# Development of Speed Crash Modification Factors (CMFs) Using SHRP2 Roadway Information Database (RID), Volume I: Final Report

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U.S. Department of Transportation
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## FOREWORD

This research was conducted under transportation pooled fund study TPF-5(361): *SHRP2 Naturalistic Driving Study Pooled Fund: Advancing Implementable Solutions* (NCHRP 2023), for which the goal is to develop novel, multidisciplinary solutions based on recorded natural behavior of vehicle operators interacting with infrastructure and other vehicles. Speed can have serious safety impacts, especially on the severity of crashes. However, these effects are complex and generally have not been captured in the *Highway Safety Manual* (HSM) (American Association of State Highway and Transportation Officials 2010). This project developed speed-related crash modification factors (CMFs) for the existing crash prediction models of the HSM.

The project used three databases from the States of Washington and North Carolina: roadway geometric and operational data from the Second Strategic Highway Research Program Roadway Information Database; operating speed data from the National Performance Management Research Dataset; and crash data from the Highway Safety Information System (Iowa State University of Science and Technology 2023; National Academies of Sciences 2023; RITIS 2023; Federal Highway Administration (FHWA) n.d.). Speed-related CMFs for 12 different roadway facility types covering rural highways, urban and suburban arterials, and rural and urban freeways were developed. These CMFs were prepared to meet the quality standards for CMF Clearinghouse (FHWA 2023a) submission. The research demonstrates that inclusion of speed CMFs can improve crash prediction precision for certain facility types. The speed CMF development approach used in this study can be used to develop speed CMFs at the jurisdiction level, if required data are available.This research will be of interest to roadway designers, safety professionals, and others with an interest in speed management. This volume is the first in a series. The other volume in the series is FHWA-HRT-24-130, Volume II: *Development of Speed Crash Modification Factors (CMFs) Using SHRP2 Roadway Information Database (RID): Appendices.*

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Acting Director, Office of Safety and Operations
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16. Abstract
Speed is widely recognized as having significant safety impacts, especially on the severity of crashes. However, these effects are complex and generally have not been captured in the *Highway Safety Manual* (HSM) (American Association of State Highway and Transportation Officials 2010). The current Federal Highway Administration (FHWA) project developed speed-related crash modification factors (CMFs) for 12 different roadway facility types—rural highways, urban and suburban arterials, and rural and urban freeways—by using Washington and North Carolina data from three major databases: Second Strategic Highway Research Program Roadway Information Database, National Performance Management Research Dataset, and Highway Safety Information System (VTTI 2020; Iowa State University of Science and Technology 2023; National Academies of Sciences 2023; RITIS 2023; FHWA n.d.). The results show that speed variation (e.g., operating speed standard deviation) was the dominant speed measure for rural highways and rural and urban freeways, and speed differential (i.e., difference between the posted speed limit and average operating speed) was the dominant speed measure for urban and suburban arterials. In most cases, the association of speed variation/differential with crashes is positive. The researchers developed CMFs for 129 crash types and severity levels, and most CMFs obtained three-star CMF Clearinghouse ratings (American Association of State Highway and Transportation Officials 2010; FHWA 2023a). These CMFs were developed through a data-driven safety analysis approach, and application of these CMFs (e.g., in HSM-related evaluation tools) requires careful interpretation. The findings show that inclusion of speed-related CMFs improves model precision. While this study focused on Washington and North Carolina data, other States can use the documented approach to develop speed-related CMFs for their own jurisdictions. This volume is the first in a series. The other volume in the series is FHWA-HRT-24-130, Volume II: *Development of Speed Crash Modification Factors (CMFs) Using SHRP2 Roadway Information Database (RID): Appendices*.

17. Key Words
Speed, safety, crash modification factor, *Highway Safety Manual*, SHRP2 RID, NPMRDS, HSIS

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| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | **NOTE**: volumes greater than 1,000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2,000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2,000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/m2 | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 2.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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| | |
|---|---|
| AADT | annual average daily traffic |
| AASHTO | American Association of State Highway and Transportation Officials |
| CF | calibration factor |
| CMF | crash modification factor |
| CURE | cumulative residuals |
| CV | coefficient of variation |
| DDSA | data-driven safety analysis |
| FHWA | Federal Highway Administration |
| FI | fatal and injury |
| HSIS | Highway Safety Information System |
| HSM | *Highway Safety Manual* |
| IHSDM | Interactive Highway Safety Design Model |
| KABCO | KABCO crash severity scale (K = fatal, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, and O = no injury, property damage only) |
| MAD | mean absolute deviation |
| MV | multiple vehicle |
| MVFI | multiple-vehicle fatal and injury crashes |
| MVPDO | multiple-vehicle property damage-only crashes |
| NCDOT | North Carolina Department of Transportation |
| NPMRDS | National Performance Management Research Dataset |
| PDO | property damage only |
| PSL | posted speed limit |
| R2U | undivided rural two-lane, two-way roadway segments |
| R4D | rural four-lane divided segments |
| R4U | rural four-lane undivided segments |
| RID | Roadway Information Database |
| RMSE | root mean squared error |
| SHRP2 | Second Strategic Highway Research Program |
| SPF | safety performance function |
| Spd85 | 85th percentile operating speed |
| SpdAve | average operating speed |
| SpdFF85 | 85th percentile free-flow operating speed |
| SpdFFAve | average free-flow operating speed |
| SpdStd | standard deviation of average operating speed |
| SV | single vehicle |
| SVFI | single-vehicle fatal and injury crashes |
| SVPDO | single-vehicle property damage-only crashes |
| U2U | two-lane undivided urban and suburban arterial segments |
| U3T | three-lane urban and suburban arterials including a center two-way left-turn lane |
| U4D | four-lane divided urban and suburban arterials (including a raised or depressed median) |
| U4U | four-lane undivided urban and suburban arterial segments |
| U5T | five-lane urban and suburban arterials including a center two-way left-turn lane |

| | |
|---|---|
| U6D | six-lane divided urban and suburban arterials (including a raised or depressed median) |
| U6U | six-lane undivided urban and suburban arterial segments |
| U7T | seven-lane urban and suburban arterials including a center two-way left-turn lane |
| U8D | eight-lane divided urban and suburban arterials including a raised or depressed median |
| WSDOT | Washington State Department of Transportation |

# CHAPTER 1. INTRODUCTION AND OBJECTIVES

Investigating the effects of operating speed, roadway geometry, and traffic exposure on crash outcomes would significantly improve our understanding of traffic safety and would lead to subsequent improvements in roadway safety. If these relationships are well understood and defined, the information can be used to advance existing safety improvement procedures to reduce crash frequencies and crash severities. Data-driven methods should be used to better understand the relationships. Conventional assessments typically use the corridor traffic volume and physical site characteristics. The lack of reliable operating speed data is the primary limitation on the development of reliable models of this relationship, especially on rural roadways.

Speed is widely recognized as having serious safety impacts, especially on the severity of crashes. However, these effects are complex and generally have not been captured in the *Highway Safety Manual* (HSM) Part C crash prediction models (American Association of State Highway and Transportation Officials (AASHTO) 2010). These models include safety performance functions (SPFs), which the researchers developed based on the traffic exposure (annual average daily traffic (AADT) and segment lengths), and crash modification factors (CMFs), which capture the effect of other roadway and traffic characteristics. However, no developed CMF reflects the direct effect of operating speed or speed differentials (i.e., operating speed versus posted speed) on safety. The few places in HSM Part C that reflect the partial effect of speed on safety are:

- The CMF for the effect of automated speed enforcement (several chapters).
- A speed category (low versus intermediate or high) included in the vehicle-pedestrian crash prediction models in chapter 12 ("Urban/Suburban Arterials").
- The entering curve speed in the curve CMF on-ramp crash prediction models in chapter 19 ("Ramps").
- National Cooperative Highway Research Program (NCHRP) Project 17-68 (Torbic, Porter, and Medina 2021), titled *Intersection Crash Prediction Methods for the Highway Safety Manual*, which contains some models for intersections of high-speed (50 mph or higher on the major roads) urban and suburban arterials. (These models are expected to be included in the second edition of the HSM.)

Studies have shown that a vehicle's operating speed during a crash can affect the injury severity of crash victims and that the speed differential between vehicles can affect crash frequencies. Rosen and Sander (2009) found that fatality risks are highly related to impact speed. Intuitively, speed plays a significant role in safety; however, evidence of a direct association between operational speed measures and crash counts is limited. Safety professionals expect that speed also influences crash likelihood, but this relationship is more complex and not as well understood. Table 17 (appendix B in volume II of this report) lists the key findings of the major studies on speed-crash association (Das et al. 2024). The results show that speed-crash association requires additional investigation due to the inconclusive findings.

The Second Strategic Highway Research Program (SHRP2) Roadway Information Database (RID) contains roadway and crash data from six States (Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington) (National Academies of Sciences 2023; Iowa State University of Science and Technology (ISU) 2023). The six geodatabases of the RID include data for more than 200,000 mi of highways between all six States. This database also includes detailed information on about 12,500 mi of highways in these States. These data are called RID mobile data and are a rich source of information when details are needed to apply crash prediction models. The National Performance Management Research Dataset (NPMRDS) database contains travel time data for 5-min epochs for National Highway System roadways (RITIS 2023). RID data do not have operating speed-related information. Both databases are developed on a spatial network of links matched by greater than 85 percent. Linking these two databases provides researchers with a rich source of data with roadway, crash, and operating speed characteristics.

Additionally, the Highway Safety Information System (HSIS) is a multistate database that contains crash data, roadway information, and traffic volume data for a select group of States (California, Illinois, North Carolina, Maine, Ohio, Michigan, Utah, Minnesota, Washington, and the city of Charlotte, NC). The presence of different variables in these datasets in a single database provides researchers with a unique opportunity to study the effect of operating speed and/or operating and posted speed differentials on crash frequency and/or crash severity. The most useful of these effects would be the development of speed-related CMFs for the HSM (AASHTO 2010) crash prediction models, which supports data-driven safety analysis (DDSA).

The common States among the three aforementioned databases are North Carolina and Washington, which the research team, therefore, selected for this research study.

This report summarizes research activities performed for part B of the project, "Development of Speed CMFs Using SHRP2 RID Section" (Federal Highway Administration (FHWA) 2023c). The project was divided into two parts: part A and part B. Part A included tasks 1–4 of the work plan. Tasks 1–3 covered the project kickoff meeting, the project work plan, and the webinar[1] of planned research, respectively. The webinar was delivered on May 28, 2020, to a broad audience, supporting efforts to disseminate the goals and work plan of the project and to conduct outreach to different groups in the transportation community. Task 4 included the technical and research efforts of part A, which were intended to determine the feasibility of a larger, more complete analysis in part B and to produce final research products. Part B included task 5, which was to continue the implementation of the work plan under part B.

The main objective of this research was to develop speed-related CMFs for the existing crash prediction models of the HSM. In part A, the main objectives focused on the feasibility of the speed CMF development by using rural two-lane and rural multilane undivided roadways. The analysis used three databases (RID, NPMRDS, and HSIS) for these two facilities in Washington and North Carolina (ISU 2023; RITIS 2023; FHWA n.d.). In part B, the main objective was the

[1]Subasish Das and Seyedehsan Dadvar, Development of Speed Crash Modification Factors (CMFs) Using SHRP2 Roadway Information Database (RID) Webinar, May 28, 2020.

expansion of the work done in part A by speed CMF development for different rural highways, urban and suburban arterials, and rural and urban freeways in North Carolina and Washington.

The following chapters (in volume I) include data acquisition and preparation, which contain descriptions of the main datasets used in this study and the analysis performed to develop speed CMFs on the selected rural and urban facility types. The report concludes with a summary of findings. Several appendices (in volume II of this report) provide detailed information on data acquisition, preparation, and manual data collection; supporting tables; and details of developed speed CMFs by different severity levels (total, fatal and injury (FI), and property damage-only (PDO) crashes) and crash types (single vehicle (SV) and multiple vehicle (MV)) (Das et al. 2024).

# CHAPTER 2. DATA ACQUISITION AND PREPARATION

## INTRODUCTION

This chapter provides a brief description of the datasets as well as the data acquisition and preparation framework.

## DATA SOURCES

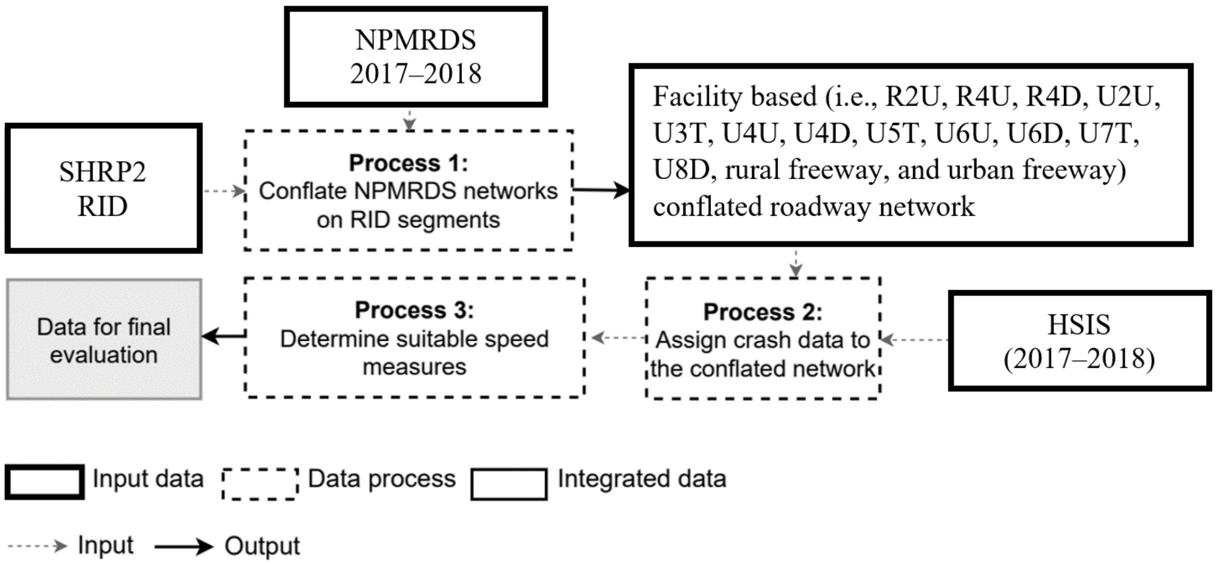
To perform the analysis, the research team used the following three datasets for both Washington and North Carolina:

1. Crash data from the HSIS (2017–18) (FHWA n.d.).
2. Roadway geometric and operational data from the RID (2010–12) (ISU 2023).
3. Operating speed data from the NPMRDS (2017–18) (RITIS 2023).

## DATA PREPARATION AND REDUCTION

To prepare the data for the analysis, the researchers adopted three processes, as illustrated in figure 1. The first process involves the conflation of the RID network with the NPMRDS network (ISU 2023; RITIS 2023). The team considered the following 14 facility types during the conflation process:

1. Undivided rural two-lane, two-way roadway segment (R2U).
2. Rural four-lane undivided segment (R4U).
3. Rural four-lane divided segment (R4D).
4. Two-lane undivided urban and suburban arterial segment (U2U).
5. Three-lane urban and suburban arterial, including a center two-way, left-turn lane (U3T).
6. Four-lane undivided urban and suburban arterial segment (U4U).
7. Four-lane divided urban and suburban arterial (i.e., including a raised or depressed median) (U4D).
8. Five-lane urban and suburban arterial, including a center two-way, left-turn lane (U5T).
9. Six-lane undivided urban and suburban arterial segment (U6U).
10. Six-lane divided urban and suburban arterial (i.e., including a raised or depressed median) (U6D).
11. Seven-lane urban and suburban arterial, including a center two-way, left-turn lane (U7T).
12. Eight-lane divided urban and suburban arterial, including a raised or depressed median (U8D).
13. Rural freeway.
14. Urban freeway.




Source: FHWA.

**Figure 1. Flowchart. Data preparation.**

In the second process, the team assigned crash data to the conflated network from the first process. Finally, the team selected suitable speed measures in the third process. Additional details on data preparation are described in appendix A in volume II of this report (Das et al. 2024). Figure 1 describes the overall data process for the data acquisition and preparation.

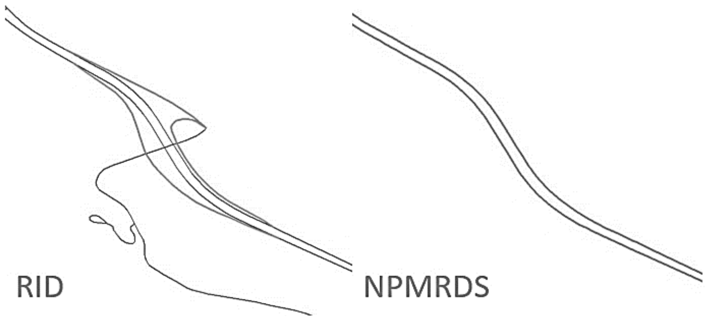
This project required the conflation of two linear networks (RID and NPMRDS) (ISU 2023; RITIS 2023). In this study, the team aggregated crashes by severity as total (KABCO), FI, and PDO crashes using the KABCO scale (AASHTO 2010), where:

- K = fatal.
- A = incapacitating injury.
- B = non-incapacitating injury.
- C = possible injury.
- O = no injury; PDO.

Moreover, the researchers categorized crash data by SV and MV crashes according to HSM definitions of these crash types (AASHTO 2010). The combination of crash severity and type resulted in the following seven crash aggregations:

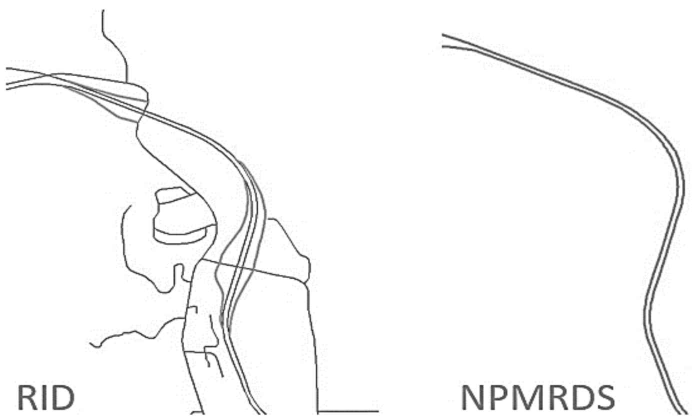
- KABCO = total crashes.
- KABC = fatal and injury crashes.
- O = property damage-only crashes.
- SVFI = single-vehicle fatal and injury crashes.
- SVPDO = single-vehicle property damage-only crashes.
- MVFI = multiple-vehicle fatal and injury crashes.
- MVPDO = multiple-vehicle property damage-only crashes.

During the conflation process, the researchers excluded certain facility types from the study scope. The team excluded one-way arterials, ramps, and collector-distributor roads due to low NPMRDS coverage. Figure 2 and figure 3 provide two examples showing the lack of NPMRDS data coverage on ramps and local roads for equivalent RID coverage (ISU 2023; RITIS 2023).




Source: FHWA

**Figure 2. Illustration. Example of low NPMRDS coverage for ramps.**




Source: FHWA.

**Figure 3. Illustration. Example of low NPMRDS coverage for ramps and local roads.**

Also, the team excluded freeway speed-change lanes from the study scope due to complexities in their identification, applicability of NPMRDS speed measures to them, and difficulties in assigning their corresponding crashes because freeway speed-change lanes are directional, and crashes must be assigned directionally as well (RITIS 2023). Freeway speed-change lanes usually have two flows of traffic: the vehicles on the main-lane freeway, and the vehicles either decreasing speed to exit the freeway or increasing speed to join the freeway.

Table 1 and table 2 summarize the datasets by State after the team completed the automated data conflation process (note, however, that these datasets are not the final ones used for the analysis). Detailed descriptions of the automated conflation process for both States are provided in appendix A in volume II of this report. Also, appendix B summarizes the HSM part C data needs by facility type, HSM base conditions, and data availability for each data item. Although RID data were collected during 2010–12, these data provide detailed information of geometric variables, which is lacking in other State-maintained geometric data. For certain facility types, as table 1 and table 2 indicate, the researchers took some manual data collection efforts to complement HSM (AASHTO 2010) part C data needs that either were not available in RID or could not be automatically collected. For facility types with a larger number of segments and higher total mileages, the team conducted regional sampling based on Washington State Department of Transportation (WSDOT) and North Carolina Department of Transportation (NCDOT) divisions to minimize data collection efforts, while a representative sample of data was complemented for analysis. The manual data collection efforts are summarized in appendix C (Das et al. 2024). Base conditions are used in case of missing information in the RID (ISU 2023).

**Table 1. Washington final dataset after automated data conflation process (2017–18).**

| Facility Type | Segments (No.) | Total Length (mi) | Minimum Length (mi) | Maximum Length (mi) | Average Length (mi) | Observed Crash (KABCO) (Count) | Observed Crash (KABC) (Count) | Observed Crash (O) (Count) | Manual Data Collection |
|---|---|---|---|---|---|---|---|---|---|
| R2U | 1,946 | 1,569.23 | 0.10 | 2.00 | 0.81 | 4,239 | 1,271 | 2,968 | No |
| R4U | 160 | 49.09 | 0.05 | 1.72 | 0.31 | 453 | 124 | 329 | No |
| R4D | 4 | 4.02 | 0.43 | 1.49 | 1.01 | 19 | 4 | 15 | No |
| U2U | 1,257 | 519.82 | 0.10 | 1.99 | 0.41 | 1,740 | 523 | 1,217 | Regional sampling |
| U3T | 155 | 19.95 | 0.05 | 0.87 | 0.13 | 125 | 33 | 92 | Yes |
| U4U | 1,022 | 365.90 | 0.10 | 1.96 | 0.36 | 2,196 | 679 | 1,517 | Regional sampling |
| U4D | 214 | 45.47 | 0.05 | 1.72 | 0.21 | 1,011 | 307 | 704 | Yes |
| U5T | 551 | 68.02 | 0.05 | 0.78 | 0.12 | 825 | 268 | 557 | Regional sampling |
| U6U | 153 | 29.53 | 0.05 | 1.88 | 0.19 | 795 | 229 | 566 | Yes |
| U6D | 15 | 2.83 | 0.05 | 0.90 | 0.19 | 93 | 41 | 52 | Yes |
| U7T | 86 | 11.38 | 0.05 | 0.40 | 0.13 | 463 | 177 | 286 | Yes |
| Rural freeway | 1,157 | 560.64 | 0.10 | 1.00 | 0.48 | 5,101 | 1,259 | 3,842 | Regional sampling |
| Urban freeway | 951 | 326.17 | 0.10 | 1.00 | 0.34 | 8,608 | 2,360 | 6,248 | Regional sampling |
| **Total** | **7,671** | **3,572.05** | **0.05** | **2.00** | **—** | **25,668** | **7,275** | **18,393** | **—** |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

**Table 2. North Carolina final dataset after automated data conflation process (2017–18).**

| Facility Type | Segments (No.) | Total Length (mi) | Minimum Length (mi) | Maximum Length (mi) | Average Length (mi) | Observed Crash (KABCO) (Count) | Observed Crash (KABC) (Count) | Observed Crash (O) (Count) | Manual Data Collection |
|---|---|---|---|---|---|---|---|---|---|
| R2U | 1,080 | 1,111.57 | 0.10 | 2.00 | 1.03 | 4,735 | 1,376 | 3,359 | No |
| R4U | 373 | 209.40 | 0.05 | 1.97 | 0.56 | 1,949 | 563 | 1,386 | No |
| R4D | 1,794 | 479.42 | 0.10 | 1.94 | 0.27 | 3,544 | 893 | 2,651 | No |
| U2U | 794 | 412.34 | 0.10 | 1.98 | 0.52 | 4,209 | 1,218 | 2,991 | Regional sampling |
| U3T | 31 | 3.23 | 0.05 | 0.46 | 0.10 | 63 | 13 | 50 | Yes |
| U4U | 784 | 402.58 | 0.10 | 1.99 | 0.51 | 13,586 | 3,932 | 9,654 | Regional sampling |
| U4D | 730 | 137.63 | 0.10 | 1.30 | 0.19 | 3,327 | 852 | 2,475 | Regional sampling |
| U5T | 112 | 13.55 | 0.05 | 0.39 | 0.12 | 455 | 110 | 345 | Yes |
| U6U | 82 | 31.84 | 0.05 | 1.94 | 0.39 | 2,588 | 743 | 1,845 | Yes |
| U6D | 324 | 36.69 | 0.05 | 0.81 | 0.11 | 2,309 | 586 | 1,723 | Yes |
| U8D | 14 | 1.53 | 0.05 | 0.28 | 0.11 | 268 | 53 | 215 | Yes |
| Rural freeway | 2,409 | 844.85 | 0.10 | 1.00 | 0.35 | 12,066 | 2,923 | 9,143 | Regional sampling |
| Urban freeway | 1,140 | 281.71 | 0.10 | 0.96 | 0.25 | 11,336 | 2,531 | 8,805 | Regional sampling |
| **Total** | **5,780** | **2,801.54** | **0.05** | **2.00** | **—** | **34,456** | **9,700** | **24,756** | **—** |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

# CHAPTER 3. DATA ANALYSIS

## INTRODUCTION

This chapter presents a comprehensive discussion of the data analysis process. First, detailed descriptive statistics are provided listing the segment number and length, crash counts, average traffic volume (AADT), and statistics of the speed measures, such as average operating speed (SpdAve), standard deviation of average operating speed (SpdStd), 85th percentile operating speed (Spd85), posted speed limit (PSL), average free-flow operating speed (SpdFFAve), and 85th percentile free-flow operating speed (SpdFF85) for both Washington and North Carolina. Next, this chapter describes the development and validation of speed CMFs for 13 roadway facility types considering different speed measures, including speed variation and speed differentials. Additionally, this chapter also reports the evaluation of the developed speed CMFs by comparing those with the HSM (AASHTO 2010) default based on several metrics, such as mean absolute deviation (MAD), root mean squared error (RMSE), cumulative residuals (CURE) plots, and CMF Clearinghouse star quality rating (FHWA 2023a).

## DESCRIPTIVE ANALYSIS

As mentioned, in chapter 2, data preparation efforts conflated two linear networks (RID and NPMRDS) of 14 types of facilities (i.e., R2U, R4U, R4D, U2U, U3T, U4U, U4D, U5T, U6U, U6D, U7T, U8D, rural freeway, and urban freeway) to perform the analysis (ISU 2023; RITIS 2023). Then for certain facility types, the team collected some data items manually. These data items either were not available in RID or could not be automatically collected. For example, number of driveways by land use type is needed for all urban and suburban roadway segments by HSM crash prediction (AASHTO 2010). As stated in chapter 2, for facility types with a larger number of segments and higher total mileages, the team conducted regional sampling based on WSDOT and NCDOT divisions to minimize data collection efforts while a representative sample of data was complemented for analysis. Therefore, the final datasets that were used for analysis were different from table 1 and table 2. The manual data collection efforts are summarized in appendix C in volume II of this report (Das et al. 2024). The final Washington dataset contains 5,174 roadway segments and 15,411 crashes (KABCO scale). The North Carolina dataset contains 6,226 roadway segments and 30,640 crashes (KABCO scale) (AASHTO 2010). Table 3 and table 4 summarize the final study datasets of Washington and North Carolina, respectively. According to mileage, R2U is the dominant facility type in both States.

**Table 3. Final study datasets of Washington.**

| Facility Type | Segments (No.) | Total Length (mi) | KABC (Count) | PDO (Count) | Total (Count) |
|---|---|---|---|---|---|
| R2U | 1,946 | 1,569.3 | 1,271 | 2,968 | 4,239 |
| R4U | 160 | 49.1 | 124 | 329 | 453 |
| R4D | 4 | 4.0 | 4 | 15 | 19 |
| U2U | 447 | 176.9 | 144 | 346 | 490 |
| U3T | 226 | 41.8 | 54 | 152 | 206 |
| U4U | 206 | 49.4 | 188 | 407 | 595 |
| U4D | 232 | 44.7 | 360 | 789 | 1,149 |
| U5T | 716 | 131.2 | 570 | 1,232 | 1,802 |
| U6U | 100 | 20.7 | 103 | 242 | 345 |
| U6D | 8 | 1.7 | 20 | 30 | 50 |
| U7T | 117 | 16.7 | 258 | 476 | 734 |
| U8D | — | — | — | — | — |
| Rural freeway | 684 | 328.8 | 765 | 2,269 | 3,034 |
| Urban freeway | 328 | 95.9 | 637 | 1,658 | 2,295 |
| **Total** | **5,174** | **2,530.2** | **4,498** | **10,913** | **15,411** |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

**Table 4. Final study datasets of North Carolina.**

| Facility Type | Segments (No.) | Total Length (mi) | KABC (Count) | PDO (Count) | Total (Count) |
|---|---|---|---|---|---|
| R2U | 1,080 | 1,111.6 | 1,376 | 3,359 | 4,735 |
| R4U | 373 | 209.4 | 563 | 1,386 | 1,949 |
| R4D | 1,794 | 479.5 | 893 | 2,651 | 3,544 |
| U2U | 374 | 197.1 | 547 | 1,270 | 1,817 |
| U3T | 96 | 27.2 | 110 | 298 | 408 |
| U4U | 119 | 37.6 | 364 | 792 | 1,156 |
| U4D | 526 | 99.4 | 601 | 1,740 | 2,341 |
| U5T | 322 | 106.3 | 755 | 2,028 | 2,783 |
| U6U | 23 | 4.1 | 106 | 213 | 319 |
| U6D | 304 | 34.7 | 556 | 1,662 | 2,218 |
| U7T | 5 | 0.8 | 25 | 85 | 110 |
| U8D | 12 | 1.1 | 36 | 132 | 168 |
| Rural freeway | 609 | 206.0 | 910 | 2,818 | 3,728 |
| Urban freeway | 589 | 144.5 | 1,213 | 4,151 | 5,364 |
| **Total** | **6,226** | **2,659.3** | **8,055** | **22,585** | **30,640** |

Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Table 5 summarizes the mileage, average traffic volume (AADT), and crash data for the 2017–18 Washington facility types (i.e., R2U, R4U, R4D, U2U, U3T, U4U, U4D, U5T, U6U, U6D, U7T, U8D, and freeways). As expected, freeways have the highest average traffic volumes in Washington. Urban arterials with six through lanes (undivided, divided, and with a center two-way, left-turn lane, e.g., U7T) have the highest crash rates (crash/mile) among Washington facility types.

**Table 5. Mileage, AADT, and crash counts of Washington.**

| Facility Type | Segments (No.) | Count (%) | Mileage (mi) | Mileage (%) | Average AADT (Count) | KABCO (2017–18) (Count) | KABCO (%) | Crash/ Mile (Count) |
|---|---|---|---|---|---|---|---|---|
| R2U | 1,946 | 38 | 1,569.3 | 62 | 6,654 | 4,239 | 28 | 3.6 |
| R4U | 160 | 3 | 49.1 | 2 | 19,548 | 453 | 3 | 15.3 |
| R4D | 4 | 0 | 4.0 | 0 | 471 | 19 | 0 | 4.5 |
| U2U | 447 | 9 | 176.9 | 7 | 13,879 | 490 | 3 | 3.8 |
| U3T | 226 | 4 | 41.8 | 2 | 16,825 | 206 | 1 | 5.8 |
| U4U | 206 | 4 | 49.4 | 2 | 24,101 | 595 | 4 | 13.9 |
| U4D | 232 | 4 | 44.7 | 2 | 30,137 | 1,149 | 7 | 30.1 |
| U5T | 716 | 14 | 131.2 | 5 | 25,354 | 1,802 | 12 | 16.0 |
| U6U | 100 | 2 | 20.7 | 1 | 10,237 | 345 | 2 | 31.7 |
| U6D | 8 | 0 | 1.7 | 0 | 442 | 50 | 0 | 44.9 |
| U7T | 117 | 2 | 16.7 | 1 | 33,536 | 734 | 5 | 44.1 |
| U8D | — | — | — | — | — | — | — | — |
| Rural freeways | 684 | 13 | 328.8 | 13 | 30,719 | 3,034 | 20 | 12.5 |
| Urban freeways | 328 | 6 | 95.9 | 4 | 52,747 | 2,295 | 15 | 30.5 |
| **Total** | **5,174** | **100** | **2530.2** | **100** | **—** | **15,411** | **100** | **—** |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Table 6 summarizes the mean measures of several speed measures by facility type in Washington based on 2017–18 NPMRDS data (RITIS 2023). Freeways have the highest SpdAve, Spd85, PSLs, and SpdFFAve, followed by R2U highways. However, freeways have the lowest SpdStd among Washington facility types.

**Table 6. Average values of selected speed measures of Washington.**

| Facility Type | SpdAve (mph) | SpdStd | Spd85 (mph) | PSL (mph) | SpdFFAve (mph) | SpdFF85 (mph) |
|---|---|---|---|---|---|---|
| R2U | 50.5 | 7.80 | 57.1 | 60.0 | 64.4 | 67.1 |
| R4U | 39.4 | 9.30 | 48.4 | 55.0 | 59.7 | 63.5 |
| R4D | 51.8 | 7.20 | 57.7 | 60.0 | 64.8 | 66.5 |
| U2U | 41.2 | 8.13 | 48.5 | 55.0 | 59.8 | 63.6 |
| U3T | 30.3 | 8.30 | 38.1 | 45.0 | 52.6 | 57.4 |
| U4U | 29.7 | 8.42 | 38.2 | 50.0 | 53.3 | 57.9 |
| U4D | 30.0 | 8.70 | 38.9 | 50.0 | 55.0 | 60.1 |
| U5T | 27.8 | 8.52 | 36.4 | 45.0 | 52.3 | 57.2 |
| U6U | 26.2 | 8.61 | 35.2 | 45.0 | 53.6 | 59.1 |
| U6D | 23.8 | 7.60 | 32.0 | 40.0 | 46.9 | 50.0 |
| U7T | 26.2 | 8.80 | 35.2 | 50.0 | 56.2 | 63.0 |
| U8D | — | — | — | — | — | — |
| Rural freeways | 60.8 | 4.79 | 64.2 | 65.0 | 69.3 | 71.8 |
| Urban freeways | 57.2 | 5.8 | 61.7 | 65.0 | 69.3 | 72.0 |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Table 7 summarizes the mileage, average traffic volume (AADT), and crash data for the 2017–18 North Carolina facility types (i.e., R2U, R4U, R4D, U2U, U3T, U4U, U4D, U5T, U6U, U6D, U7T, U8D, and freeways). As expected, similar to Washington, freeways in North Carolina have the highest average traffic volumes. Also, urban arterials with a higher number of through lanes have the highest crash rates (crash/mile) among North Carolina facility types.

**Table 7. Mileage, AADT, and crash counts of North Carolina.**

| Facility Type | Segments (No.) | Count (%) | Mileage (mi) | Mileage (%) | Average AADT (Count) | KABCO (Count) (2017–18) | KABCO (%) | Crash/ Mile (Count) |
|---|---|---|---|---|---|---|---|---|
| R2U | 1,080 | 17 | 1,111.6 | 42 | 6,438 | 4,735 | 15 | 5.3 |
| R4U | 373 | 6 | 209.4 | 8 | 16,977 | 1,949 | 6 | 13.5 |
| R4D | 1,794 | 29 | 479.5 | 18 | 6,088 | 3,544 | 12 | 8.1 |
| U2U | 374 | 6 | 197.1 | 7 | 11,837 | 1,817 | 6 | 10.1 |
| U3T | 96 | 2 | 27.2 | 1 | 15,481 | 408 | 1 | 16.7 |
| U4U | 119 | 2 | 37.6 | 1 | 17,435 | 1,156 | 4 | 35.5 |
| U4D | 526 | 8 | 99.4 | 4 | 26,904 | 2,341 | 8 | 25.2 |
| U5T | 322 | 5 | 106.3 | 4 | 22,078 | 2,783 | 9 | 32.1 |
| U6U | 23 | 0 | 4.1 | 0 | 32,779 | 319 | 1 | 67.5 |
| U6D | 304 | 5 | 34.7 | 1 | 39,221 | 2,218 | 7 | 71.1 |
| U7T | 5 | 0 | 0.8 | 0 | 29,887 | 110 | 0 | 152.0 |
| U8D | 12 | 0 | 1.1 | 0 | 47,489 | 168 | 1 | 189.9 |
| Rural freeways | 609 | 10 | 206.0 | 8 | 42,999 | 3,728 | 12 | 22.8 |
| Urban freeways | 589 | 9 | 144.5 | 5 | 60,379 | 5,364 | 18 | 46.4 |
| **Total** | **6,226** | **100** | **2659.3** | **100** | — | **22,585** | **100** | — |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Table 8 summarizes the mean measures of several different speed measures by facility type in North Carolina based on 2017–18 NPMRDS data (RITIS 2023). Freeways have the highest SpdAve, Spd85, PSL, and SpdFFAve, followed by R4D highways. However, freeways have the lowest SpdStd among North Carolina facility types.

**Table 8. Average values of selected speed measures of North Carolina.**

| Facility Type | SpdAve (mph) | SpdStd | Spd85 (mph) | PSL (mph) | SpdFFAve (mph) | SpdFF85 (mph) |
|---|---|---|---|---|---|---|
| R2U | 48.3 | 7.93 | 55.1 | 60.0 | 64.7 | 67.6 |
| R4U | 45.2 | 8.06 | 52.5 | 60.0 | 62.6 | 65.6 |
| R4D | 55.0 | 6.66 | 60.7 | 65.9 | 68.5 | 70.9 |
| U2U | 38.9 | 8.37 | 46.6 | 55.0 | 58.5 | 62.0 |
| U3T | 35.0 | 8.72 | 43.3 | 50.0 | 58.1 | 62.7 |
| U4U | 32.3 | 8.60 | 40.8 | 50.0 | 54.3 | 58.2 |
| U4D | 42.9 | 8.47 | 51.0 | 60.0 | 63.2 | 66.5 |
| U5T | 36.4 | 8.62 | 44.9 | 55.0 | 58.2 | 61.9 |
| U6U | 29.4 | 9.31 | 38.7 | 50.0 | 57.9 | 63.1 |
| U6D | 35.5 | 9.24 | 44.7 | 55.9 | 61.0 | 66.1 |
| U7T | 31.8 | 8.22 | 40.0 | 50.0 | 54.4 | 58.8 |
| U8D | 33.0 | 9.81 | 43.4 | 55.0 | 61.2 | 65.0 |
| Rural freeways | 64.5 | 4.96 | 68.0 | 70.0 | 73.7 | 75.6 |
| Urban freeways | 63.2 | 5.81 | 67.2 | 70.0 | 73.9 | 76.1 |

Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Comparing the SpdAve measures in Washington and North Carolina reveals that, on average, speed measures were slightly higher in North Carolina, and the SpdStd were slightly higher in North Carolina.

## SPEED CMF DEVELOPMENT

The most straightforward method to develop CMFs is to collect before and after data and conduct this type of study. However, speed cannot be easily and widely controlled and managed. Therefore, cross-sectional data, such as the conflated SHRP2 RID, NPMRDS, and HSIS data, are the most practical way of developing speed-related CMFs for the HSM crash prediction models (ISU 2023; RITIS 2023; FHWA n.d.; AASHTO 2010). The methodology for developing the speed-related CMFs is given in the following steps for each facility type within each of the two States selected. The methodology was proposed by Banihashemi (2015, 2016) and was followed by other researchers for CMF development, such as Wu, Lord, and Geedipally (2017):

1. Apply the HSM model to all segments of the facility type to estimate the predicted crashes for each highway segment.

2. Estimate the calibration factor (CF) for the facility type using all segments (figure 4).

$$CF = {\sum O}/{\sum P}$$

**Figure 4. Equation. CF for facility type using all segments.**

Where:
*O* = observed crashes.
*P* = predicted crashes if speed measure had no effect.

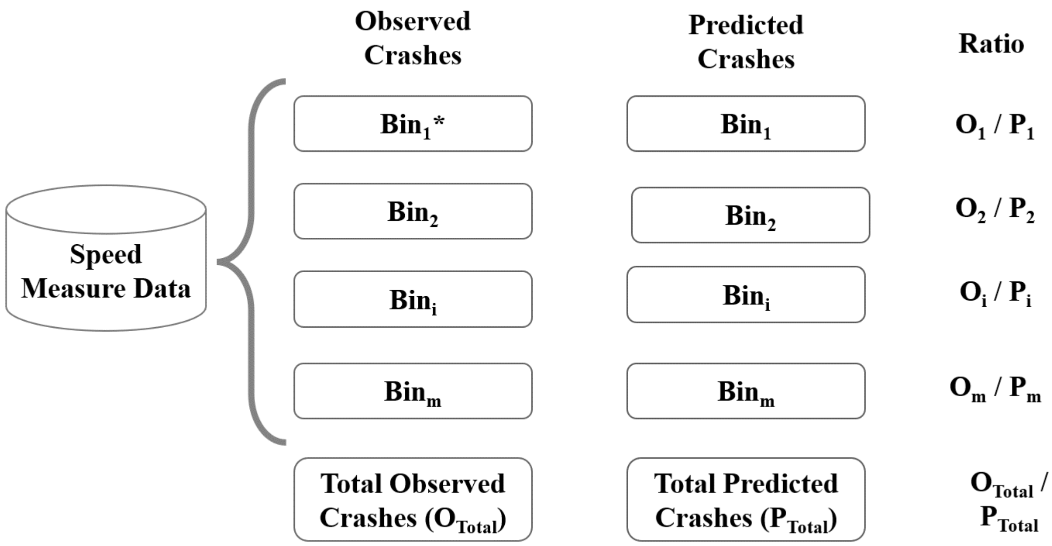
3. Estimate and examine different speed-related measures in relation to total crashes. If the facility type crash prediction method in the HSM has separate models for FI (KABC) crashes and PDO crashes, conduct this step for both KABC and PDO models (AASHTO 2010). At the end of this step, identify the speed measures that may produce an effective CMF.

4. For each speed-related measure identified in the previous step, break down the data into different subsets (bins). The project team suggests five or six subsets.

5. For each subset of data in each bin, calculate the CF using only segments of that subset. Each facility type will have five or six of these subset CFs.

6. Calculate the ratios of the subsets' CFs estimated in step 5 to the CF for the facility type estimated in step 2. If the five or six values of ratios define a pattern, derive the speed-related measure CMF using that pattern; otherwise, conclude that no effective CMF is derived from these data for that speed-related measure. This pattern could show a linear or nonlinear relationship between the speed-related measure and the calculated ratios. If more than one speed-related measure is present that can produce an effective CMF for a facility type, choose the best one.

Figure 5 presents the overall protocol for developing a CMF for a particular speed measure. FHWA's Interactive Highway Safety Design Model (IHSDM) software (FHWA 2023b) was used to estimate the predicted safety if the speed measure had no effect.




Source: FHWA.
*Bins are developed based on the distribution of the speed measure. After the ranges of each bin are selected, associated observed and predicted crashes (assuming speed measures have no effect) are used for ratio calculations.
O = observed; P = predicted; *i* = individual bin number in the series; *m* = total number of bins in the series.

**Figure 5. Illustration. Protocol for developing CMF for speed measure.**

The research team used IHSDM software (FHWA 2023b) to estimate the HSM crash predictions (AASHTO 2010). The team examined 12 different speed measures. The core speed measures and their definitions—such as SpdAve, SpdStd, Spd85, and PSL—are provided in table 4 in appendix A in volume II of this report. Among the 12 speed measures, the researchers calculated differential speed measures, such as (SpdAve − PSL), and the coefficient of variation (CV) of SpdAve (i.e., SpdStd divided by SpdAve). Appendix A provides more details on these speed measures (Das et al. 2024). Table 9 summarizes the 12 speed measures by category.

**Table 9. Speed measures by category.**

| Speed Measure Abbreviation | Description | Category |
|---|---|---|
| SpdAve | Average operating speed | Direct measurement |
| Spd85 | 85th percentile operating speed | Direct measurement |
| $SpdAve_{Day}$ | Average operating speed during daytime | Direct measurement |
| $SpdAve_{Night}$ | Average operating speed during nighttime | Direct measurement |
| $SpdAve_{MTWT}$ | Average operating speed during weekdays (MTWT = Monday, Tuesday, Wednesday, Thursday) | Direct measurement |
| $SpdAve_{FSS}$ | Average operating speed during weekend (FSS = Friday, Saturday, Sunday) | Direct measurement |
| SpdFFAve | Average free-flow speed | Direct measurement |
| SpdFF85 | 85th percentile free-flow operating speed | Direct measurement |
| SpdStd | Standard deviation of average operating speed | Speed variation |
| SpdStd/SpdAve | CV of average operating speed | Speed variation |
| (SpdAve − PSL) | Speed differential of average operating speed and posted speed limit (PSL) | Speed differential |
| \|SpdAve − PSL\| | Absolute value of speed differential of average operating speed and posted speed limit (PSL) | Speed differential |

Following the protocol depicted in figure 5, the team initially broke down the speed measures into five or six subsets (bins). The summary statistics for SpdAve for rural freeways (Washington) and total crashes (KABCO) are presented in table 10 as an example (AASHTO 2010). Appendix D in volume II of this report provides additional information on descriptive statistics (Das et al. 2024).

**Table 10. Summary statistics of SpdStd for Washington rural freeways.**

| SpdStd (mph) | Length (mi) | Length (%) | KABCO (Count) | KABCO (%) | Predicted Crashes (Count) | Predicted Crashes (%) |
|---|---|---|---|---|---|---|
| 2.6–4.4 | 209.067 | 64 | 1,517 | 50 | 1,668 | 63 |
| 4.4–6.1 | 68.424 | 21 | 780 | 26 | 590.5 | 22 |
| 6.1–7.9 | 36.13 | 11 | 546 | 18 | 305.7 | 11 |
| 7.9–9.6 | 7.647 | 2 | 134 | 4 | 75 | 3 |
| 9.6–11.4 | 0.956 | 0 | 12 | 0 | 8.4 | 0 |
| 11.4–15 | 6.598 | 2 | 45 | 1 | 14.2 | 1 |
| **Total** | **328.822** | **100** | **3,034** | **100** | **2,661.8** | **100** |

Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Since the speed measures were divided into equal-range subsets (bins), the lengths and crashes were distributed disproportionately. To address this disproportionality, consistent with the past work done by Wu, Lord, and Geedipally (2017), the team divided the speed measures into subsets (bins) that resulted in more uniformly distributed lengths and crashes. The modified ranges and associated summary statistics for SpdStd for rural freeways and total crashes (KABCO) are presented in table 11 as an example (AASHTO 2010). This procedure was followed for all speed measures in this study. This approach prevented drastic changes in distributions and prospect results due to the bins with few segments, short segments, and outliers.

**Table 11. Summary statistics of SpdStd (modified bins) for Washington rural freeways.**

| Minimum SpdStd (mph) | Maximum SpdStd (mph) | Length (mi) | Length (%) | KABCO (Count) | KABCO (%) | Predicted Crashes (Count) | Predicted Crashes (%) |
|---|---|---|---|---|---|---|---|
| 2.6 | 3.2 | 52.0 | 16 | 393 | 13 | 448.7 | 17 |
| 3.2 | 3.5 | 53.3 | 16 | 368 | 12 | 437.5 | 16 |
| 3.5 | 3.9 | 58.6 | 18 | 373 | 12 | 398.4 | 15 |
| 3.9 | 4.5 | 49.3 | 15 | 448 | 15 | 461.3 | 17 |
| 4.5 | 6.0 | 60.3 | 18 | 682 | 22 | 490.7 | 18 |
| 6.0 | 15.5 | 55.2 | 17 | 770 | 25 | 425.2 | 16 |
| — | — | **328.8** | **100** | **3,034** | **100** | **2,661.8** | **100** |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

## Training Data

To validate the developed CMFs, the researchers randomly divided the data into training (75 percent) and test (25 percent) datasets. Table 12 and table 13 summarize training and test datasets for Washington and North Carolina, respectively. The crash statistics provided in these tables represent observed crashes from HSIS for 2017–18. A small number of segments and/or mileage and/or number of crashes for certain facility types and/or crash type/severity levels might not produce reliable speed CMFs; these statistics are indirectly reflected in performance metrics that were used for validation (MAD and RMSE) and estimated CMF Clearinghouse star quality ratings (FHWA 2023a).

Using the training dataset, the researchers examined different speed measures in relationship with different crash type/severity levels as considered in the HSM (AASHTO 2020). The team developed the CMF equations using linear and power functions. The developed speed CMF equations and associated performance indexes for rural highways, urban arterials, and freeways are provided in appendix D through appendix F, respectively, in volume II of this report (Das et al. 2024). As an example, table 14 summarizes the *R*-square values of potential CMF equations for Washington rural freeways. *R*-square is a goodness-of-fit measure for regression models. The common interpretation of *R*-square is how well the regression model explains observed data. (For this research study, observed data are the observed crash data from HSIS (FHWA n.d.).) *R*-square is always between 0.0 and 1.0 (or 0 and 100 percent). For example, an *R*-square of 0.6 (or 60 percent) reveals that the regression model explains 60 percent of the variability observed in the target variable. Generally, a higher *R*-square value indicates that the regression model explains more variability observed in the target variable. The direct speed measures (e.g., SpdAve) were excluded from the potential CMF equations based on the following steps:

### Table 12. Summary of training and test datasets for Washington.

| Facility Type | Dataset | Segments (No.) | Length (mi) | KABC (Count) | PDO (Count) | Total (Count) | SVFI (Count) | SVPDO (Count) | MVFI (Count) | MVPDO (Count) |
|---|---|---|---|---|---|---|---|---|---|---|
| R2U | Training | 1,460 | 1,196.2 | 962 | 2,281 | 3,243 | — | — | — | — |
| R2U | Test | 486 | 373.1 | 309 | 687 | 996 | — | — | — | — |
| R4U | Training | 120 | 34.9 | 91 | 257 | 348 | — | — | — | — |
| R4U | Test | 40 | 14.2 | 33 | 72 | 105 | — | — | — | — |
| U2U | Training | 335 | 132.7 | 111 | 277 | 388 | 40 | 108 | 71 | 169 |
| U2U | Test | 112 | 44.17 | 33 | 69 | 102 | 9 | 26 | 24 | 43 |
| U3T | Training | 170 | 32.7 | 47 | 137 | 184 | 6 | 22 | 41 | 115 |
| U3T | Test | 56 | 9.1 | 7 | 15 | 22 | 0 | 1 | 7 | 14 |
| U4U | Training | 155 | 39.3 | 131 | 300 | 431 | 28 | 28 | 103 | 272 |
| U4U | Test | 51 | 10.1 | 57 | 107 | 164 | 9 | 16 | 48 | 91 |
| U4D | Training | 174 | 34.7 | 268 | 614 | 882 | 71 | 106 | 197 | 508 |
| U4D | Test | 58 | 10.0 | 92 | 175 | 267 | 29 | 24 | 63 | 151 |
| U5T | Training | 537 | 99.7 | 420 | 925 | 1,345 | 71 | 94 | 349 | 831 |
| U5T | Test | 179 | 31.5 | 150 | 307 | 457 | 23 | 30 | 127 | 277 |
| U6U | Training | 75 | 14.4 | 71 | 165 | 236 | 17 | 13 | 54 | 152 |
| U6U | Test | 25 | 6.3 | 32 | 77 | 109 | 10 | 6 | 22 | 71 |
| U7T | Training | 88 | 12.6 | 192 | 363 | 555 | 21 | 21 | 171 | 342 |
| U7T | Test | 29 | 4.1 | 66 | 113 | 179 | 7 | 2 | 59 | 111 |
| Rural freeways | Training | 513 | 246.7 | 594 | 1,753 | 2,347 | 359 | 1,130 | 235 | 623 |
| Rural freeways | Test | 171 | 82.1 | 171 | 516 | 687 | 114 | 334 | 57 | 182 |
| Urban freeways | Training | 246 | 71.4 | 486 | 1,238 | 1,724 | 153 | 431 | 333 | 807 |
| Urban freeways | Test | 82 | 24.5 | 151 | 420 | 571 | 44 | 160 | 107 | 260 |

—Not applicable.

Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

Table 13. Summary of training and test datasets for North Carolina.

| Facility Type | Dataset | Segments (No.) | Length (mi) | KABC (Count) | PDO (Count) | Total (Count) | SVFI (Count) | SVPDO (Count) | MVFI (Count) | MVPDO (Count) |
|---|---|---|---|---|---|---|---|---|---|---|
| R2U | Training | 810 | 839.5 | 1,033 | 2,522 | 3,555 | — | — | — | — |
| R2U | Test | 270 | 272.1 | 343 | 837 | 1,180 | — | — | — | — |
| R4U | Training | 280 | 155.1 | 439 | 1,055 | 1,494 | — | — | — | — |
| R4U | Test | 93 | 54.3 | 124 | 331 | 455 | — | — | — | — |
| R4D | Training | 1,346 | 360.9 | 672 | 1,968 | 2,640 | — | — | — | — |
| R4D | Test | 448 | 118.6 | 221 | 683 | 904 | — | — | — | — |
| U2U | Training | 281 | 147.3 | 430 | 960 | 1,390 | 90 | 208 | 338 | 744 |
| U2U | Test | 93 | 49.8 | 117 | 310 | 427 | 28 | 79 | 87 | 229 |
| U3T | Training | 72 | 21.7 | 84 | 220 | 304 | 16 | 33 | 65 | 184 |
| U3T | Test | 24 | 5.5 | 26 | 78 | 104 | 4 | 19 | 21 | 59 |
| U4U | Training | 89 | 28.3 | 269 | 583 | 852 | 39 | 60 | 228 | 522 |
| U4U | Test | 30 | 9.3 | 95 | 209 | 304 | 7 | 21 | 85 | 187 |
| U4D | Training | 395 | 74.0 | 433 | 1,258 | 1,691 | 73 | 208 | 357 | 1,038 |
| U4D | Test | 131 | 25.4 | 168 | 482 | 650 | 37 | 92 | 130 | 386 |
| U5T | Training | 242 | 84.0 | 582 | 1,556 | 2,138 | 62 | 156 | 515 | 1,388 |
| U5T | Test | 80 | 22.3 | 173 | 472 | 645 | 15 | 41 | 155 | 427 |
| U6U | Training | 17 | 3.1 | 92 | 171 | 263 | 9 | 8 | 83 | 162 |
| U6U | Test | 6 | 1.0 | 14 | 42 | 56 | 0 | 1 | 14 | 41 |
| U6D | Training | 228 | 25.7 | 406 | 1,184 | 1,590 | 43 | 72 | 358 | 1,106 |
| U6D | Test | 76 | 9.0 | 150 | 478 | 628 | 24 | 30 | 124 | 448 |
| Rural freeways | Training | 457 | 157.9 | 709 | 2,173 | 2,882 | 306 | 979 | 400 | 1,163 |
| Rural freeways | Test | 152 | 48.1 | 201 | 645 | 846 | 81 | 273 | 117 | 355 |
| Urban freeways | Training | 442 | 108.2 | 915 | 3,217 | 4,132 | 285 | 992 | 623 | 2,181 |
| Urban freeways | Test | 147 | 36.3 | 298 | 934 | 1,232 | 108 | 302 | 186 | 623 |

—Not applicable.
Data are from SHRP2 RID (ISU 2023) and HSIS (FHWA n.d.).

## Table 14. *R*-square values of CMF equations for Washington rural freeways.

| Speed Measure | KABCO | | KABC | | O | | SVFI | | SVPDO | | MVFI | | MVPDO | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power |
| SpdAve | 0.54 | 0.48 | 0.47 | 0.41 | 0.59 | 0.53 | 0.47 | 0.41 | 0.70 | 0.65 | 0.62 | 0.56 | 0.55 | 0.48 |
| Spd85 | 0.53 | 0.49 | ***0.67*** | ***0.62*** | 0.49 | 0.46 | 0.51 | 0.46 | 0.42 | 0.39 | ***0.85*** | ***0.83*** | 0.55 | 0.52 |
| $SpdAve_{Day}$ | 0.48 | 0.42 | 0.43 | 0.37 | 0.50 | 0.44 | 0.37 | 0.31 | 0.55 | 0.50 | 0.59 | 0.53 | 0.35 | 0.29 |
| $SpdAve_{Night}$ | 0.59 | 0.52 | 0.56 | 0.49 | 0.62 | 0.56 | ***0.56*** | 0.49 | 0.73 | 0.68 | 0.65 | 0.60 | 0.57 | 0.49 |
| $SpdAve_{MTWT}$ | 0.61 | 0.55 | 0.47 | 0.41 | 0.68 | 0.62 | 0.50 | 0.43 | 0.72 | 0.68 | 0.57 | 0.51 | 0.63 | 0.56 |
| $SpdAve_{FSS}$ | 0.49 | 0.43 | 0.44 | 0.39 | 0.54 | 0.48 | 0.48 | 0.42 | 0.63 | 0.58 | 0.54 | 0.48 | 0.51 | 0.44 |
| SpdFFAve | 0.55 | 0.55 | 0.31 | 0.31 | 0.64 | 0.63 | 0.31 | 0.32 | 0.67 | 0.65 | 0.13 | 0.12 | 0.30 | 0.29 |
| SpdFF85 | 0.24 | 0.23 | 0.08 | 0.08 | 0.30 | 0.28 | 0.20 | 0.21 | 0.46 | 0.43 | 0.03 | 0.03 | 0.01 | 0.01 |
| SpdStd | ***0.91*** | ***0.93*** | ***0.72*** | ***0.73*** | ***0.92*** | ***0.93*** | ***0.66*** | ***0.67*** | ***0.95*** | ***0.96*** | ***0.79*** | ***0.82*** | ***0.81*** | ***0.83*** |
| (SpdAve − PSL) | 0.46 | — | 0.45 | — | 0.46 | — | 0.51 | — | 0.64 | — | 0.14 | — | 0.02 | — |
| \|SpdAve − PSL\| | 0.37 | 0.46 | 0.41 | 0.48 | 0.34 | 0.45 | 0.46 | 0.52 | 0.48 | 0.55 | 0.14 | 0.19 | 0.01 | 0.05 |
| SpdStd/SpdAve | 0.70 | ***0.77*** | 0.52 | 0.59 | 0.74 | ***0.82*** | 0.47 | 0.54 | 0.81 | ***0.87*** | 0.54 | 0.61 | 0.55 | 0.63 |

—Corresponding function could not be developed.
Note: Bold italic numbers indicate the top five potential speed CMFs for each crash type/severity level.

1. The part A results, which showed 9 out of 14 (65 percent) of developed speed CMFs for rural highways were based on either speed variation or speed differential variable.

2. Some of the findings from relevant literature (Lave 1985; Taylor, Lynam, and Baruya 2008; Malyshkina and Mannering 2008; Pei, Wong, and Sze 2012; Yu et al. 2013, 2018; Montella and Imbriani 2015; Imprialou et al. 2016; Dutta and Fontaine 2019; Hutton et al. 2020), which showed more importance of speed variance in crash likelihood and crash data analysis and the negative relationship of mean speed (which is a direct measurement) to crash frequencies.

3. Some part B preliminary analyses on data from Washington and North Carolina (FHWA 2023c).

As examples, table 15 summarizes the *R*-square values of potential CMF equations for Washington rural freeways based on only speed measures pertaining to speed variation and speed differential. Table 16 is a similar summary table for North Carolina rural freeways. *R*-square summary tables are provided for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024). The final four speed measures—SpdStd, (SpdAve − PSL), |SpdAve − PSL| (where vertical bars around the variables denote the absolute value and parentheses denote the speed differential), and SpdStd/SpdAve—for CMF development were selected based on the highest *R*-square values of potential CMF equations, engineering judgment, and the findings and recommendations from previous studies (which are listed above in number 2).

**Table 15. *R*-square values of CMF equations for Washington rural freeways (speed variation and speed differential measures).**

| Speed Measure | KABCO | | KABC | | O | | SVFI | | SVPDO | | MVFI | | MVPDO | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power |
| SpdStd | ***0.91*** | ***0.93*** | ***0.72*** | ***0.73*** | ***0.92*** | ***0.93*** | ***0.66*** | ***0.67*** | ***0.95*** | ***0.96*** | ***0.79*** | ***0.82*** | ***0.81*** | ***0.83*** |
| (SpdAve − PSL) | ***0.46*** | — | 0.45 | — | ***0.46*** | — | ***0.51*** | — | ***0.64*** | — | 0.14 | — | 0.02 | — |
| \|SpdAve − PSL\| | 0.37 | 0.46 | 0.41 | ***0.48*** | 0.34 | 0.45 | 0.46 | ***0.52*** | 0.48 | 0.55 | 0.14 | ***0.19*** | 0.01 | ***0.05*** |
| SpdStd/SpdAve | ***0.70*** | ***0.77*** | ***0.52*** | ***0.59*** | ***0.74*** | ***0.82*** | 0.47 | ***0.54*** | ***0.81*** | ***0.87*** | ***0.54*** | ***0.61*** | ***0.55*** | ***0.63*** |

—Corresponding function could not be developed.
Note: Bold italic numbers indicate the top five potential speed CMFs for each crash type/severity level.

**Table 16. *R*-square values of CMF equations for North Carolina rural freeways (speed variation and speed differential measures).**

| Speed Measure | KABCO | | KABC | | O | | SVFI | | SVPDO | | MVFI | | MVPDO | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power | Linear | Power |
| SpdStd | ***0.95*** | ***0.97*** | ***0.84*** | ***0.86*** | ***0.95*** | ***0.97*** | 0.02 | 0.07 | ***0.75*** | ***0.77*** | ***0.87*** | ***0.88*** | ***0.91*** | ***0.93*** |
| (SpdAve − PSL) | ***0.57*** | — | 0.64 | — | ***0.51*** | — | ***0.46*** | — | ***0.17*** | — | ***0.41*** | — | 0.29 | — |
| \|SpdAve − PSL\| | 0.51 | 0.55 | 0.70 | ***0.71*** | 0.43 | 0.47 | ***0.53*** | ***0.46*** | 0.13 | 0.15 | 0.35 | 0.37 | 0.30 | ***0.32*** |
| SpdStd/SpdAve | ***0.87*** | ***0.92*** | ***0.71*** | ***0.76*** | ***0.90*** | ***0.95*** | ***0.25*** | ***0.31*** | ***0.89*** | ***0.87*** | ***0.75*** | ***0.80*** | ***0.76*** | ***0.83*** |

—Corresponding function could not be developed.
Note: Bold italic numbers indicate the top five potential speed CMFs for each crash type/severity level.

### Test Data

Since two different functions (i.e., linear and power) were used to estimate *R*-square values and CMF equations, the team made eight potential speed measure-estimation function pairs for each crash type/severity level for each facility type. The team identified the top five speed measure-estimation function pairs for each crash type/severity level based on the *R*-square values and then validated the developed CMFs based on these top five speed measure-estimation function pairs using training datasets and the test data (i.e., 25 percent of all data for each facility type). As examples, table 17 summarizes the details of crash predictions, including the top five speed CMFs along the default HSM (without speed CMF) for Washington rural freeways for KABCO (i.e., total) crashes (AASHTO 2010). Table 18 is a similar summary table for North Carolina rural freeways. The research team used two performance metrics (i.e., MAD and RMSE) to rank speed CMFs. MAD is a measure of the average absolute distance between each data value and the mean of a dataset, and RMSE is the standard deviation of the residuals (prediction errors), which indicate how far from the regression line data points are. RMSE is a measure of how spread out these residuals are. In other words, RMSE shows how concentrated the data are around the line of best fit. Both of these metrics are commonly used in crash prediction studies. For Washington rural freeway KABCO crashes, SpdStd was the best speed CMF that improved MAD and RMSE compared with the default HSM by 7.7 percent and 9.2 percent, respectively. Similarly, for North Carolina rural freeways for KABCO crashes, SpdStd was the best speed CMF that improved MAD and RMSE compared with the default HSM by 9.8 percent and 9.2 percent, respectively. Similar summary tables are provided for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024).

**Table 17. Summary of speed CMF development statistics for Washington rural freeways—KABCO.**

| Speed CMF | CF | Observed Crashes (Count) | Predicted Crashes (Count) | MAD | Change (%) | RMSE | Change (%) |
|---|---|---|---|---|---|---|---|
| HSM default (no speed CMF) | 1.15 | 687 | 705.3 | 2.337 | — | 3.242 | — |
| SpdStd | 1.23 | 687 | 695.2 | 2.169 | −7.2 | 2.966 | −8.5 |
| ***SpdStd*** | ***1.22*** | ***687*** | ***693.8*** | ***2.158*** | ***−7.7*** | ***2.943*** | ***−9.2*** |
| *SpdStd/SpdAve* | *1.30* | *687* | *700.4* | *2.226* | *−4.8* | *3.057* | *−5.7* |
| SpdStd/SpdAve | 1.29 | 687 | 703.6 | 2.291 | −2.0 | 3.168 | −2.3 |
| (SpdAve − PSL) | 1.18 | 687 | 699.3 | 2.260 | −3.3 | 3.120 | −3.8 |

—Not applicable.

Note: Italic row indicates power function; bold italic row indicates the best speed CMF with power function.

**Table 18. Summary of speed CMF development statistics for North Carolina rural freeways—KABCO.**

| Speed CMF | CF | Observed Crashes (Count) | Predicted Crashes (Count) | MAD | Change (%) | RMSE | Change (%) |
|---|---|---|---|---|---|---|---|
| HSM default (no speed CMF) | 1.31 | 846 | 771.7 | 3.242 | — | 5.505 | — |
| SpdStd | 1.42 | 846 | 783.7 | 2.929 | −9.7 | 5.009 | −9.0 |
| ***SpdStd*** | ***1.41*** | ***846*** | ***785.2*** | ***2.925*** | ***−9.8*** | ***4.998*** | ***−9.2*** |
| *SpdStd/SpdAve* | *1.52* | *846* | *775.7* | *3.034* | *−6.4* | *5.222* | *−5.2* |
| SpdStd/SpdAve | 1.54 | 846 | 773.3 | 3.149 | −2.9 | 5.373 | −2.4 |
| (SpdAve − PSL) | 1.31 | 846 | 781.8 | 3.025 | −6.7 | 5.183 | −5.8 |

—Not applicable.
Note: Italic row indicates power function; bold italic row indicates the best speed CMF with power function.

## All Data

After the developed CMFs are cross validated using test data, Montgomery, Peck, and Vining (2012) recommend developing the final models for the best CMFs that were identified through the validation process using all data (i.e., training and test datasets combined). As examples, table 19 and table 20 summarize speed CMFs developed using all data for rural freeways in Washington and North Carolina, respectively. The summary tables include speed measure, CMF equation, *R*-square value, CMF boundaries, base condition, *t*-test, *p*-value (comparing the HSM default (no speed CMF) with inclusion of the speed CMF in crash prediction), and estimated CMF Clearinghouse star quality rating (FHWA 2023a). Similar summary tables are provided for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024).

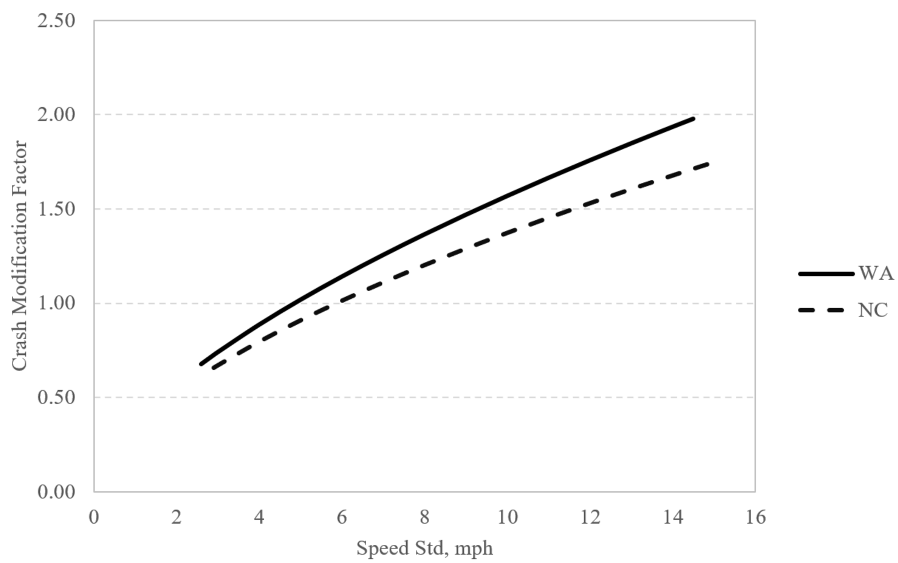
**Table 19. Washington rural freeways—KABCO speed CMF.**

| Speed CMF | Value |
|---|---|
| Speed measure | SpdStd |
| CMF equation | $y = 0.3731 \times x^{0.6237}$ |
| *R*-square | 0.93 |
| Speed measure boundaries | (2.60, 14.50) |
| Base condition | 5 |
| *t*-Test (*p*-value) | 0.00 |
| Estimated CMF Clearinghouse star quality rating | ★★★ (3) |
| CMF standard error | 0.23 |

**Table 20. North Carolina rural freeways—KABCO speed CMF.**

| Speed CMF | Value |
|---|---|
| Speed measure | SpdStd |
| CMF equation | $y = 0.3492 \times x^{0.5952}$ |
| $R$-square | 0.93 |
| Speed measure boundaries | (2.90, 15.20) |
| Base condition | 6 |
| $t$-Test ($p$-value) | 0.00 |
| Estimated CMF Clearinghouse star quality rating | ★★★ (3) |
| CMF standard error | 0.17 |

As an example, figure 6 depicts the speed CMFs graph for SpdStd as the best speed CMF for rural freeways in Washington and North Carolina. SpdStd has a positive correlation with predicted crashes, and the CMFs follow almost similar functions in both States. Similar graphs are provided for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024). For the cases where both States have a mutual speed CMF, a graph includes both States, unless separate graphs are provided.




Source: FHWA.

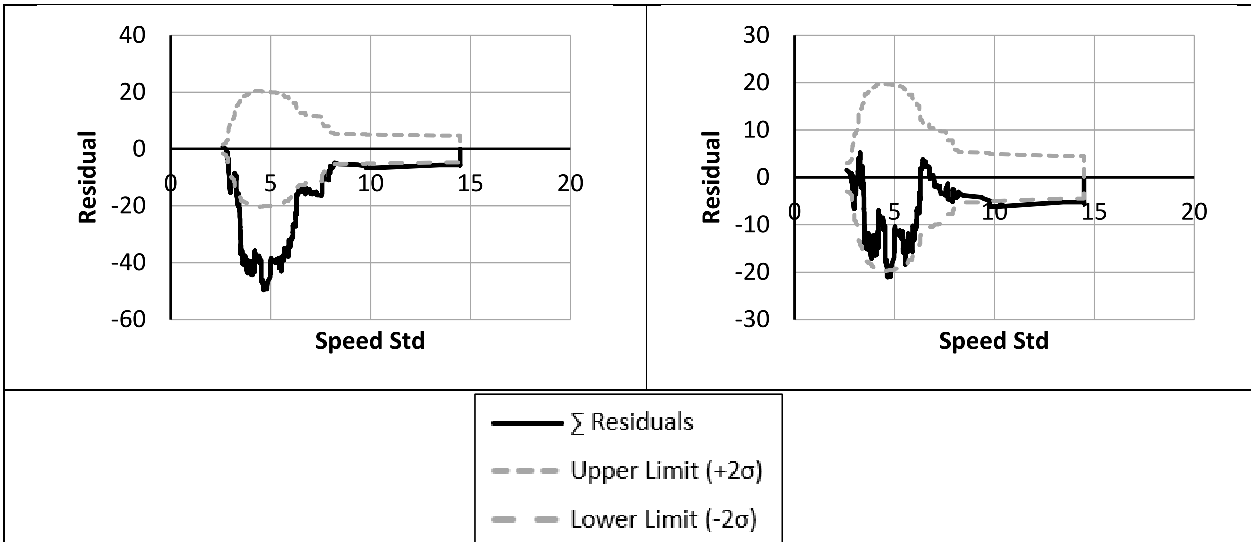
**Figure 6. Graph. Washington and North Carolina rural freeways—KABCO speed CMF.**

## SPEED CMF VALIDATION

In addition to the use of performance metrics (i.e., MAD and RMSE) to rank speed CMFs based on training and test datasets, the team used CURE plots (Hauer 2015) and a CMF Clearinghouse new star quality rating method (FHWA 2023a).

## CURE Plots

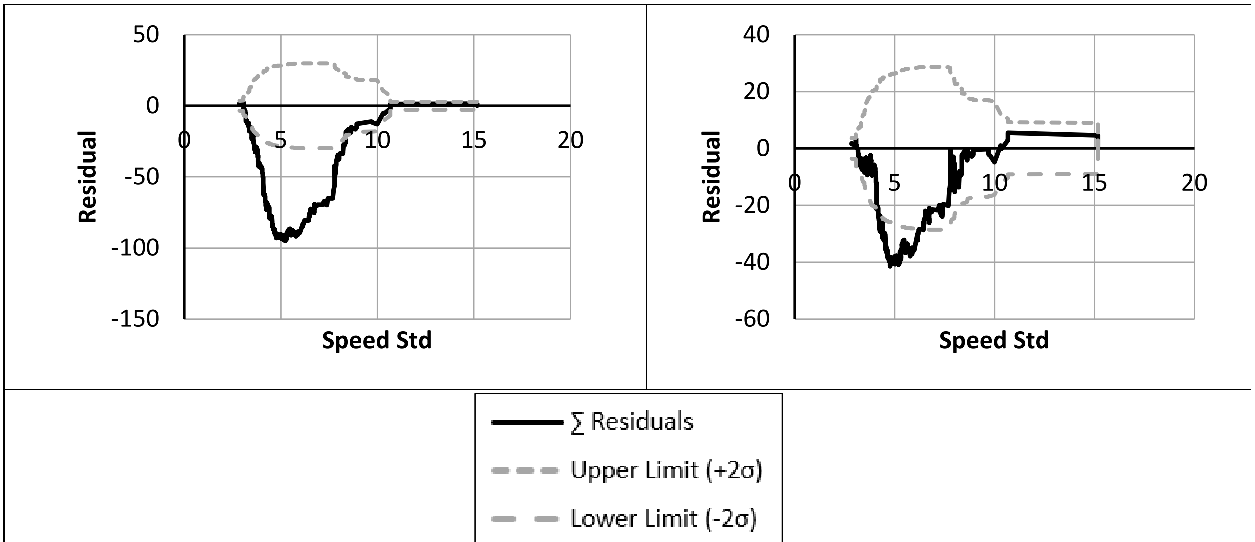
To validate the developed CMFs, the researchers developed CURE plots to compare the HSM (AASHTO 2010) predictions (without speed-related CMFs) to models with speed-related CMFs. The CURE plots show, at a glance, how good a fit is and what the remaining concerns are (Hauer 2015). As examples, Figure 7 and figure 8 show the CURE plots for rural freeways in Washington and North Carolina MVFI crashes, respectively, without and with the speed-related CMF (SpdStd).




| *Crash prediction without speed CMF* | *Crash prediction with speed CMF* |
|---|---|

Source: FHWA.
$\sigma$ = standard deviation.

**Figure 7. Graph. CURE plots for Washington rural freeways—MVFI speed CMF.**




| *Crash prediction without speed CMF* | *Crash prediction with speed CMF* |
| --- | --- |

Source: FHWA.

**Figure 8. Graph. CURE plots for North Carolina rural freeways—MVFI speed CMF.**

Based on figure 7, the plot for Washington rural freeways was about 10 percent within the upper and lower boundaries (±2 standard deviation) without the speed-related CMF, and it increased to about 97 percent with the addition of the speed-related CMF (an 87-percent increase). Based on figure 8, the plot for North Carolina rural freeways was about 10 percent within the upper and lower boundaries (±2 standard deviation) without the speed-related CMF, and it increased to about 53 percent with the addition of the speed-related CMF (a 43-percent increase). The addition of the speed-related CMF (SpdStd) improved the goodness of fit for rural freeways significantly in both States. Table 21 and table 22 summarize CURE plots for all different crash type/severity levels for Washington and North Carolina, respectively. CURE plots and summary tables are provided for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024).

**Table 21. Washington rural freeways CURE plots summary.**

| Crash Severity/ Type | Crash Prediction Method | Within CURE (%) | Change to HSM (%) | \|Maximum CURE Deviation\| | Change to HSM (%) |
|---|---|---|---|---|---|
| KABCO | HSM (without speed CMF) | 2.34 | — | 328.78 | — |
| KABCO | HSM × speed CMF | 50.15 | 48 | 92.31 | −72 |
| KABC | HSM (without speed CMF) | 9.06 | — | 99.87 | — |
| KABC | HSM × speed CMF | 59.06 | 50 | 25.89 | −74 |
| O | HSM (without speed CMF) | 3.36 | — | 218.16 | — |
| O | HSM × speed CMF | 69.88 | 67 | 53.38 | −76 |
| SVFI | HSM (without speed CMF) | 22.51 | — | 60.70 | — |
| SVFI | HSM × speed CMF | 56.14 | 34 | 16.37 | −73 |
| SVPDO | HSM (without speed CMF) | 9.80 | — | 94.55 | — |
| SVPDO | HSM × speed CMF | 84.06 | 74 | 16.20 | −83 |
| MVFI | HSM (without speed CMF) | 9.94 | — | 29.41 | — |
| MVFI | HSM × speed CMF | 97.08 | 87 | 1.46 | −95 |
| MVPDO | HSM (without speed CMF) | 4.68 | — | 105.86 | — |
| MVPDO | HSM × speed CMF | 77.78 | 73 | 28.23 | −73 |

—Not applicable.
|Maximum CURE Deviation| = absolute value of maximum CURE deviation.

**Table 22. North Carolina rural freeways CURE plots summary.**

| Crash Severity/ Type | Crash Prediction Method | Within CURE (%) | Change to HSM (%) | \|Maximum CURE Deviation\| | Change to HSM (%) |
|---|---|---|---|---|---|
| KABCO | HSM (without speed CMF) | 7.39 | — | 375.94 | — |
| KABCO | HSM × speed CMF | 41.71 | 34 | 91.51 | −76 |
| KABC | HSM (without speed CMF) | 20.69 | — | 80.18 | — |
| KABC | HSM × speed CMF | 56.16 | 35 | 16.26 | −80 |
| O | HSM (without speed CMF) | 6.40 | — | 280.08 | — |
| O | HSM × speed CMF | 33.66 | 27 | 60.80 | −78 |
| SVFI | HSM (without speed CMF) | 89.16 | — | 5.35 | — |
| SVFI | HSM × speed CMF | 96.22 | 7 | 4.39 | −18 |
| SVPDO | HSM (without speed CMF) | 25.29 | — | 54.64 | — |
| SVPDO | HSM × speed CMF | 93.60 | 68 | 5.95 | −89 |
| MVFI | HSM (without speed CMF) | 9.52 | — | 66.12 | — |
| MVFI | HSM × speed CMF | 53.20 | 44 | 15.55 | −76 |
| MVPDO | HSM (without speed CMF) | 2.13 | — | 205.19 | — |
| MVPDO | HSM × speed CMF | 2.63 | 1 | 176.36 | −14 |

—Not applicable.

## CMF Clearinghouse New Rating

To assess the quality of the developed speed-related CMFs, the team rated them using the new CMF Clearinghouse quality rating procedure (FHWA 2023a), which is based on NCHRP Project 17-72, "Update of Crash Modification Factors for the Highway Safety Manual" (National Academies of Sciences 2021). The rating procedure assigns a maximum possible score of 150 to different aspects of underlying research studies on CMF development, as follows:

- Before/after and cross-sectional studies:
    - Sample size.
    - Study design and statistical methodology.
    - Statistical significance (standard error is used to determine statistical significance).
- Meta-analysis and meta-regression studies:
    - Methodology and data.
    - Individual CMF quality.
    - Appropriateness of combining/developing CMF functions.
    - Statistical significance/appropriateness of analysis.

Depending on the obtained scores, the CMFs are assigned a star quality rating from one star to five stars, as shown in table 23.

**Table 23. Star rating in CMF Clearinghouse.**

| NCHRP 17-72 Rating Score (150-Point Scale) | Star Rating in CMF Clearinghouse |
|---|---|
| 135–150 | ★★★★★(5) |
| 110–134 | ★★★★(4) |
| 75–109 | ★★★ (3) |
| 35–74 | ★★ (2) |
| 0–34 | ★ (1) |

The team rated the speed-related CMFs using the new CMF Clearinghouse methodology (FHWA 2023a), and corresponding star quality ratings were obtained. These ratings are summarized for all facility types by crash type/severity level in appendix D through appendix F in volume II of this report (Das et al. 2024).

Most of the developed speed CMFs obtained a three-star rating. Three-star rating CMFs are among the acceptable CMFs for many States within their selected CMF short lists. The largest proportion of the CMFs in the CMF Clearinghouse belong to the three-star rating category, as demonstrated in table 24.

**Table 24. CMFs in CMF Clearinghouse by star quality rating.**

| Star Quality Rating | Count | Percent | Average No. of Points |
|---|---|---|---|
| ★ (1) | 742 | 9 | 20 |
| ★★ (2) | 1,625 | 20 | 53 |
| ★★★ (3) | 3,050 | 37 | 91 |
| ★★★★(4) | 2,189 | 26 | 120 |
| ★★★★★(5) | 463 | 6 | 140 |
| Cannot be rated (HSM) | 148 | 2 | — |
| Cannot be rated (insufficient information) | 107 | 1 | — |
| Total | 7,736 | 100 | 87 |

—Not applicable.
Data are from the CMF Clearinghouse (as of September 21, 2022) (FHWA 2023a).

Using "speed" as a search term for "Countermeasure Name" in the CMF Clearinghouse search tool (FHWA 2023a) resulted in 658 individual CMFs. Among the 658 found CMFs, 295 CMFs are under the "Speed management" category, 286 CMFs are under the "Advanced technology and ITS" category, and 77 CMFs belong to other categories.

None of the found CMFs under "Advanced technology and ITS" and other categories (except the "Speed management" category) were related to a speed measure (e.g., operating speed). Most of these CMFs were related to signs (e.g., "Changeable Curve Speed Warning signs"), cameras (e.g., "Implement automated speed enforcement cameras"), speed limits (e.g., "Install Variable Speed Limit (VSL)"), or other intelligent transportation-system-related technologies (e.g., "Install automated section speed enforcement system"). Some of them also referred to speed in general terms (e.g., "Convert high-speed rural intersection to roundabout"). Also, under the "Speed management" category, many CMFs were related to modifying PSLs (e.g., "Lower posted speed," "Increase speed limit from *X* to *Y* mph," or "Set posted speed limit 5 mph below engineering recommendations"), and still many CMFs were related to cameras (e.g., "Installation of fixed speed cameras"). Only 15 CMFs (0.19 percent of all CMFs in the CMF Clearinghouse (FHWA 2023a)) were related to a speed measure under the "Speed management" category (table 25). All these 15 CMFs had three-star ratings. The 12 CMFs from the work done by Elvik, Christensen, and Amundsen (2004) demonstrated a positive association between mean speed and considered crashes; however, their work was based on a meta-analysis of 460 studies from 1960 to 2004 from 20 different countries. The "Change 85th percentile speed from *X* to *Y*" CMF that was developed by Ksaibati, Zhong, and Evans (2009) indicated a relatively weak positive association between speed and crashes ($e^{0.0111\,(Y-X)}$); however, the *p*-value was insignificant (0.2540). The two CMFs developed by Dell'Acqua and Russo (2011) were based on a number of low-volume, rural, undivided roadways within the Province of Salerno, Italy.

**Table 25. Speed measure-related CMFs in CMF Clearinghouse.**

| CMF ID | Study | Countermeasure | CMF | Crash Type | KABCO Crash Severity | Roadway Type | Area Type | Publication Year | Star Quality Rating |
|---|---|---|---|---|---|---|---|---|---|
| 141 | Elvik, Christensen, and Amundsen (2004) | 5-percent reduction in mean speed | 0.83 | All | K | All | All | 2004 | ★★★ (3) |
| 142 | Elvik, Christensen, and Amundsen (2004) | 5-percent reduction in mean speed | 0.93 | All | A, B, C | All | All | 2004 | ★★★ (3) |
| 143 | Elvik, Christensen, and Amundsen (2004) | 5-percent reduction in mean speed | 0.95 | All | O | All | All | 2004 | ★★★ (3) |
| 144 | Elvik, Christensen, and Amundsen (2004) | 10-percent reduction in mean speed | 0.68 | All | K | All | All | 2004 | ★★★ (3) |
| 145 | Elvik, Christensen, and Amundsen (2004) | 10-percent reduction in mean speed | 0.85 | All | A, B, C | All | All | 2004 | ★★★ (3) |
| 146 | Elvik, Christensen, and Amundsen (2004) | 10-percent reduction in mean speed | 0.9 | All | O | All | All | 2004 | ★★★ (3) |
| 147 | Elvik, Christensen, and Amundsen (2004) | 15-percent reduction in mean speed | 0.56 | All | K | All | All | 2004 | ★★★ (3) |
| 148 | Elvik, Christensen, and Amundsen (2004) | 15-percent reduction in mean speed | 0.78 | All | A, B, C | All | All | 2004 | ★★★ (3) |
| 149 | Elvik, Christensen, and Amundsen (2004) | 15-percent reduction in mean speed | 0.85 | All | O | All | All | 2004 | ★★★ (3) |
| 150 | Elvik, Christensen, and Amundsen (2004) | 5-percent increase in mean speed | 1.19 | All | K | All | All | 2004 | ★★★ (3) |
| 151 | Elvik, Christensen, and Amundsen (2004) | 5-percent increase in mean speed | 1.08 | All | A, B, C | All | All | 2004 | ★★★ (3) |
| 152 | Elvik, Christensen, and Amundsen (2004) | 5-percent increase in mean speed | 1.05 | All | O | All | All | 2004 | ★★★ (3) |
| 2730 | Ksaibati, Zhong, and Evans (2009) | Change 85th percentile speed from $X$ to $Y$ | Equation | All | All | Not specified | Rural | 2009 | ★★★ (3) |
| 2987 | Dell'Acqua and Russo (2011) | Change mean speed (km/h) (flat/rolling terrain) | Equation | All | K, A, B, C | Not specified | Rural | 2010 | ★★★ (3) |
| 2994 | Dell'Acqua and Russo (2011) | Change mean speed (km/h) (mountainous terrain) | Equation | All | K, A, B, C | Not specified | Rural | 2010 | ★★★ (3) |

Data are from the CMF Clearinghouse (as of October 3, 2022) (FHWA 2023a).

## FINDINGS

The researchers developed speed CMFs based on the final four speed measures (i.e., SpdStd, (SpdAve − PSL), |SpdAve − PSL|, and SpdStd/SpdAve) out of the original 12 speed measures (summarized in Table 9) for rural highways, urban and suburban arterials, and rural and urban freeways.

### Rural Highway Speed CMFs

Table 26 summarizes the final speed CMFs for rural highways in Washington and North Carolina. Speed variation (i.e., SpdStd) was the best speed CMF for R2U in Washington, R4U in both States, and R4D (PDO crashes) in North Carolina. Overall, more than two-thirds of developed speed CMFs were SpdStd, followed by speed differential for R2U and R4D (KABCO crashes) in North Carolina. No speed CMFs could improve the HSM (AASHTO 2010) default crash prediction for R4D (KABC crashes) in North Carolina (i.e., for 14 out of 15 crash type/severity levels (93 percent), speed CMFs improved HSM default crash prediction) (AASHTO 2010).

**Table 26. Final speed CMFs for rural highways.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) |
|---|---|---|---|---|
| Washington | R2U | SpdStd† | SpdStd† | SpdStd† |
| Washington | R4U | SpdStd† | SpdStd† | SpdStd† |
| North Carolina | R2U | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ |
| North Carolina | R4U | SpdStd† | SpdStd† | SpdStd† |
| North Carolina | R4D | \|Diff\|‡ | None | SpdStd† |

†Speed variation measure.
‡Speed differential measure.
None = no speed CMF was found to improve HSM default crash prediction (without speed CMF) (AASHTO 2010); |Diff| = |SpdAve − PSL|.

Table 27 through table 29 summarize the percent change in MAD, RMSE, and within-CURE plot boundaries after applying speed CMFs to the HSM default (without speed CMF) predicted crashes (AASHTO 2010). These three tables show that R2U and R4U in North Carolina had a consistent improvement in all three performance metrics. This observation was followed by R2U and R4U in Washington, which had relatively high improvements for MAD and RMSE but slight improvements for CURE plots (except R2U (KABC crashes)) (AASHTO 2010). R4D in North Carolina had insignificant improvements for MAD and RMSE, but CURE plots were improved for KABCO and PDO crashes. KABC crashes had no effective speed CMF. Table 30 summarizes the estimated CMF Clearinghouse star quality ratings for speed CMFs for rural highways (FHWA 2023a). Most of the CMFs received three-star ratings, except R4U in Washington, due to a limited number of sites.

**Table 27. Percent change in MAD by applying speed CMFs to HSM default (without speed CMF) for rural highways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) |
|---|---|---|---|---|
| Washington | R2U | −3.2 | −3.7 | −2.3 |
| Washington | R4U | −9.0 | −6.8 | −10.0 |
| North Carolina | R2U | −4.6 | −3.7 | −4.7 |
| North Carolina | R4U | −8.5 | −8.3 | −7.1 |
| North Carolina | R4D | 0.0 | — | −0.5 |

—Not applicable.

**Table 28. Percent change in RMSE by applying speed CMFs to HSM default (without speed CMF) for rural highways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) |
|---|---|---|---|---|
| Washington | R2U | −13.8 | −14.6 | −11.0 |
| Washington | R4U | −12.0 | −7.1 | −10.0 |
| North Carolina | R2U | −16.3 | −11.9 | −14.6 |
| North Carolina | R4U | −9.7 | −7.8 | −8.0 |
| North Carolina | R4D | −0.3 | — | −0.5 |

—Not applicable.

**Table 29. Percent change within CURE plot boundaries by applying speed CMFs to HSM default (without speed CMF) for rural highways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) |
|---|---|---|---|---|
| Washington | R2U | 10 | 44 | 0 |
| Washington | R4U | 11 | 8 | 11 |
| North Carolina | R2U | 72 | 26 | 85 |
| North Carolina | R4U | 78 | 67 | 73 |
| North Carolina | R4D | 66 | — | 60 |

—Not applicable.

**Table 30. Summary of estimated CMF Clearinghouse star quality ratings for speed CMFs for rural highways.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) |
|---|---|---|---|---|
| Washington | R2U | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| Washington | R4U | ★★ (2) | ★★ (2) | ★★ (2) |
| North Carolina | R2U | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| North Carolina | R4U | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| North Carolina | R4D | ★★★ (3) | — | ★★★ (3) |

—Not applicable.

### Urban and Suburban Arterials Speed CMFs

Table 31 summarizes the final speed CMFs for urban and suburban arterials in Washington and North Carolina. Speed differential (i.e., (SpdAve − PSL) or |SpdAve − PSL|) was the dominant speed measure category. For 87 out of 98 crash type/severity levels (89 percent), speed CMFs improved HSM default crash prediction.

Table 32 through table 34 summarize percent change in MAD, RMSE, and within-CURE plot boundaries after applying speed CMFs to the HSM default (without speed CMF) predicted crashes (AASHTO 2010). As these three tables show, U2U in both States and U4U, U4D, and U5T in North Carolina showed a consistent improvement on the three performance metrics. This observation was followed by U6U in both States, which showed relatively high improvements for MAD and RMSE but slight improvements for CURE plots, except for U6U in North Carolina for KABCO crashes for which no speed CMF could improve HSM default crash prediction (AASHTO 2010). This result was a reflection of the fact that speed CMFs were not necessarily consistent among all crash type/severity levels for different facility types. Table 35 summarizes the estimated CMF Clearinghouse star quality ratings for speed CMFs for urban and suburban arterials (FHWA 2023a). U2U in both States received three-star ratings for all crash type/severity levels. U4D, U5T, and U6D in North Carolina had mostly three-star ratings, but most of the remaining CMFs received two-star ratings due to limited sample sizes.

**Table 31. Final speed CMFs for urban and suburban arterials.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|---|
| Washington | U2U | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† | \|Diff\|‡ | \|Diff\|‡ |
| Washington | U3T | SpdStd† | Speed CV† | SpdStd† | None | Speed CV† | SpdStd† | None |
| Washington | U4U | (Diff)‡ | (Diff)‡ | (Diff)‡ | Speed CV† | SpdStd† | \|Diff\|‡ | Speed CV† |
| Washington | U4D | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† | \|Diff\|‡ | None | None |
| Washington | U5T | None | SpdStd† | None | SpdStd† | \|Diff\|‡ | SpdStd† | None |
| Washington | U6U | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | (Diff)‡ | SpdStd† | (Diff)‡ | \|Diff\|‡ |
| Washington | U7T | Speed CV† | Speed CV† | Speed CV† | Speed CV† | \|Diff\|‡ | Speed CV† | Speed CV† |
| North Carolina | U2U | (Diff)‡ | (Diff)‡ | (Diff)‡ | SpdStd† | Speed CV† | (Diff)‡ | (Diff)‡ |
| North Carolina | U3T | SpdStd† | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ | (Diff)‡ |
| North Carolina | U4U | (Diff)‡ | \|Diff\|‡ | Speed CV† | None | \|Diff\|‡ | \|Diff\|‡ | Speed CV† |
| North Carolina | U4D | Speed CV† | Speed CV† | Speed CV† | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† |
| North Carolina | U5T | \|Diff\|‡ | (Diff)‡ | \|Diff\|‡ | SpdStd† | None | (Diff)‡ | \|Diff\|‡ |
| North Carolina | U6U | None | (Diff)‡ | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | (Diff)‡ | (Diff)‡ |
| North Carolina | U6D | Speed CV† | SpdStd† | Speed CV† | \|Diff\|‡ | None | SpdStd† | Speed CV† |

†Speed variation measure.
‡Speed differential measure.
None = no speed CMF was found to improve HSM default crash prediction (without speed CMF) (AASHTO 2010); (Diff) = (SpdAve − PSL), Speed CV = (SpdStd/SpdAve).

**Table 32. Percent change in MAD by applying speed CMFs to HSM default (without speed CMF) for urban and suburban arterials.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | U2U | −7.1 | −4.4 | −7.3 | −1.8 | −0.5 | −10.0 | −15.0 |
| Washington | U3T | −2.3 | −1.3 | −2.8 | — | −13.7 | −0.4 | — |
| Washington | U4U | −1.3 | −0.8 | −1.7 | 1.3 | −3.1 | −1.2 | 0.7 |
| Washington | U4D | −2.2 | −1.9 | −1.8 | −4.1 | 1.1 | — | — |
| Washington | U5T | — | 0.4 | — | 0.0 | −0.9 | 0.9 | — |
| Washington | U6U | −10.7 | −11.0 | −9.8 | −3.3 | −3.2 | −12.5 | −11.3 |
| Washington | U7T | −2.1 | −0.8 | −0.9 | −3.6 | −4.2 | −0.6 | −1.1 |
| North Carolina | U2U | −6.4 | −3.3 | −6.0 | −0.4 | −0.4 | −4.6 | −8.3 |
| North Carolina | U3T | 2.2 | −1.9 | 2.6 | −9.4 | −1.4 | 3.1 | −1.2 |
| North Carolina | U4U | −3.8 | −5.7 | 0.3 | — | −7.3 | −7.5 | −3.0 |
| North Carolina | U4D | −4.5 | −2.7 | −5.6 | −2.2 | −2.0 | −4.8 | −11.1 |
| North Carolina | U5T | −4.2 | −1.1 | −6.7 | −2.4 | — | −2.3 | −8.0 |
| North Carolina | U6U | — | −18.9 | −46.8 | −24.9 | −9.8 | −14.9 | −40.8 |
| North Carolina | U6D | 0.0 | 1.3 | −1.8 | −4.0 | — | 1.4 | −2.7 |

—Not applicable.

**Table 33. Percent change in RMSE by applying speed CMFs to HSM default (without speed CMF) for urban and suburban arterials.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | U2U | −6.1 | −6.1 | −6.3 | −0.4 | 1.7 | −15.9 | −20.0 |
| Washington | U3T | −0.2 | −1.6 | 0.7 | — | −16.3 | −0.9 | — |
| Washington | U4U | −1.6 | −1.2 | −1.2 | −1.1 | −3.8 | −2.0 | −0.2 |
| Washington | U4D | 3.7 | 0.4 | −0.6 | −1.8 | −0.4 | — | — |
| Washington | U5T | — | −0.5 | — | −0.1 | −0.7 | −0.1 | — |
| Washington | U6U | −7.9 | −7.6 | −8.0 | 1.6 | 0.7 | −10.2 | −9.4 |
| Washington | U7T | 6.7 | 5.0 | 4.3 | −1.9 | −2.4 | 5.6 | 6.6 |
| North Carolina | U2U | −14.6 | −8.3 | −15.5 | 0.3 | −0.4 | −11.1 | −18.5 |
| North Carolina | U3T | −0.3 | −0.2 | −1.7 | −8.3 | −3.1 | −1.9 | −3.5 |
| North Carolina | U4U | −3.3 | −9.3 | −0.5 | — | −4.8 | −13.2 | −0.4 |
| North Carolina | U4D | −5.8 | −3.8 | −5.9 | −0.5 | −2.4 | −5.8 | −9.4 |
| North Carolina | U5T | −9.8 | −2.8 | −12.7 | 0.4 | — | −3.5 | −14.3 |
| North Carolina | U6U | — | −17.8 | −41.6 | −34.5 | −12.8 | −12.8 | −36.1 |
| North Carolina | U6D | −0.7 | −0.4 | −0.9 | −0.4 | — | −0.6 | −0.9 |

—Not applicable.

**Table 34. Percent change within CURE plot boundaries by applying speed CMFs to HSM default (without Speed CMF) for urban and suburban arterials.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | U2U | 38 | 56 | 36 | 20 | 25 | 63 | 64 |
| Washington | U3T | 8 | 0 | 7 | — | 12 | 8 | — |
| Washington | U4U | 0 | 0 | 1 | 26 | 44 | 0 | 13 |
| Washington | U4D | 25 | 20 | 3 | 18 | 49 | — | — |
| Washington | U5T | — | 72 | — | 49 | 0 | 42 | — |
| Washington | U6U | 20 | 5 | 15 | 0 | 0 | 5 | 15 |
| Washington | U7T | 29 | 6 | 14 | 17 | 7 | 5 | 27 |
| North Carolina | U2U | 32 | 10 | 33 | 0 | 1 | 7 | 30 |
| North Carolina | U3T | 0 | 0 | 10 | 21 | 45 | 0 | 41 |
| North Carolina | U4U | 24 | 3 | 39 | — | 36 | 12 | 37 |
| North Carolina | U4D | 20 | 51 | 21 | 22 | 47 | 21 | 12 |
| North Carolina | U5T | 91 | 74 | 81 | 0 | — | 84 | 79 |
| North Carolina | U6U | — | 0 | 9 | 5 | 5 | 0 | 5 |
| North Carolina | U6D | 13 | 22 | 13 | 46 | — | 24 | 9 |

—Not applicable.

**Table 35. Summary of estimated CMF Clearinghouse star quality ratings for speed CMFs for urban and suburban arterials.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|---|
| Washington | U2U | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| Washington | U3T | ★★ (2) | ★★ (2) | ★★ (2) | — | ★★ (2) | ★★ (2) | — |
| Washington | U4U | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| Washington | U4D | ★★ (2) | ★★ (2) | ★★★ (3) | ★★ (2) | ★★ (2) | — | — |
| Washington | U5T | — | ★★★ (3) | — | ★★★ (3) | ★★ (2) | ★★ (2) | — |
| Washington | U6U | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| Washington | U7T | ★★★ (3) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| North Carolina | U2U | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| North Carolina | U3T | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| North Carolina | U4U | ★★ (2) | ★★ (2) | ★★★ (3) | — | ★★ (2) | ★★★ (3) | ★★★ (3) |
| North Carolina | U4D | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★ (2) | ★★ (2) | ★★ (2) | ★★★ (3) |
| North Carolina | U5T | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | — | ★★★ (3) | ★★★ (3) |
| North Carolina | U6U | — | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| North Carolina | U6D | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★ (2) | — | ★★ (2) | ★★★ (3) |

—Not applicable.

### Freeways Speed CMFs

Table 36 summarizes the final speed CMFs for rural and urban freeways in Washington and North Carolina. Speed variation was the dominant category for rural freeways 100-percent of the time in both States and covered more than three-quarters of urban freeways in both States. The speed differential perform better in only three urban freeway cases (SV CMFs for Washington and MVPDO for North Carolina). Also, no cases occurred where no speed CMFs could be developed (i.e., for all 28 out of 28 crash type/severity levels (100 percent), speed CMFs improved HSM default crash prediction) (AASHTO 2010).

Table 37 through table 39 summarize the percent change in MAD, RMSE, and within-CURE plot boundaries by applying speed CMFs to the HSM default (without speed CMF) predicted crashes. In all three tables, all four facility types showed a consistent improvement for all three performance metrics for all crash type/severity levels, except SV CMFs. This finding was an indication of how well speed CMFs could improve HSM default crash predictions for freeways. Table 40 summarizes the estimated CMF Clearinghouse star quality ratings for speed CMFs for rural and urban freeways (FHWA 2023a). All speed CMFs received three-star ratings in both States.

**Table 36. Final speed CMFs for rural and urban freeways.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|---|
| Washington | Rural freeway | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† |
| Washington | Urban freeway | SpdStd† | Speed CV† | SpdStd† | (Diff) ‡ | \|Diff\|‡ | SpdStd† | Speed CV† |
| North Carolina | Rural freeway | SpdStd† | SpdStd† | SpdStd† | Speed CV† | SpdStd† | SpdStd† | Speed CV† |
| North Carolina | Urban freeway | SpdStd† | SpdStd† | SpdStd† | Speed CV† | SpdStd† | SpdStd† | \|Diff\|‡ |

†Speed variation measure.
‡Speed differential measure.
None = no speed CMF was found to improve HSM default crash prediction (without speed CMF) (AASHTO 2010).

**Table 37. Percent change in MAD by applying speed CMFs to HSM default (without speed CMF) for rural and urban freeways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | Rural freeway | −7.7 | −4.5 | −6.1 | −2.1 | −1.8 | −2.3 | −4.4 |
| Washington | Urban freeway | −3.6 | −3.9 | −0.3 | 0.0 | −0.8 | −14.0 | −8.7 |
| North Carolina | Rural freeway | −9.8 | −4.5 | −8.4 | −0.1 | −1.5 | −4.4 | −1.3 |
| North Carolina | Urban freeway | −5.1 | −2.8 | −5.1 | −0.6 | −5.3 | −5.9 | −4.3 |

**Table 38. Percent change in RMSE by applying speed CMFs to HSM default (without speed CMF) for rural and urban freeways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | Rural freeway | −9.2 | −6.5 | −6.9 | −3.1 | −3.0 | −2.4 | −6.0 |
| Washington | Urban freeway | −11.3 | −7.4 | −7.3 | −0.2 | 1.7 | −17.4 | −9.3 |
| North Carolina | Rural freeway | −9.2 | −4.3 | −8.7 | 0.0 | −3.1 | −4.4 | −0.9 |
| North Carolina | Urban freeway | −7.8 | −4.5 | −8.1 | −0.4 | −5.5 | −5.0 | −7.8 |

**Table 39. Percent change within CURE plot boundaries by applying speed CMFs to HSM default (without speed CMF) for rural and urban freeways.**

| State | Facility Type | Change (KABCO) (%) | Change (KABC) (%) | Change (O) (%) | Change (SVFI) (%) | Change (SVPDO) (%) | Change (MVFI) (%) | Change (MVPDO) (%) |
|---|---|---|---|---|---|---|---|---|
| Washington | Rural freeway | 48 | 50 | 67 | 34 | 74 | 87 | 73 |
| Washington | Urban freeway | 84 | 18 | 77 | 0 | 8 | 63 | 23 |
| North Carolina | Rural freeway | 34 | 35 | 27 | 7 | 68 | 44 | 0 |
| North Carolina | Urban freeway | 56 | 89 | 55 | 18 | 86 | 88 | 54 |

**Table 40. Summary of estimated CMF Clearinghouse star quality ratings for speed CMFs for rural and urban freeways.**

| State | Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|---|
| Washington | Rural freeway | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| Washington | Urban freeway | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| North Carolina | Rural freeway | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| North Carolina | Urban freeway | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |

# CHAPTER 4. CONCLUSIONS

## INTRODUCTION

Speed is widely recognized as having serious safety impacts, especially on the severity of crashes. However, these effects are complex and generally have not been captured in the HSM (AASHTO 2010). Keeping this research need in mind, this project aimed to develop speed-related CMFs for the existing crash prediction models of the HSM for different rural highways, urban and suburban arterials, and rural and urban freeways. This chapter summarizes the developed speed CMFs, provides key findings, describes practical applications, and highlights potential scopes for future studies.

## SPEED CMFs

In this research, the team developed speed CMFs for rural highways, urban and suburban arterials, and rural and urban freeways using data from Washington and North Carolina. The common States among the three databases (i.e., SHRP2 RID, HSIS, and NPMRDS) used in this research are North Carolina and Washington, which were, therefore, selected for this research study (ISU 2023; FHWA n.d.; RITIS 2023). However, the similar speed CMF development approach used in this study can also be used to develop speed CMFs in other States, such as those in the SHRP2 pooled fund. The findings show that inclusion of speed-related CMFs improves model precision for certain facility types. Also, this research successfully demonstrated the value of using the NPMRDS, HSIS, and SHRP2 RID in crash data modeling. Table 41 and table 42 summarize developed speed CMFs by facility type and crash type/severity level for Washington and North Carolina, respectively. Table 41 and table 42 also include the estimated CMF Clearinghouse star quality ratings for developed speed CMFs (FHWA 2023a). Additionally, table 43 summarizes developed speed CMFs by speed measure category. The common speed measure category for developed speed CMFs was speed variation (i.e., SpdStd or SpdStd/SpdAve), which covered 58 percent of speed CMFs in Washington and 52 percent of speed CMFs for both States combined. North Carolina had a large split between speed variation and speed differential categories. In most cases, the association of speed variation/differentials with crashes was positive. Also, some variations within facility types were present: speed variation was the dominant category100 percent of the time for rural freeways in both States and covered more than three-quarters of urban freeways in both States. Certain crash type/severity levels did not result in speed CMFs (10 percent of potential speed CMFs for Washington, 7 percent for North Carolina, and 9 percent combined), and except for rural highways in North Carolina, the rest were all for urban and suburban arterials.

As a part of speed CMF development, the research team examined two performance metrics (MAD and RMSE) for different facility types and crash type/severity levels. In addition to the use of performance metrics, the team employed CURE plots and the CMF Clearinghouse new star quality rating method.

**Table 41. Final Washington speed CMFs.**

| Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|
| R2U | SpdStd† | SpdStd† | SpdStd† | — | — | — | — |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | — | — | — | — |
| R4U | SpdStd† | SpdStd† | SpdStd† | — | — | — | — |
| | ★★ (2) | ★★ (2) | ★★ (2) | — | — | — | — |
| U2U | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† | \|Diff\|‡ | \|Diff\|‡ |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| U3T | SpdStd† | Speed CV† | SpdStd† | None | Speed CV† | SpdStd† | None |
| | ★★ (2) | ★★ (2) | ★★ (2) | NA | ★★ (2) | ★★ (2) | NA |
| U4U | (Diff) ‡ | (Diff) ‡ | (Diff)‡ | Speed CV† | SpdStd† | \|Diff\|‡ | Speed CV† |
| | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| U4D | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† | \|Diff\|‡ | None | None |
| | ★★ (2) | ★★ (2) | ★★★ (3) | ★★ (2) | ★★ (2) | NA | NA |
| U5T | None | SpdStd† | None | SpdStd† | \|Diff\|‡ | SpdStd† | None |
| | NA | ★★★ (3) | NA | ★★★ (3) | ★★ (2) | ★★ (2) | NA |
| U6U | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | (Diff)‡ | SpdStd† | (Diff) ‡ | \|Diff\|‡ |
| | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| U7T | Speed CV† | Speed CV† | Speed CV† | Speed CV† | \|Diff\|‡ | Speed CV† | Speed CV† |
| | ★★★ (3) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| Rural freeway | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† | SpdStd† |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| Urban freeway | SpdStd† | Speed CV† | SpdStd† | (Diff)‡ | \|Diff\|‡ | SpdStd† | Speed CV† |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |

—Inapplicable crash type/severity level.
†Speed variation measure.
‡Speed differential measure.
★ = Estimated CMF Clearinghouse star quality rating (FHWA 2023a).
None = no speed CMF was found to improve HSM default crash prediction (without speed CMF) (AASHTO 2010); NA = not applicable.

## Table 42. Final North Carolina speed CMFs.

| Facility Type | Speed CMF (KABCO) | Speed CMF (KABC) | Speed CMF (O) | Speed CMF (SVFI) | Speed CMF (SVPDO) | Speed CMF (MVFI) | Speed CMF (MVPDO) |
|---|---|---|---|---|---|---|---|
| R2U | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ | — | — | — | — |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | — | — | — | — |
| R4U | SpdStd† | SpdStd† | SpdStd† | — | — | — | — |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | — | — | — | — |
| R4D | \|Diff\|‡ | None | SpdStd† | — | — | — | — |
| | ★★★ (3) | NA | ★★★ (3) | — | — | — | — |
| U2U | (Diff)‡ | (Diff)‡ | (Diff) | SpdStd† | Speed CV† | (Diff)‡ | (Diff)‡ |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| U3T | SpdStd† | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | \|Diff\|‡ | \|Diff\|‡ | (Diff)‡ |
| | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| U4U | (Diff)‡ | \|Diff\|‡ | Speed CV† | None | \|Diff\|‡ | \|Diff\|‡ | Speed CV† |
| | ★★ (2) | ★★ (2) | ★★★ (3) | NA | ★★ (2) | ★★★ (3) | ★★★ (3) |
| U4D | Speed CV† | Speed CV† | Speed CV† | \|Diff\|‡ | \|Diff\|‡ | Speed CV† | Speed CV† |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★ (2) | ★★ (2) | ★★ (2) | ★★★ (3) |
| U5T | \|Diff\|‡ | (Diff)‡ | \|Diff\|‡ | SpdStd† | None | (Diff)‡ | \|Diff\|‡ |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | NA | ★★★ (3) | ★★★ (3) |
| U6U | None | (Diff)‡ | (Diff)‡ | (Diff)‡ | \|Diff\|‡ | (Diff)‡ | (Diff)‡ |
| | NA | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) | ★★ (2) |
| U6D | Speed CV† | SpdStd† | Speed CV† | \|Diff\|‡ | None | SpdStd† | Speed CV† |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★ (2) | NA | ★★ (2) | ★★★ (3) |
| Rural freeway | SpdStd† | SpdStd† | SpdStd† | Speed CV† | SpdStd† | SpdStd† | Speed CV† |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |
| Urban freeway | SpdStd† | SpdStd† | SpdStd† | Speed CV† | SpdStd† | SpdStd† | \|Diff\|‡ |
| | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) | ★★★ (3) |

—Inapplicable crash type/severity level.
†Speed variation measure.
‡Speed differential measure.
★ = Estimated CMF Clearinghouse star quality rating (FHWA 2023a).
None = no speed CMF was found to improve HSM default crash prediction (without speed CMF) (AASHTO 2010).

**Table 43. Developed speed CMFs by speed measure category.**

| State | Speed CMF Category | Rural Highways | | Urban Arterials | | Rural Freeways | | Urban Freeways | | All | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **No.** | **Percent** | **No.** | **Percent** | **No.** | **Percent** | **No.** | **Percent** | **No.** | **Percent** |
| Washington | Speed variation† | 6 | 100 | 22 | 45 | 7 | 100 | 5 | 71 | 40 | 58 |
| Washington | Speed differential‡ | 0 | 0 | 20 | 41 | 0 | 0 | 2 | 29 | 22 | 32 |
| Washington | HSM default | 0 | 0 | 7 | 14 | 0 | 0 | 0 | 0 | 7 | 10 |
| Washington | **Total** | **6** | **100** | **49** | **100** | **7** | **100** | **7** | **100** | **69** | **100** |
| North Carolina | Speed variation† | 4 | 44 | 16 | 33 | 7 | 100 | 6 | 86 | 33 | 46 |
| North Carolina | Speed differential‡ | 4 | 44 | 29 | 59 | 0 | 0 | 1 | 14 | 34 | 47 |
| North Carolina | HSM default | 1 | 11 | 4 | 8 | 0 | 0 | 0 | 0 | 5 | 7 |
| North Carolina | **Total** | **9** | **100** | **49** | **100** | **7** | **100** | **7** | **100** | **72** | **100** |
| Combined | Speed variation† | 10 | 67 | 38 | 39 | 14 | 100 | 11 | 79 | 73 | 52 |
| Combined | Speed differential‡ | 4 | 27 | 49 | 50 | 0 | 0 | 3 | 21 | 56 | 40 |
| Combined | HSM default | 1 | 7 | 11 | 11 | 0 | 0 | 0 | 0 | 12 | 9 |
| Combined | **Total** | **15** | **100** | **98** | **100** | **14** | **100** | **14** | **100** | **141** | **100** |

†Speed variation measure.
‡Speed differential measure.

## RECOMMENDATIONS FOR APPLICATION OF DEVELOPED CMFS

Following are recommendations for the application of developed speed CMFs in this study:

- The team developed CMFs through a DDSA approach. Application of these CMFs (e.g., in HSM-related evaluation tools (AASHTO 2010)) requires careful interpretation, and their application to the speed measures significantly outside the provided ranges may not provide reliable results.

- CMFs are available for different crash type/severity levels. They should not be applied in a manner that results in overlapping target crash type/severity levels (e.g., if the CMF for KABCO is applied, then neither of the other developed CMFs for that facility type should be used).

- The developed CMFs are based on data from Washington and North Carolina, so they are theoretically going to perform effectively in Washington and North Carolina. However, similar to many CMFs in the CMF Clearinghouse (FHWA 2023a) and other CMF sources, these CMFs can also be used in other jurisdictions. Regardless, their application in other jurisdictions should be examined beforehand. Specifically, State decisionmakers may conduct a transferability test on developed CMFs in this study. Such a test can be performed by applying the desired developed CMFs on a sample of representative data from their jurisdiction and use some metrics—such as MAD, RMSE, and CURE plots—to investigate how well the CMFs fit their jurisdiction. Appendix G in volume II of this report demonstrates an implementation sample case of one of the developed CMFs (Das et al. 2024).

- The similar speed CMF development approach used in this study can also be used to develop speed CMFs at the jurisdiction level if required data are available. For this purpose, the six-step speed CMF development described in chapter 3, "Data Analysis," can be used.

## RECOMMENDATIONS FOR FUTURE RESEARCH

While the findings from this research resulted in the development of some statistically significant speed CMFs for some rural highways, urban and suburban arterials, and rural and urban freeways, the study had several limitations that could be addressed in future research:

- Due to reasons discussed as follows, the team excluded certain facility types from the scope of this study. One-way arterials, ramps, and collector-distributor roads were excluded due to low NPMRDS coverage (RITIS 2023). Also, freeway speed-change lanes were excluded from the study scope due to complexities in their identification, applicability of NPMRDS speed measures to them (freeway speed-change lanes usually have two flows of traffic: the vehicles on the main-lane freeway and the vehicles either decreasing speed to exit the freeway or increasing speed to join the freeway), and difficulties in assigning their corresponding crashes because freeway speed-change lanes are directional and crashes must be assigned directionally as well. Using different data sources may address these issues, and speed CMFs can be investigated for the excluded facility types as well.

- Due to small sample sizes of some crash type/severity levels, some of the urban and suburban arterials had two-star quality rating CMFs. Using larger sample sizes may result in better-quality speed CMFs for these crash type/severity levels.

- Since the objective of this research was the development of speed CMFs for HSM SPFs (AASHTO 2010), the HSM default SPFs were calibrated to Washington and North Carolina conditions, and then speed CMFs were added to crash prediction. Investigation of speed CMF development along with jurisdiction-specific SPFs may be worthy of further research.

- The developed speed CMFs can be incorporated into HSM crash prediction as external CMFs; however, in preparation of the next edition of the HSM, integration of the developed speed CMFs as an adjustment factor among other HSM Part C adjustment factors can be investigated. Upon acceptable performance of this integration, the developed speed CMFs (or a subset of them) or similar functions with slightly modified coefficients can be added to the HSM crash prediction method.

- The structure of crash prediction models in the first edition of the HSM is bidirectional for roadway segments; however, for certain facility types (e.g., freeways), a directional format is expected to be selected for the next edition of the HSM. In this study, a bidirectional format was followed; however, investigation of developing speed CMFs by direction of travel may be considered for future research. This approach will allow researchers to account for significant differences in speed CMFs for facility types with significantly different directional traffic volumes and speed measures that could not be captured in bidirectional speed CMF development.

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