermeasures that focus on speed or the need to travel slower, such as SLOW and curve symbol markings, advisory speed plaques, speed feedback signs, and dynamic curve warning signs.

## Countermeasure Configurations

Often these three types of countermeasures are used alone or in combination. Most are currently used by VDOT or others. Such configurations were divided into base and enhanced groups as follows:

*Base:*
1. Curve warning sign
2. Curve warning sign and chevrons.

*Enhanced:*
1. Curve warning sign, chevrons, centerlines, and edge lines
2. Curve warning sign, chevrons, PMDs, centerlines, and edge lines; for long curves, three or four chevrons followed by PMDs to limit the number of chevrons
3. Curve warning sign, chevrons, CLRS, and edge lines
4. Curve warning sign, chevrons, CLRS, edge lines, and plastic inlaid markers (PIMs)
5. Curve warning sign and large chevrons with retroreflective posts, CLRS, edge lines, and PIMs
6. Curve warning sign and chevrons with retroreflective posts, CLRS, edge lines, curve symbol and SLOW markings
7. Fluorescent curve warning sign and fluorescent yellow chevrons with retroreflective posts, CLRS, edge lines, and PIMs.

Although many combinations exist, a possible progression for adding additional countermeasures is presented here. This is by no means the only progression but rather an example of an approach. A possible progression of combinations is as follows:

- Add a centerline if not existing.
- Add a fluorescent yellow curve warning sign and chevrons.
- Add retroreflective posts.
- Add edge lines.
- Add transverse rumble strips.
- Add curve symbol and slow legends.

The following three should be used only if earlier measures are not effective because of the cost of implementation for isolated locations, but they could be considered for a systemic application for long sections or classes of roads.

1. Add PIMs.
2. Add shoulder rumble strips (or stripes since shoulders are typically limited).
3. Add CLRS.

## Plan for Systemic Deployment of Countermeasures

### Process

The process for systemic deployment covers some general principles to consider when investigating countermeasures to deploy and a step-by-step plan for conducting the analysis and deployment. The research team developed the following based on the findings gleaned from this study.

*Principles to Consider*

Some overall guiding principles for the systemic deployment of countermeasures to address RD crashes include the following:

- Consider treating the entire section of road rather than just selecting curves. For example, using markings or CLRS along the entire section may be preferred rather than using them only for select curves.

- Consider the need for maintenance/remarking, especially for markings that have a shorter service life.

- Balance treating an entire section versus treating a curve (consistency versus distinct treatments). For segments with a higher crash frequency, countermeasures may be considered that provide more warning and delineation such as larger signs or retroreflective posts on signs, curve marking symbols, etc. Such segments would be distinct along the road section.

*Step-by-Step Action Plan*

The following is a brief step-by-step process for implementing the RD systemic analysis process. This plan is modeled after the unsignalized intersection systemic improvement plan implemented by VDOT's TED.

1. The TED provides an Excel spreadsheet with candidate sites prioritized by the total number of RD crashes and GIS Shapefile to VDOT's district traffic engineers (DTEs).

2. The DTEs review the list and then plan and conduct safety studies for selected locations.

3. The DTEs select sites and propose treatments and an estimated B/C. This can be an iterative to process to determine the preferred treatments.

4. The DTEs request and then allocate funds for treatment and initiate implementation.

The list of candidate sites was screened based on RD crashes. It would be advantageous to review all crashes along the section as part of the safety study with a focus on RDs to determine if other safety improvements might be beneficial.

**Case Study/Sample Plan**

To demonstrate what the results of a completed safety review might look like, a partial case study is presented for one site. The road section is Route 638 in Warren County, east of Front Royal. This route was eighth on the Staunton District spreadsheet (Appendix, Table A9) based on the number of total RD crashes. Information on this section is summarized here and in Figure 11.

- *Route ID:* 93000638
- *2014-2018 total crashes:* 79
- *2014-2018 total RD crashes:* 65
- *Total lengths of target segments on the route:* 13.61 miles
- *Length of target RD improvement segment:* 7.19 miles
- *Length of target RD dark improvement segment:* 5.47 miles
- *Length of target RD speed improvement segment:* 5.33 miles.

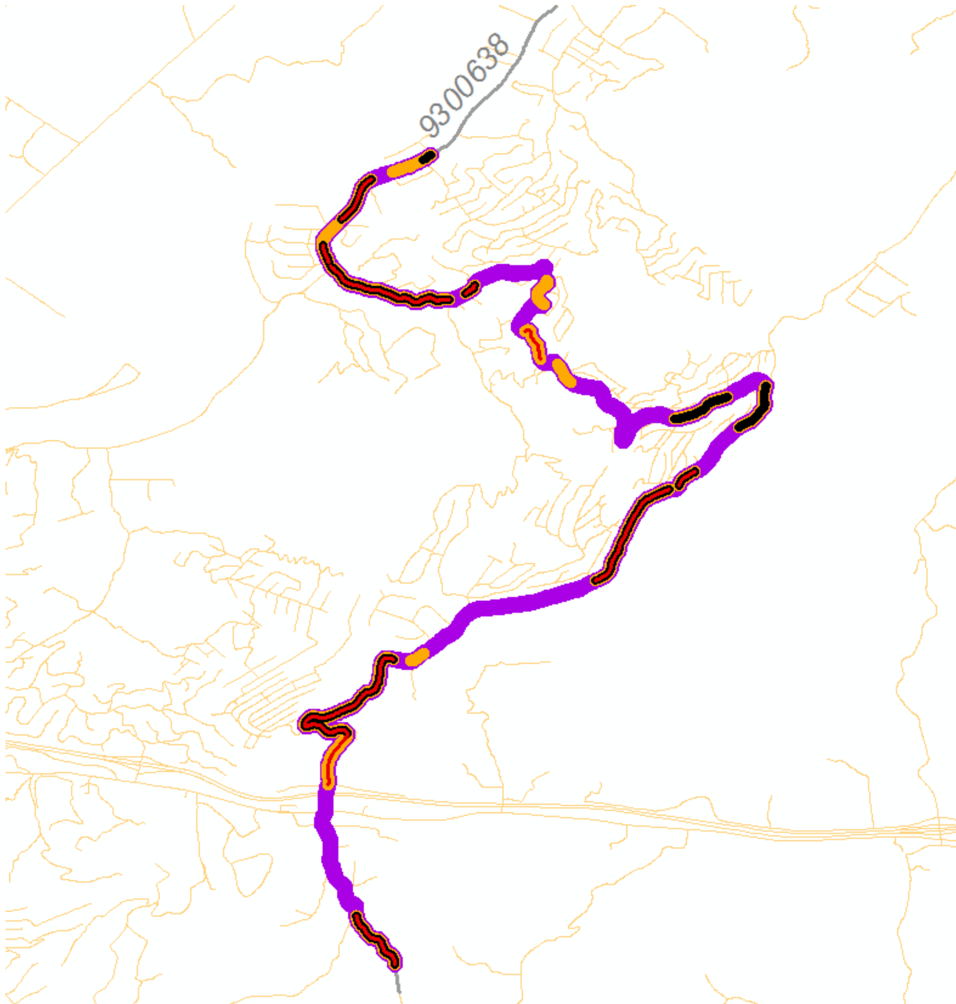


**Figure 11. Example of Target Road's RD Crash on Route 638 in Warren County East of Front Royal. RD = road departure; purple = corridors of RD crash; orange = RD PSI > 0 segments; black = RD darkness; red = RD speeding.**

As can be seen in Figure 11, this section is a winding road section with many curves. VDOT's iVision video log (a web application for pavement and asset management) was used to review the section traveling north. There were approximately 12 curve warning signs, 2 large arrows, and 1 chevron-delineated curve.

Tables 9 and 10 describe some characteristics of the section such as AADT, surface width, presence of centerlines, and speed limit. Table 9 was generated from the analysis database, and Table 10 was generated from a review of VDOT's iVision video log.

**Table 9. Case Study AADT and Surface Width by Section**

| Route Milepoint | AADT (veh/day) | Lane Width (ft) |
|---|---|---|
| 0.230 | 441 | 9.0 |
| 2.000-3.93 | 2566 | 9.0 |
| 4.540-7.13 | 480 | 9.0 |
| 7.13-10.65 | 480 | 8.0 |
| 11.306-12.12 | 1544 | 9.0 |
| 12.510-14.89 | 1871 | 11.0 |

AADT = annual average daily traffic.

**Table 10. Case Study Presence of Centerlines and Speed Limit by Section**

| Route Milepoint | Centerline | Speed Limit (mph) |
|---|---|---|
| 0-1.7 | No | 30 |
| 1.7-5.2 | Yes | 35 |
| 5.2-7.5 | Yes | 45 |
| 7.5-9.8 | No | 35 |
| 9.8-12.9 | Yes | 35 |
| 12.9-14.9 | Yes | End 35 (55) |

The list of crashes sorted by milepost was reviewed to identify clusters of three or more crashes within 0.1 miles. Three clusters were identified. One section with two crashes was added to make four sections. Screenshots of these sections were reviewed using the iVision video. A planning level review was conducted to identify potential countermeasures. Costs and benefits were then estimated. It is possible that a detailed field review could result in different conclusions than this review. Screenshots of the four sections are shown in Figures 12 through 15 to capture the road features and existing traffic control.

**Figure 12. Segment Near MP 2.45**

**Figure 13. Segment Near MP 6.52**

**Figure 14. Segment Near MP 12.71**

**Figure 15. Segment Near MP 2.57**

Table 11 shows the number of crashes for the 5-year period, suggested countermeasures and estimated costs, CMFs, present value benefits and costs, and the B/C for each segment. The CMF for the large arrow sign countermeasure was assumed to be 0.85, and the cost of reflectors on guardrail were estimated at $500. VDOT's HSIP proposal form B/C spreadsheet was used to calculate present value benefits and costs using a 3% discount rate and the B/C. For these four segments, the planning level B/C estimates ranged from 10.8 to 30.1.

Suggestions for other actions for this road segment include refreshing the centerlines as needed; inspecting the existing curve warning signs and delineators and replacing or maintaining them as needed; and adding/replacing reflectors on guardrail as needed since this may delineate curves at a minimal cost. Also, since the speed limit changes multiple times, the speed limit could be reviewed throughout the section. Because each district has numerous sites to study and consider for treatment, there is the option of choosing a higher crash frequency threshold, such as five or more crashes, before countermeasures are considered. This may be viewed as a targeted systemic approach.

**Table 11. Case Study Countermeasures, Costs, Benefits, and B/C**

| Location (MP) | No. Crashes | Counter-measures (CM) | CM Cost ($) | CMFs | Present Value Benefit ($) | Present Value Cost ($) | B/C |
|---|---|---|---|---|---|---|---|
| 2.45-2.48 | 6 | 6 chevrons with retro posts | 5,040 | 0.75 | 59,607 | 5,544 | 10.8 |
| 6.52-6.58 | 3 | Large arrow reflectors on guardrail | 1,400 | 0.85 | 29,803 | 1,540 | 19.4 |
| 12.71-12.8 | 3 | Large arrow | 900 | 0.85 | 29,803 | 990 | 30.1 |
| 2.57-2.58 | 2 | 3 chevrons | 2,400 | 0.75 | 33,115 | 2,640 | 12.5 |

MP = mile point; CMF = crash modification factor; B/C = benefit/cost ratio.

## Discussion

### Roadway Inventory Data for SPFs

This study used VDOT's RD-SPF with AADT and length of segment in a logarithmic functional form model for network screening. The RD-SPF may be improved by adding other roadway features that have been proven to be related to the RD crashes on rural roadways (Appiah and Zhao, 2020), such as shoulder width and horizontal curves of segment. Unfortunately, some of these data, most notably horizontal curvature, are not currently available in VDOT databases. Old Dominion University is working on a project to add roadway horizontal curvature data to VDOT's Roadway Inventory database, so additional consideration of roadway attribute data could improve this analysis in the future.

### Low-Cost Delineation and VDOT TED Project on Road Curvature Data

VDOT has several activities that relate to this study, specifically with regard to systemic safety countermeasures. For the ongoing VTRC study "Guidance for and Effectiveness of Low-Cost Delineation Treatments" (VTRC, n.d.), Gibbons et al. (unpublished data) compiled an extensive spreadsheet list of CMFs from the literature for low-cost delineation countermeasures. That information was used in Table 9, and Gibbons et al. will also develop additional Virginia-specific CMFs. This study will be completed in 2021. The recommendations from this study on the safety effectiveness of countermeasures should be added to the implementation for the systemic safety improvement plan for two-lane rural roads. This study is a strong complement to the current study in that its focus on the safety effectiveness of countermeasures supports this study's emphasis on a data-driven systemic analysis to identify candidate sites for treatment and a process to facilitate the implementation of countermeasures. There may be an interest in combining these results in the future.

### VDOT's Eight Systemic Safety Countermeasures—Implementation Criteria

Eight systemic safety countermeasures are part of VDOT's Systemic Safety Implementation Plan approved by the Commonwealth Transportation Board in September 2019. These eight systemic safety countermeasures include the following:

1. High-Visibility Signal Backplates
2. Flashing Yellow Arrow
3. Pedestrian Crossing Improvements
4. CLRS
5. Edge Line Rumble Strip/Stripes
6. Curve Delineation
7. Unsignalized Intersection Improvements
8. SafetyEdge.

Items 4, 5, 6, and 8 are countermeasures for RD crashes. Funding has already been allocated to install chevrons at all curves that meet the criteria of the *Manual on Uniform Traffic*

*Control Devices for Streets and Highways.* CLRS and edge line rumble strips are planned for primary routes as needed. SafetyEdge is to be used with paving projects as appropriate and ultimately/ideally on every road. The next phase of implementation will include wider edge lines on selected routes. With this activity/plan as a base, the results of this analysis can be used to expand the program further. This could include plans to install rumble strips on secondary routes.

## CONCLUSIONS

- *About 8,000 miles of two-lane rural roads in Virginia had positive PSIs for RD crashes.* VDOT's RD-SPF with AADT and length of segment in a logarithmic functional form model was used for network screening.

- *From the systemic analysis, this study found about 5,500 miles of target segments with roadway characteristics for safety improvement of RD crashes on two-lane rural roads.* Among two-lane rural road RD PSI > 0 segments, target segments with roadway characteristics of RD darkness and RD speeding for crash reduction were also found.

- *A system safety improvement plan was developed combining the RD countermeasure options.* A process to conduct a study of each segment is included in the plan to determine the countermeasures. A conservative planning level B/C estimate ranging from 10 to 30 was successfully estimated using a case study.

## RECOMMENDATIONS

1. *VDOT's TED should lead and promote the systemic safety improvement plan for two-lane rural road RD crashes developed in this study as an element of its safety program.* A partial list of the potential locations to consider that were identified in this study is provided in the Appendix. An Excel spreadsheet with the complete lists will be made available to the TED. The DTE staff should conduct a field review and study of selected sections and then determine the appropriate treatment for implementation and develop an implementation plan.

## IMPLEMENTATION AND BENEFITS

### Implementation

The VDOT TED's Assistant Division Administrator for Safety has agreed to implement Recommendation 1. The TED will develop a plan to implement the results of this study within 18 months of the publication of this report. The plan will include the results of this study along with the results of the ongoing VTRC-funded study "Guidance for and Effectiveness of Low-Cost Delineation Treatments" by Gibbons et al.. which is expected to be finished in 2021 (VTRC, n.d.). Implementation will begin when funding becomes available. Possible funding sources include state funds, funds from the High Risk Rural Roads (HRRR) Program, and SMART SCALE funds.

### Benefits

Implementation of this systemic safety approach to address RD crashes could result in significant improvements in safety across Virginia. In addition to the benefits noted for the systemic safety approach, implementing the study recommendation will help continue the deployment of targeted systemic safety countermeasure projects on two-lane rural roads across Virginia with an ultimate goal of reducing the number of RD crashes. The plan developed in this study targets road sections that have the highest potential for safety improvement. The low-cost approach enables more sections to be treated in a comprehensive manner. Based on the case study example, potential B/C estimates may range from 10 to 30.

## ACKNOWLEDGMENTS

The contributions of the following members of the technical review panel are appreciated: Mark Cole for serving as the project champion and being a member of the technical review panel and the other members of the technical review panel, Justice Appiah, Peter Hedrich, and Keith Rider. VTRC staff who provided assistance included Michael Fitch, Michael Fontaine, and Linda Evans. Thanks are extended to the VTTI research team for their work on the ongoing VTRC-funded project "Guidance for and Effectiveness of Low Cost Delineation Treatments."

It should be noted that In-Kyu Lim, a co-author of this report, is now employed with the FHWA. He worked on this report while previously employed by VDOT as an HSIP Program Manager–Data & Analysis in VDOT's TED. Neither the FHWA nor the U.S. Department of Transportation is responsible for the contents of this report and makes no claims, promises, or guarantees about the accuracy, completeness, or adequacy of its contents.

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# APPENDIX
# LISTS OF RD CRASH HIGH-RISK ROUTES

**Table A1. Bristol RD Crash High-Risk Routes From 2014-2018 Crash Data**

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00016NB | Primary | 0.80 | 77.20 | 34.1 | 146 | 80.2 |
| R-VA US00058EB | Primary | 31.90 | 177.97 | 13.3 | 135 | 64.6 |
| R-VA SR00080NB | Primary | 1.66 | 66.17 | 32.4 | 113 | 79.0 |
| R-VA SR00083EB | Primary | 0.66 | 59.48 | 16.6 | 105 | 65.2 |
| R-VA SR00091NB | Primary | 0.00 | 52.37 | 18.1 | 86 | 77.5 |
| R-VA SR00071EB | Primary | 4.04 | 34.42 | 25.2 | 70 | 75.3 |
| R-VA SR00063NB | Primary | 0.90 | 38.45 | 26.9 | 66 | 81.5 |
| R-VA US00021NB | Primary | 0.96 | 31.51 | 29.4 | 61 | 76.3 |
| R-VA013SC00643NB | Secondary | 0.29 | 15.57 | 60.7 | 60 | 88.2 |
| R-VA SR00072NB | Primary | 7.33 | 48.88 | 20.9 | 58 | 69.9 |
| R-VA SR00067EB | Primary | 0.30 | 22.33 | 29.4 | 50 | 68.5 |
| R-VA092SC00637NB | Secondary | 0.11 | 16.85 | 73.5 | 48 | 88.9 |
| R-VA US00421EB | Primary | 0.35 | 13.01 | 34.1 | 47 | 78.3 |
| R-VA SR00065EB | Primary | 0.20 | 33.58 | 30.1 | 46 | 76.7 |
| R-VA092SC00609NB | Secondary | 0.00 | 11.60 | 56.4 | 41 | 80.4 |
| R-VA US00052NB | Primary | 28.20 | 82.43 | 19.7 | 39 | 67.2 |
| R-VA SR00094NB | Primary | 3.13 | 27.99 | 19.2 | 37 | 68.5 |
| R-VA SR00061EB | Primary | 0.53 | 30.48 | 29.6 | 36 | 73.5 |
| R-VA013SC00624NB | Secondary | 2.15 | 9.21 | 59.3 | 34 | 73.9 |
| R-VA SR00068EB | Primary | 0.00 | 5.21 | 91.3 | 34 | 91.9 |
| R-VA095SC00633EB | Secondary | 0.20 | 17.38 | 43.1 | 34 | 72.3 |

**Table A2. Culpeper RD Crash High-Risk Routes From 2014-2018 Crash Data**

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00020NB | Primary | 20.19 | 84.03 | 21.4 | 192 | 59.8 |
| R-VA US00522NB | Primary | 18.32 | 111.50 | 19.3 | 161 | 66.3 |
| R-VA US00033EB | Primary | 48.23 | 106.81 | 27.6 | 149 | 64.5 |
| R-VA SR00231NB | Primary | 0.90 | 49.39 | 21.8 | 83 | 65.4 |
| R-VA SR00022EB | Primary | 0.04 | 19.22 | 38.6 | 70 | 73.7 |
| R-VA030SC00616NB | Secondary | 0.32 | 20.19 | 49.0 | 65 | 66.3 |
| R-VA030SC00612NB | Secondary | 0.55 | 5.85 | 80.4 | 63 | 76.8 |
| R-VA030SC00806NB | Secondary | 0.00 | 14.23 | 51.6 | 63 | 64.9 |
| R-VA US00250EB | Primary | 77.03 | 118.85 | 10.9 | 58 | 40.3 |
| R-VA030SC00651NB | Secondary | 0.23 | 22.92 | 37.7 | 57 | 77.0 |
| R-VA002SC00810NB | Secondary | 1.06 | 19.73 | 46.0 | 56 | 84.8 |
| R-VA SR00053EB | Primary | 0.84 | 17.53 | 20.7 | 55 | 62.5 |
| R-VA SR00006EB | Primary | 23.10 | 58.93 | 23.1 | 51 | 77.3 |
| R-VA US00211EB | Primary | 24.01 | 31.17 | 56.6 | 50 | 78.1 |
| R-VA SR00028NB | Primary | 3.37 | 12.49 | 29.8 | 49 | 47.6 |
| R-VA054SC00613EB | Secondary | 0.56 | 22.56 | 61.3 | 49 | 86.0 |
| R-VA030SC00688NB | Secondary | 2.58 | 25.77 | 38.7 | 48 | 75.0 |
| R-VA002SC00631NB | Secondary | 1.07 | 8.60 | 79.5 | 47 | 88.7 |
| R-VA SR00208NB | Primary | 1.48 | 23.17 | 17.4 | 45 | 52.9 |
| R-VA023SC00669NB | Secondary | 0.70 | 5.64 | 86.9 | 43 | 65.2 |
| R-VA023SC00729NB | Secondary | 0.46 | 9.99 | 48.0 | 43 | 60.6 |
| R-VA002SC00620NB | Secondary | 0.05 | 6.21 | 95.2 | 43 | 76.8 |

**Table A3. Fredericksburg RD Crash High-Risk Routes From 2014-2018 Crash Data**

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00218EB | Primary | 4.24 | 26.32 | 41.2 | 134 | 77.9 |
| R-VA088SC00601NB | Secondary | 0.25 | 18.36 | 49.2 | 69 | 75.8 |
| R-VA SR00003EB | Primary | 58.25 | 144.19 | 6.8 | 65 | 58.6 |
| R-VA089SC00616NB | Secondary | 0.00 | 9.82 | 60.6 | 58 | 62.4 |
| R-VA SR00014EB | Primary | 0.69 | 70.28 | 20.0 | 58 | 66.7 |
| R-VA SR00198EB | Primary | 0.00 | 22.75 | 28.6 | 55 | 58.5 |
| R-VA088SC00606EB | Secondary | 1.68 | 19.70 | 34.2 | 51 | 52.6 |
| R-VA036SC00614NB | Secondary | 2.00 | 15.90 | 45.4 | 48 | 80.0 |
| R-VA088SC00612NB | Secondary | 0.51 | 22.25 | 45.3 | 44 | 67.7 |
| R-VA088SC00608EB | Secondary | 0.00 | 13.11 | 59.0 | 40 | 74.1 |
| R-VA089SC00627NB | Secondary | 3.65 | 11.97 | 35.4 | 38 | 66.7 |
| R-VA088SC00613NB | Secondary | 3.43 | 11.70 | 35.9 | 34 | 73.9 |
| R-VA036SC00606NB | Secondary | 2.11 | 12.55 | 45.8 | 34 | 91.9 |
| R-VA016SC00721EB | Secondary | 0.00 | 6.34 | 83.5 | 33 | 58.9 |
| R-VA079SC00624NB | Secondary | 2.61 | 16.47 | 42.2 | 30 | 88.2 |
| R-VA089SC00651EB | Secondary | 0.00 | 4.59 | 41.0 | 29 | 70.7 |
| R-VA016SC00652NB | Secondary | 0.00 | 16.24 | 44.9 | 29 | 82.9 |
| R-VA088SC00618EB | Secondary | 1.48 | 6.26 | 57.3 | 28 | 70.0 |
| R-VA088SC00648NB | Secondary | 0.00 | 3.41 | 99.6 | 28 | 93.3 |
| R-VA016SC00658EB | Secondary | 0.00 | 6.54 | 63.1 | 28 | 77.8 |
| R-VA088SC00605EB | Secondary | 1.09 | 12.88 | 40.5 | 28 | 63.6 |
| R-VA050SC00600NB | Secondary | 3.66 | 20.35 | 40.0 | 27 | 75.0 |
| R-VA016SC00601EB | Secondary | 0.40 | 27.85 | 39.2 | 27 | 84.4 |
| R-VA088SC00738NB | Secondary | 1.48 | 12.53 | 40.3 | 26 | 68.4 |
| R-VA SR00030EB | Primary | 6.44 | 41.92 | 8.5 | 25 | 52.1 |
| R-VA036SC00605NB | Secondary | 0.00 | 6.26 | 74.6 | 25 | 83.3 |
| R-VA US00017NB | Primary | 154.18 | 160.74 | 44.5 | 24 | 72.7 |
| R-VA089SC00612NB | Secondary | 2.19 | 8.91 | 48.1 | 24 | 61.5 |
| R-VA089SC00652NB | Secondary | 5.14 | 6.76 | 100.0 | 23 | 76.7 |

Table A4. Hampton Roads RD Crash High-Risk Routes From 2014-2018 Crash Data

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA US00258EB | Primary | 6.39 | 42.97 | 19.2 | 59 | 60.2 |
| R-VA SR00010EB | Primary | 41.89 | 70.15 | 21.3 | 54 | 62.1 |
| R-VA001SC00609NB | Secondary | 0.00 | 15.05 | 65.8 | 48 | 68.6 |
| R-VA046SC00665NB | Secondary | 1.01 | 5.68 | 57.8 | 44 | 67.7 |
| R-VA046SC00620EB | Secondary | 0.17 | 14.99 | 44.8 | 42 | 66.7 |
| R-VA040SC00610NB | Secondary | 1.44 | 9.88 | 54.1 | 34 | 81.0 |
| R-VA SR00040EB | Primary | 194.61 | 227.85 | 23.2 | 34 | 66.7 |
| -VA001SC00679NB | Secondary | 2.47 | 22.50 | 35.8 | 33 | 73.3 |
| R-VA SR00035NB | Primary | 3.05 | 43.94 | 14.4 | 31 | 81.6 |
| R-VA SR00178NB | Primary | 1.34 | 11.46 | 39.2 | 27 | 58.7 |
| R-VA SR00031NB | Primary | 2.59 | 18.14 | 27.8 | 26 | 81.3 |
| R-VA065SC00600NB | Secondary | 1.75 | 31.36 | 33.1 | 26 | 96.3 |
| R-VA046SC00603EB | Secondary | 0.00 | 12.05 | 32.8 | 25 | 83.3 |
| R-VA SR00175EB | Primary | 0.56 | 10.86 | 22.7 | 24 | 43.6 |
| R-VA SR00180EB | Primary | 0.00 | 9.09 | 48.5 | 24 | 85.7 |
| R-VA090SC00617EB | Secondary | 0.36 | 17.40 | 46.0 | 24 | 85.7 |
| R-VA087SC00671EB | Secondary | 0.23 | 14.34 | 23.6 | 23 | 71.9 |
| R-VA040SC00608EB | Secondary | 0.17 | 11.25 | 60.3 | 23 | 79.3 |
| R-VA091SC00602EB | Secondary | 0.91 | 16.42 | 69.7 | 23 | 85.2 |
| R-VA SR00316NB | Primary | 6.42 | 9.09 | 71.5 | 20 | 74.1 |
| R-VA SR00183EB | Primary | 0.00 | 6.49 | 40.5 | 20 | 64.5 |
| R-VA040SC00627NB | Secondary | 6.46 | 13.76 | 59.8 | 20 | 76.9 |

Table A5. Lynchburg RD Crash High-Risk Routes From 2014-2018 Crash Data

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00040EB | Primary | 50.21 | 121.70 | 28.4 | 109 | 77.3 |
| R-VA SR00360EB | Primary | 2.49 | 41.66 | 45.3 | 95 | 67.4 |
| R-VA US00501NB | Primary | 18.54 | 100.19 | 13.2 | 93 | 65.5 |
| R-VA US00060EB | Primary | 69.04 | 139.04 | 27.5 | 93 | 72.7 |
| R-VA SR00151NB | Primary | 2.44 | 32.61 | 27.7 | 70 | 67.3 |
| R-VA SR00057EB | Primary | 47.17 | 88.38 | 35.3 | 57 | 70.4 |
| R-VA071SC00640NB | Secondary | 0.04 | 37.90 | 33.5 | 56 | 67.5 |
| R-VA SR00056EB | Primary | 6.13 | 60.43 | 20.8 | 48 | 78.7 |
| R-VA SR00045NB | Primary | 3.63 | 34.14 | 20.2 | 43 | 68.3 |
| R-VA US00015NB | Primary | 20.97 | 98.54 | 5.1 | 38 | 55.1 |
| R-VA SR00024EB | Primary | 38.57 | 87.23 | 11.2 | 38 | 55.1 |
| R-VA024SC00600NB | Secondary | 0.89 | 27.64 | 38.5 | 35 | 79.5 |
| R-VA041SC00603EB | Secondary | 0.98 | 22.54 | 53.8 | 34 | 72.3 |
| R-VA073SC00604NB | Secondary | 0.99 | 7.26 | 87.5 | 32 | 76.2 |
| R-VA015SC00682NB | Secondary | 7.30 | 13.72 | 60.0 | 31 | 79.5 |
| R-VA071SC00668NB | Secondary | 0.00 | 14.91 | 46.8 | 31 | 83.8 |
| R-VA014SC00636EB | Secondary | 8.74 | 23.50 | 82.2 | 31 | 79.5 |
| R-VA073SC00630NB | Secondary | 0.77 | 18.75 | 55.4 | 30 | 90.9 |
| R-VA015SC00696NB | Secondary | 3.24 | 12.75 | 61.4 | 27 | 84.4 |
| R-VA071SC00703NB | Secondary | 2.40 | 19.86 | 36.9 | 27 | 73.0 |
| R-VA SR00020NB | Primary | 2.41 | 18.20 | 20.0 | 26 | 44.8 |
| R-VA SR00130EB | Primary | 13.58 | 30.25 | 22.7 | 25 | 64.1 |
| R-VA015SC00622EB | Secondary | 5.04 | 11.79 | 62.3 | 25 | 65.8 |
| R-VA071SC00729NB | Secondary | 1.34 | 17.69 | 31.9 | 25 | 61.0 |
| R-VA073SC00658EB | Secondary | 1.27 | 13.43 | 62.3 | 25 | 89.3 |

**Table A6. Northern Virginia RD Crash High-Risk Routes From 2014-2018 Crash Data**

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00009EB | Primary | 0.00 | 8.40 | 61.6 | 98 | 37.5 |
| R-VA US00015NB | Primary | 200.32 | 230.74 | 16.1 | 84 | 38.2 |
| R-VA076SC00619EB | Secondary | 16.40 | 24.55 | 91.5 | 81 | 76.4 |
| R-VA053SC00690NB | Secondary | 1.34 | 15.78 | 44.7 | 53 | 67.1 |
| R-VA053SC00734EB | Secondary | 0.00 | 14.98 | 40.2 | 37 | 68.5 |
| R-VA SR00287NB | Primary | 2.76 | 9.24 | 39.2 | 35 | 44.9 |
| R-VA076SC00611NB | Secondary | 0.60 | 3.44 | 88.7 | 34 | 65.4 |
| R-VA053SC00704NB | Secondary | 1.60 | 5.07 | 72.6 | 33 | 57.9 |
| R-VA053SC00611NB | Secondary | 0.72 | 17.13 | 38.1 | 27 | 67.5 |
| R-VA US00050EB | Primary | 34.79 | 42.29 | 43.8 | 26 | 49.1 |
| R-VA SR00234NB | Primary | 26.82 | 29.70 | 50.3 | 24 | 52.2 |
| R-VA053SC00665NB | Secondary | 1.22 | 5.33 | 52.8 | 15 | 78.9 |
| R-VA053SC00662EB | Secondary | 2.84 | 18.16 | 18.5 | 15 | 68.2 |
| R-VA053SC00672EB | Secondary | 0.08 | 5.21 | 41.0 | 14 | 73.7 |
| R-VA053SC00733EB | Secondary | 3.50 | 10.32 | 69.3 | 13 | 92.9 |
| R-VA053SC00673EB | Secondary | 1.65 | 5.78 | 20.2 | 12 | 92.3 |
| R-VA053SC00722NB | Secondary | 3.47 | 4.58 | 99.8 | 12 | 75.0 |
| R-VA076SC00646EB | Secondary | 0.55 | 7.87 | 25.2 | 12 | 44.4 |
| R-VA053SC00671NB | Secondary | 1.11 | 7.55 | 36.3 | 12 | 37.5 |
| R-VA053SC00626NB | Secondary | 1.26 | 13.56 | 31.4 | 12 | 75.0 |
| R-VA053SC00661EB | Secondary | 0.00 | 5.47 | 51.3 | 11 | 73.3 |
| R-VA053SC00719NB | Secondary | 2.45 | 16.96 | 20.7 | 11 | 64.7 |
| R-VA053SC00711EB | Secondary | 3.39 | 10.25 | 48.9 | 10 | 43.5 |

Table A7. Richmond RD Crash High-Risk Routes From 2014-2018 Crash Data

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA020SC00602EB | Secondary | 0.00 | 18.13 | 65.2 | 92 | 63.9 |
| R-VA US00033EB | Primary | 108.09 | 123.70 | 32.7 | 75 | 54.7 |
| R-VA012SC00611EB | Secondary | 0.85 | 22.90 | 60.8 | 62 | 75.6 |
| R-VA020SC00626NB | Secondary | 0.14 | 9.48 | 66.7 | 61 | 50.0 |
| R-VA042SC00623EB | Secondary | 0.57 | 9.27 | 69.3 | 54 | 63.5 |
| R-VA072SC00711EB | Secondary | 0.00 | 11.66 | 53.7 | 54 | 64.3 |
| R-VA058SC00903NB | Secondary | 0.33 | 16.92 | 60.1 | 48 | 71.6 |
| R-VA004SC00616NB | Secondary | 0.00 | 23.00 | 47.9 | 46 | 76.7 |
| R-VA SR00054EB | Primary | 3.73 | 18.56 | 34.0 | 45 | 53.6 |
| R-VA042SC00606EB | Secondary | 3.82 | 15.27 | 34.3 | 43 | 76.8 |
| R-VA020SC00604EB | Secondary | 0.00 | 4.52 | 100.0 | 41 | 77.4 |
| R-VA US00522NB | Primary | 2.53 | 17.18 | 32.8 | 41 | 59.4 |
| R-VA SR00010EB | Primary | 30.10 | 41.81 | 50.0 | 41 | 64.1 |
| R-VA SR00040EB | Primary | 122.43 | 190.91 | 13.7 | 41 | 63.1 |
| R-VA SR00013EB | Primary | 7.19 | 23.91 | 40.6 | 34 | 72.3 |
| R-VA SR00092NB | Primary | 0.47 | 15.30 | 55.4 | 34 | 72.3 |
| R-VA SR00249EB | Primary | 0.91 | 17.87 | 23.2 | 33 | 54.1 |
| R-VA012SC00644NB | Secondary | 0.89 | 26.05 | 40.1 | 33 | 80.5 |
| R-VA012SC00634NB | Secondary | 1.20 | 16.57 | 60.3 | 32 | 86.5 |
| R-VA037SC00632NB | Secondary | 0.03 | 3.21 | 63.2 | 31 | 60.8 |
| R-VA042SC00657EB | Secondary | 0.04 | 17.71 | 33.8 | 30 | 69.8 |
| R-VA042SC00715NB | Secondary | 0.06 | 15.89 | 45.4 | 29 | 78.4 |
| R-VA020SC00631NB | Secondary | 0.00 | 3.66 | 76.0 | 28 | 73.7 |
| R-VA020SC00611EB | Secondary | 0.05 | 3.84 | 78.9 | 28 | 47.5 |
| R-VA026SC00613EB | Secondary | 0.00 | 32.84 | 30.0 | 28 | 87.5 |

**Table A8. Salem RD Crash High-Risk Routes From 2014-2018 Crash Data**

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA SR00122NB | Primary | 5.07 | 54.80 | 19.3 | 131 | 49.1 |
| R-VA SR00008NB | Primary | 5.43 | 54.33 | 27.2 | 111 | 62.0 |
| R-VA SR00311NB | Primary | 4.15 | 41.22 | 30.4 | 90 | 73.2 |
| R-VA060SC00603EB | Secondary | 0.46 | 15.58 | 71.7 | 85 | 77.3 |
| R-VA SR00024EB | Primary | 9.34 | 35.58 | 24.6 | 72 | 62.1 |
| R-VA SR00040EB | Primary | 0.68 | 49.83 | 25.7 | 66 | 55.5 |
| R-VA US00058EB | Primary | 203.31 | 234.92 | 26.7 | 63 | 70.0 |
| R-VA033SC00619EB | Secondary | 0.00 | 20.40 | 54.4 | 63 | 69.2 |
| R-VA SR00043NB | Primary | 9.47 | 60.23 | 26.9 | 62 | 92.5 |
| R-VA017SC00620NB | Secondary | 0.33 | 24.40 | 34.4 | 54 | 71.1 |
| R-VA060SC00615NB | Secondary | 0.09 | 8.57 | 60.1 | 53 | 59.6 |
| R-VA033SC00834NB | Secondary | 2.81 | 10.69 | 68.6 | 52 | 66.7 |
| R-VA044SC00687EB | Secondary | 0.51 | 18.14 | 40.7 | 43 | 84.3 |
| R-VA US00011NB | Primary | 110.94 | 178.51 | 4.7 | 42 | 60.0 |
| R-VA009SC00619EB | Secondary | 0.74 | 11.59 | 48.0 | 41 | 83.7 |
| R-VA060SC00663NB | Secondary | 0.00 | 4.52 | 91.2 | 40 | 67.8 |
| R-VA009SC00746EB | Secondary | 0.00 | 11.63 | 56.4 | 39 | 84.8 |
| R-VA SR00042NB | Primary | 55.41 | 108.94 | 24.6 | 39 | 72.2 |
| R-VA SR00116NB | Primary | 0.30 | 10.13 | 33.7 | 37 | 56.9 |
| R-VA SR00057EB | Primary | 1.80 | 35.83 | 11.1 | 37 | 74.0 |
| R-VA077SC00627EB | Secondary | 2.21 | 5.47 | 99.5 | 36 | 80.0 |
| R-VA033SC00676NB | Secondary | 0.95 | 3.80 | 88.2 | 35 | 94.6 |
| R-VA033SC00670EB | Secondary | 0.16 | 7.71 | 61.3 | 35 | 52.2 |
| R-VA SR00100NB | Primary | 1.11 | 52.08 | 6.1 | 34 | 73.9 |
| R-VA033SC00890EB | Secondary | 0.36 | 20.53 | 35.7 | 33 | 80.5 |
| R-VA US00501NB | Primary | 83.98 | 93.14 | 39.3 | 31 | 83.8 |
| R-VA033SC00636NB | Secondary | 0.44 | 7.85 | 54.1 | 31 | 75.6 |
| R-VA033SC00697EB | Secondary | 0.51 | 8.53 | 57.7 | 31 | 62.0 |

Table A9. Staunton RD Crash High-Risk Routes From 2014-2018 Crash Data

| Route Name | Road Classification | RD PSI > 0 Starting Mile Point | RD PSI > 0 Ending Mile Point | % RD PSI > 0 Length in Length of Ending-Starting Mile Point | Total No. of RD Crashes for 5 Years (2014-2018) | % RD Crash in Total Crash |
|---|---|---|---|---|---|---|
| R-VA US00340NB | Primary | 20.05 | 93.04 | 12.7 | 117 | 60.0 |
| R-VA SR00042NB | Primary | 155.28 | 268.91 | 14.4 | 103 | 64.4 |
| R-VA US00250EB | Primary | 0.02 | 54.28 | 39.9 | 98 | 86.0 |
| R-VA SR00039EB | Primary | 1.97 | 58.09 | 28.3 | 90 | 85.7 |
| R-VA SR00055EB | Primary | 0.03 | 33.93 | 21.8 | 78 | 68.4 |
| R-VA007SC00608NB | Secondary | 1.18 | 28.51 | 33.5 | 72 | 85.7 |
| R-VA US00033EB | Primary | 0.00 | 17.34 | 38.8 | 68 | 71.6 |
| R-VA093SC00638NB | Secondary | 0.23 | 13.84 | 52.8 | 65 | 82.3 |
| R-VA034SC00600NB | Secondary | 4.29 | 36.55 | 42.1 | 58 | 78.4 |
| R-VA US00220NB | Primary | 128.82 | 183.51 | 19.8 | 55 | 85.9 |
| R-VA085SC00678NB | Secondary | 0.89 | 20.33 | 59.9 | 52 | 89.7 |
| R-VA085SC00675EB | Secondary | 0.00 | 21.28 | 43.4 | 44 | 77.2 |
| R-VA SR00252NB | Primary | 1.91 | 26.99 | 42.8 | 44 | 86.3 |
| R-VA007SC00616EB | Secondary | 2.69 | 10.81 | 74.9 | 42 | 91.3 |
| R-VA082SC00613NB | Secondary | 1.36 | 29.53 | 27.6 | 41 | 71.9 |
| R-VA SR00018NB | Primary | 9.10 | 23.25 | 45.3 | 39 | 73.6 |
| R-VA007SC00612EB | Secondary | 0.12 | 21.65 | 31.5 | 38 | 69.1 |
| R-VA082SC00612NB | Secondary | 2.39 | 20.22 | 40.2 | 37 | 94.9 |
| R-VA093SC00619NB | Secondary | 2.46 | 8.65 | 76.0 | 35 | 76.1 |
| R-VA SR00259NB | Primary | 2.23 | 22.57 | 14.9 | 33 | 62.3 |
| R-VA081SC00631EB | Secondary | 3.22 | 15.04 | 37.6 | 33 | 97.1 |
| R-VA081SC00608NB | Secondary | 5.52 | 32.49 | 27.7 | 33 | 75.0 |
| R-VA085SC00623NB | Secondary | 0.00 | 25.85 | 29.2 | 32 | 74.4 |
| R-VA093SC00649NB | Secondary | 0.26 | 7.05 | 48.8 | 31 | 83.8 |
| R-VA SR00254EB | Primary | 0.48 | 18.33 | 12.9 | 29 | 70.7 |
| R-VA SR00263EB | Primary | 2.32 | 12.49 | 37.6 | 29 | 90.6 |
| R-VA SR00056EB | Primary | 0.10 | 5.42 | 71.3 | 28 | 90.3 |
| R-VA US00501NB | Primary | 100.19 | 107.31 | 55.3 | 28 | 71.8 |
| R-VA US00050EB | Primary | 0.33 | 2.61 | 74.1 | 27 | 61.4 |
| R-VA093SC00603NB | Secondary | 1.43 | 5.20 | 87.2 | 25 | 78.1 |