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Review of the Virginia Department of Transportation's Truck Weight Data Plan for the Mechanistic-Empirical Pavement Design Guide

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Final Report VCTIR 12-R4

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Standard Title Page—Report on State Project

Report No.:	Report Date:	No. Pages:	Type Report:	Project No.:
VCTIR 12-R4	November 2011	62	Final	92722
			Period Covered:	Contract No.:

Title:
Review of the Virginia Department of Transportation's Truck Weight Data Plan for the Mechanistic-Empirical Pavement Design Guide

Key Words: truck weight data plan, weigh in motion, WIM, MEPDG, truck weight data analysis

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Supplementary Notes:

Abstract:

In 2003, staff of the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research) and the Virginia Department of Transportation (VDOT) developed a plan to collect traffic and truck-axle weight data to support the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,* known as the Mechanistic-Empirical Pavement Design Guide (MEPDG). The purpose of this study was to review VDOT's traffic data plan for the MEPDG and revise it as needed. The review included an assessment of the data obtained from the VDOT and Virginia Department of Motor Vehicles weigh-in-motion (WIM) sites and the appropriateness of the truck weight groups in VDOT's traffic data plan. Information on truck travel patterns and characteristics was compiled.

There is very little literature that provides specific information on the structure of a traffic data plan for the MEPDG. Guidance provided by the Federal Highway Administration allows for much flexibility in the development of such a plan. Most states are working to develop the plan, and such plans that are already in place vary considerably. The Corridors of Statewide Significance in Virginia's statewide long-range multimodal transportation plan represent the routes where truck traffic is most prominent and therefore represent routes on which the VDOT plan should focus.

The study recommends that VDOT continue with its current truck weight data plan for the MEPDG. With this plan, VDOT is positioned to implement the MEPDG from a truck data perspective. The WIM data comprise an important input to the MEPDG process that is expected to provide VDOT with more accurate pavement designs based on actual traffic loadings in Virginia. Further, staff of VDOT's MEPDG Traffic Data Team and staff of the VDOT Traffic Engineering Division's Traffic Monitoring Program should work together to develop a strategic plan for the continuing incremental expansion of the WIM program. The plan should include consideration of the resources needed not only to add sites but also to administer an expanded WIM program. VDOT's Chief Engineer and Chief of System Operations should encourage the addition of WIM sites when major projects are planned in locations that are part of the strategic plan for WIM. Site characteristics required for acceptable WIM sensor performance should be specified by VDOT's MEPDG Traffic Data Team. Implementation of the recommendations provided in this study will assist VDOT in using the MEPDG to advance pavement design and improve its cost-effectiveness. The likelihood of implementation is high.

FINAL REPORT

REVIEW OF THE VIRGINIA DEPARTMENT OF TRANSPORTATION'S TRUCK WEIGHT DATA PLAN FOR THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

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

Charlottesville, Virginia

November 2011
VCTIR 12-R4

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ABSTRACT

In 2003, staff of the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research) and the Virginia Department of Transportation (VDOT) developed a plan to collect traffic and truck-axle weight data to support the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,* known as the Mechanistic-Empirical Pavement Design Guide (MEPDG). The purpose of this study was to review VDOT's traffic data plan for the MEPDG and revise it as needed. The review included an assessment of the data obtained from the VDOT and Virginia Department of Motor Vehicles weigh-in-motion (WIM) sites and the appropriateness of the truck weight groups in VDOT's traffic data plan. Information on truck travel patterns and characteristics was compiled.

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INTRODUCTION

In 2002, the Virginia Department of Transportation (VDOT) began making plans to implement the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Sttructures,* known as the Mechanistic-Empirical Pavement Design Guide (MEPDG), developed under the National Cooperative Research Program's Projects 1-37A and 1-40 (Transportation Research Board, 2002). The use of truck weight data was a critical input in this design process. The developers of the MEPDG have stated that transportation agencies in compliance with the Federal Highway Administration's (FHWA) *Traffic Monitoring Guide* (TMG) (FHWA, 2001) will have the traffic data necessary to implement the new pavement design approach. The MEPDG was structured in a hierarchical manner with three pavement design input levels. For Level 1 input, all project-specific data will be collected, including axle load spectra information (and axle loadings by vehicle classification) and vehicle classification counts at the project location. For Level 2 input, regional data will be applied. For Level 3 input, estimated project-specific and statewide average or default data will be used in the analysis.

In 2003, staff of the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research [VCTIR]) and VDOT developed a plan to collect traffic and truck axle weight data to support the MEPDG. The purpose of the effort was to develop a plan to position VDOT to have the data required to support Level 2 input. The product of the effort was *A Traffic Data Plan for Mechanistic-Empirical Pavement Design (2002 Pavement Design Guide) in Virginia* (Cottrell et al., 2003). The report served as the basis for implementing and maintaining the truck weight program necessary for the MEPDG approach.

VDOT's program was based on the premise of starting small and providing high-quality data at a limited number of sites, then adding sites over time as appropriate. In contrast, some state departments of transportation (DOTs) have focused on installing as many weigh-in-motion (WIM) sites as possible from the start and appear to give less attention to the quality of the data. In light of this, some VDOT staff questioned whether VDOT's approach was proper and adequate to provide statewide data.

BACKGROUND

The development of VDOT's traffic data plan and a description of the current plan are provided here.

Development of VDOT's Truck Weight Groups

The TMG (FHWA, 2001) provides guidance on how a state should develop a WIM program. Some of the general principles are presented here.

> The truck weight data collection program is based on creating summary axle load distributions that can be applied with confidence and statistical precision to all roads in a State. The procedure is to group the State's roads into categories, so that each group experiences freight traffic with reasonably similar characteristics. Within each of these groups of roads, the State should operate a number of WIM sites. These sites will be used to identify truck weight patterns that apply to all roads in the group. Truck weight road groups should be based on a combination of known geographic, industrial, agricultural, and commercial patterns, along with knowledge of the trucking patterns that occur on specific roads. Road groups or systems for truck weight data collection should: 1) be easily applied within each State, and 2) provide a logical means for discriminating between roads that are likely to have very high load factors and roads that have lower load factors (that is, between roads where most trucks are fully loaded and roads where a large percentage of trucks are either partially loaded or empty).

A minimum of six sites are suggested for each group. When this is applied to the MEPDG, the truck weight groups (TWGs) are surrogates for regions.

No reliable truck weight data were available for Virginia before the development of the VDOT traffic data plan. The Virginia Department of Motor Vehicles (DMV) did not begin to save its truck weight data until DMV sites became a part of VDOT's truck weight data plan. Even if DMV data were available, the small number of sites would have limited their value from a statewide perspective. The lack of reliable truck weight data led VDOT to develop an initial set of TWGs based on truck volumes and road functional classification. It was assumed that roads with higher truck volumes had more heavy trucks, and anecdotal information from DMV personnel supported this assumption. The VDOT team focused on the roads that had most of the truck traffic, using truck volumes on interstate and arterial roads from the 2001 vehicle classification counts (Jones, 2002). Each direction of a route was analyzed separately. The TMG (FHWA, 2001) suggests that FHWA Vehicle Class 9 (five-axle tractor-trailer units) be used to represent truck traffic. However, VDOT groups FHWA Vehicle Classes 8 through 10 together for tractor-trailer units. Since Class 9 trucks are the predominant class among the three combined classes, the grouping was deemed appropriate for this use. The tractor-trailer truck volumes were then used to identify a point for dividing high and low truck volumes on interstate and arterial routes.

To provide for WIM data within the constraints of the available traffic data program budget, a decision was made to take advantage of the flexibility permitted in the TMG and the availability of WIM data from the DMV. VDOT chose to begin with a small WIM program with high-quality WIM data collected continuously and a small number of TWGs. Three TWGs were created based on the 2001 truck traffic data: (1) interstate and arterial roads with

1,000 or more tractor-trailer trucks per day in one direction, (2) interstate and arterial roads with less than 1,000 tractor-trailer trucks per day in one direction, and (3) minor arterials and major collectors. TWGs 1 and 2, roads where the majority of truck loading occurs, were the first priority for implementation. A traffic data plan and a phased approach to implement the plan were proposed and implemented.

VDOT's Current Truck Weight Data Plan

In February 2009 when the current study began, VDOT's traffic data plan (hereinafter referred to as truck weight data plan, a more accurate description) was based on 22 WIM sites. For traffic data purposes, a site is considered to be a WIM system monitoring one direction of traffic. There are 10 WIM sites with the volume of tractor-trailer trucks ≥ 1,000 per day and 12 with the volume of tractor-trailer trucks < 1,000 per day based on the 2001 traffic counts, meeting the minimum of 6 sites per TWG suggested by the TMG. Sixteen sites have been installed by VDOT, and 6 sites belong to DMV as part of its truck weight enforcement program. Eight sites are on interstate highways, and 14 are on primary highways. A list of the sites is provided in Table 1.

Table 1. WIM Sites in Virginia

Route	Direction (No. of Lanes)	Location	Agency	Technology	Truck Weight Group[a]
I-66	West (2)	Fauquier County	VDOT	Peek/Kistler	1
I-81	North (1), South (1)	Stephens City	DMV	IRD / Load cell	1
I-81	North (1), South (1)	Troutville	DMV	IRD / Load cell	1
I-95	North (1), South (1)	Dumfries	DMV	IRD / Load cell	1
I-95	North (2)	Sussex County	VDOT	Peek/Kistler	1
US 17	North (2), South (2)	Fauquier County	VDOT	Peek/Kistler	1
SR 164	East (2), West (2)	Portsmouth	VDOT	Peek/Kistler	2
SR 234	North (2), South (2)	Prince William County	VDOT	Peek/Kistler	2
SR 288	North (2), South (2)	Midlothian	VDOT	Peek/Kistler	2
US 29	North (2), South (2)	Danville	VDOT	North: Peek/Kistler South: IRD / Bending plate	2
US 58	East (2), West (2)	Lee County	VDOT	Peek/Kistler	2
US 60	East (1), West (1)	Cumberland County	VDOT	Peek/Kistler	2

VDOT = Virginia Department of Transportation; DMV = Department of Motor Vehicles; IRD = International Road Dynamics.
[a] 1 = volume of tractor-trailer trucks ≥ 1,000 per day; 2 = volume of tractor-trailer trucks < 1,000 per day (2001 traffic counts).

WIM Technology

VDOT WIM sites employ Kistler piezoquartz sensors with a life expectancy of 3 to 5 years. The Kistler sensors are being placed in existing smooth pavement to provide traffic data quality in accordance with ASTM E1318-02, Type I (American Society of Testing and Materials [ASTM], 2002). Typically, potential sites are profiled and analyzed using software developed by FHWA's Long-Term Pavement Performance (LTPP) program. If a site meets the smoothness requirements and other criteria such as the truck volume and geographic location, it is considered a candidate WIM location. Originally, load cell technology and concrete pavement runways were recommended for use at WIM sites. At the time, this was the only technology available to provide quality data and not pose a potential safety hazard to the traveling public. Given the large initial cost with load cells and the runway ($390,000 for two lanes [Cottrell et al., 2003]), staff of VDOT's WIM program determined that the Kistler technology with the smaller initial cost and shorter service life was more economical. The cost to install a two-lane Kistler WIM station is $68,250 (Williams, 2011) and the annual cost to operate, maintain, and calibrate a site is $15,000 on average (Williams, 2011). VDOT's Traffic Engineering Division (TED) has one full-time position to manage the WIM program.

The final recommendation in the report describing the original plan (Cottrell et al., 2003) was that the effectiveness of the program be evaluated and that the evaluation include an assessment of the data obtained from the DMV sites and the effectiveness of the TWGs

PURPOSE AND SCOPE

The purpose of this study was to review VDOT's truck weight data plan for the MEPDG (Cottrell et al., 2003) and revise it as needed. The review included an assessment of the data obtained from the VDOT and DMV WIM sites and the appropriateness of the TWGs.

Information on truck travel patterns and characteristics were compiled, and answers to the following questions were sought:

1. Are the current WIM sites located in the right areas?

2. Is a regional factor needed?

3. If so, is there adequate regional coverage to determine a regional factor?

4. Should unique truck loading situations such as the coal loading in VDOT's Bristol District be part of VDOT's truck weight data plan?

The study was done with assistance from VDOT's MEPDG Traffic Data Team. This team is composed of employees in VDOT's TED Traffic Monitoring Program, the Pavement Design and Evaluation Section of VDOT's Materials Division, and others. The traffic data team served as the technical peer review panel for the study.

Ideally, to evaluate VDOT's truck weight data plan effectively, a method to collect sample truck weight data at random locations throughout Virginia was needed. However, the current portable WIM systems did not appear accurate enough to satisfy this purpose. This study used the available permanent WIM data to assess the current program; as a consequence, the assessment was constrained by the limited available WIM data. The development of the traffic data plan is viewed as an iterative process; the evaluation that was the subject of this study is considered the second step in the process. The final step is to review and revise the plan as needed as new technologies, strategies, and information become available.

METHODS

Eight tasks were conducted to achieve the study objectives.

1. *Review the literature.* Literature related to WIM and truck weight data programs and plans used by other transportation agencies was reviewed. Numerous reports related to WIM-based traffic data plans were identified by computerized literature searches of transportation databases such as TRIS Online; other tools provided by the VDOT Research Library; general Internet searches; and contacts with staff of VDOT, other state DOTs; and researchers.

2. *Survey other state DOTs.* An email survey of head traffic engineers (or WIM managers if known) in state DOTs was conducted to obtain detailed information on their truck weight programs (see Appendix A for the survey). Participants were asked to respond to the survey by May 22, 2010. Two follow-up reminder emails were sent. Responses were received by email after the deadline.

3. *Examine truck traffic in Virginia.* Truck traffic in Virginia was examined to identify opportunities for other TWGs and to examine how well existing TWGs addressed trucking patterns and characteristics. Truck travel patterns were considered based on region, industry, agriculture, special sites, and port locations that generated truck trips and potential destinations and routes traveled. For example, the Virginia Port Authority (VPA) owns Norfolk International Terminals, the Newport News Marine Terminal, the Portsmouth Marine Terminal, the Virginia Inland Port in Front Royal, and APMT Virginia; combined, these five facilities make up the Port of Virginia (VPA, 2010). The impact of these facilities relative to truck traffic and the need for different TWGs was examined. In addition, a goal of having the National Highway System (NHS) covered by the TWGs was examined.

4. *Analyze WIM data.* The WIM data were reviewed by volume, vehicle classification, and equivalent single-axle loads (ESALs). To assess the validity of the TWGs, ESALs were analyzed. Emphasis was on the variability of ESALs within the two TWGs. Truck weight data for each WIM site and for the TWGs were analyzed. Some of the data to be considered included truck weight by axle configuration by direction by lane by vehicle class. Although the MEPDG uses axle load spectra (or axle load distribution) as a measure of truck loading, ESALs were chosen for this analysis because it was simpler to use one value for each site for comparative analysis. The decision to use ESALs as a surrogate for axle load spectra was made in consultation with VDOT pavement research staff and engineers.

5. *Assess DMV WIM data.* This task was to determine if VDOT should continue to use the DMV WIM data. Some state DOT staff recommend that truck weight data collected during enforcement activities not be used because they believe the heavier and overweight trucks are likely to avoid truck enforcement areas. As a result, truck weight data gathered at weight enforcement stations may be lower than the similar data collected without enforcement. To test this theory, data from DMV WIM sites

were compared to data from VDOT WIM sites in the same TWG. To remove the potential influences of factors other than enforcement such as route and direction, WIM data at a VDOT site and a DMV site on northbound I-95 were compared.

6. *Assess VDOT's current truck weight data plan for the MEPDG* (Cottrell et al., 2003). This task was to determine how well the current plan satisfies VDOT's traffic data needs for the MEPDG. Questions to be answered included: (1) Are the current WIM sites located in the right areas? (2) Is a regional factor needed? (3) If so, is there adequate regional coverage to determine a regional factor? (4) Should unique truck loading situations such as the coal loading in VDOT's Bristol District be part of VDOT's truck weight data plan? This task was performed using data analysis and subjective measures.

7. *Report the use of the WIM data by VDOT staff, the performance of WIM systems, and maintenance needs.*

8. *Revise VDOT's truck weight data plan for the MEPDG.* Based on the findings of Tasks 1 through 7, the need for revisions to the plan was considered. Resource constraints were considered.

RESULTS

Literature Review

The literature related to the latest guidance on traffic data collection for the MEPDG is discussed here. Other literature is discussed in the "Results" section.

NCHRP Report 538: *Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design*

This report (Cambridge Systematics, Inc., et al., 2005) includes guidelines for collecting traffic data to be used in pavement design and software for analyzing traffic data and producing traffic data inputs required for mechanistic pavement analysis and design. The software—TrafLoad—is available to users online (Transportation Research Board, 2011). The report also describes the actions required at the state and national level to promote successful implementation of the software. The report is a useful resource for state personnel and others involved in planning and designing highway pavements. The report includes guidelines for developing truck weight road groups. The following excerpt is specific to guidance on TWGs.

> **Level 2 WIM Sites and Truck Weight Road Groups**
>
> The basic goals in forming truck weight road groups (TWRGs) for default values are to group roads according to which axle loads are likely to be reasonably similar and to assign roads for which axle loads are not expected to be similar to different TWRGs. The TWRGs should be defined so that every road or road segment for which load spectra may be of interest is unambiguously assigned to a specific TWRG. A key principle in forming TWRGs is that all

weight limits should be essentially the same on all roads in the group. Thus, if some combinations are allowed to operate routinely at weights above 80,000 pounds on a set of designated roads, then the designated roads should be assigned to one or more TWRGs that are separate from the TWRGs to which other roads with primarily lower-weight loads are assigned. Similarly, roads on which axle weight limits vary seasonally (e.g., during spring thaw or winter freeze) should be assigned to different TWRGs than roads on which axle weight limits do not vary seasonally.

Guidelines

The above discussion leads to the following guidelines for developing a set of TWRGs to be used for load spectra defaults:

1. If there are any significant differences in the size and weight limits applied to vehicles on different roads in the state, partition all roads into two or more sets, each with uniform size and weight limits.

2. For each of these sets of roads, develop a separate set of TWRGs, and assign the roads to these TWRGs on the basis of functional class, region, and/or direction.

The second step should be performed using judgment, local knowledge of the trucks operating in various parts of the state, and available WIM data. Some observations that may be useful in carrying out this step are the following:

- There is almost certainly value in distinguishing roads by functional system: urban, rural Interstate system, and rural other.

- If there are significant regional differences in the density of commodities carried (particularly on rural other roads), these differences may warrant either using a combination of regions and functional systems or using regions instead of functional systems.

- Similarly, if, within any region, there are significant differences between the density of commodities carried on East-West roads and that carried on North-South roads, these differences may warrant using combinations of regions, functional systems, and road orientation.

- In the case of any TWRG that consists primarily or entirely of divided roads, if heavy (i.e., loaded) and light (i.e., empty) directions can be readily distinguished without using any WIM data, it is likely to be desirable to divide the TWRG into heavy and light directions.

If practical, there should be three to eight WIM sites in a TWRG. However, one or two may be used for some small TWRGs. Three sites is the minimum number necessary to provide some confidence that all sites in the TWRG have reasonably similar load spectra. On the other hand, as the number of WIM sites in a TWRG grows, opportunities also grow for splitting the TWRG to produce smaller TWRGs, each with more uniform sets of load spectra.

WIM Data Analyst's Manual

The FHWA recently published the *WIM Data Analyst's Manual* to provide information and recommended procedures to be used by an agency's staff to perform validation and quality control checks of WIM traffic data (Quinley, 2010). The manual focuses on data generated by WIM systems that have the capability to produce high-quality data. The manual was developed to ensure that high-quality WIM data are collected and used to produce reliable and representative load spectra for input into the MEPDG software, resulting in reliable and predictable pavement designs.

Survey of State DOTs

Responses for the state DOT survey (Appendix A) were received from 25 of the 49 state DOTs, for a response rate of 51%. The survey results were obtained from May through July 2009. The full results of the survey may be obtained from the authors.

The survey information was used to obtain a snapshot of the truck weight programs of other state DOTs and their future plans regarding the MEPDG. Thus, the survey summary is a composite of responses by the states. Nearly 800 permanent WIM systems were in service in the responding states (Table 2). Nineteen of the 25 responding states used WIM with piezoelectric sensors, 13 with quartz piezoelectric sensors, 9 with load cells, and 7 with bending plates; these represent the permanent WIM sensors used. The ranking in order of most sites to least sites by permanent WIM sensor type was piezoelectric, bending plate, quartz piezoelectric, and load cells. Most of the responding states (17 of 25) used more than one type of permanent WIM sensor. Five responding states used portable WIM systems; of these 5, only 1 state used a portable WIM exclusively.

Table 2. Results of Survey of State DOTs Regarding Their WIM Programs: WIM System Type by Number of Sites and Number of Responding States

Survey Question	No. of Sites	No. of the 25 Responding States	Mean	Std. Dev.	Range
Do you have weigh-in-motion (WIM) systems?					
Yes		25			
No		0			
If yes, please list how many of each type.					
Load Cells	73	9	8	8	1-22
Bending Plate	186	7	27	49	1-135
Piezoelectric	433	19	23	27	1-96
Quartz Piezoelectric	103	13	8	10	1-30
Other: Portable	251	5	50	45	3-100
Brass linguini	10	2	5	3	3-7
Portable piezo	241	3	80	26	51-100
Total sites	1038		42	35	
Permanent sites	797		32	31	
Did you follow the FHWA's Traffic Monitoring Guide's truck weight section in developing your WIM program?					
Yes		10			
No		16			

When asked “Did you follow the FHWA’s Traffic Monitoring Guide’s truck weight section in developing your WIM program?,” 9 of the 25 responding states responded “yes” and 15 responded “no.” One responded “yes” and “no.” Seven responding states used TWGs based on road classification with 3 to 7 groups. Two states each described their TWGs as (1) being based on truck routes, (2) being based on limited access / interstates, (3) evolving from the Strategic Highway Research Program or enforcement/weigh stations, and (4) a work in progress.

When asked “What input level(s) is your state planning to use?,” (i.e., the MEPDG level that had been chosen for applying truck weight data) (Table 3), the responding states cited Level 2 most frequently (11 responding states). Nine of the states responded “don’t know,” possibly suggesting that the level was not yet decided (a work in progress) or the staff completing the survey did not know the answer. Three responding states indicated all three levels, and another 3 indicated two levels. When asked “For level 2 input, please describe the regions that have been defined for your state,” 8 states responded that this was a work in progress. For the 4 responding states that had defined regions, the number of regions varied from 2 to 10. The following are examples of how the 4 states described the regions that had been defined for their state: (1) an inland and a coastal region; (2) 6 districts as regions; (3) 8 regions based on truck vehicle miles traveled, road functional classification, and local knowledge; and (4) 10 geographic regions.

Responses to three WIM questions are summarized in Table 4. Eight state DOTs use truck weight enforcement data as part of their WIM program. Seventeen state DOTs are expanding their WIM program, and 8 have completed their program. When a WIM system has served its useful life and needs to be replaced, 22 responding states replace the WIM system, 6 terminate operations, and 3 relocate the system elsewhere to increase the data pool. Most of the 8 “other” responses in Table 4 consisted of clarification regarding when one of the first three options was used. One state used the WIM site as a vehicle classification site when possible. Many responding states selected more than one of the options for this question; hence, the total number of responses exceeded 25.

Table 3. MEPDG Levels States Plan to Use

MEPDG Level	**No. of Responding States (of 25)**
1	5
2	11
3	8
“Don’t know”	9
All three	3

Table 4. Responses to Variety of WIM Data Survey Questions

Question	No. of States
Do you use truck weight data collected by truck weight enforcement program?	
Yes	8
No	17
Is your program completed or expanding?	
Completed	8
Expanding	17
When WIM system has served its useful life and needs replacement, what do you do?	
Replace the WIM system	22
Terminate operations	6
Relocate WIM system to increase data pool	3
Other , please explain	8

Examination of Trucking in Virginia

Two reports in the literature provided much information regarding truck travel patterns based on region, industry, agriculture, special sites, and port locations that generate truck trips and potential destinations and routes traveled.

The Office of Intermodal Planning and Investment in Virginia's Office of the Secretary of Transportation was created in 2002 to encourage the coordination of multimodal and intermodal planning across the various transportation modes within Virginia. This office generated two reports of particular interest to this study: *Virginia Statewide Multimodal Freight Study, Phase I Report* (Cambridge Systematics, Inc., 2008) and *Executive Summary of VTrans2035 Report* (Office of Intermodal Planning and Investment, 2010).

Virginia Statewide Multimodal Freight Study, Phase I Report

The study described in this report (Cambridge Systematics, Inc., 2008) was designed to do the following:

- Compile available freight information (which exists in multiple places, from multiple sources) and fill in gaps to tell the story of Virginia's entire intermodal freight transportation system.
- Identify current needs and projected future needs for each mode, the system as a whole, and designated multimodal corridors and subregions of critical interest.
- Develop an understanding of the contributions that freight makes to Virginia's economy; clearly understand the benefits and costs of improving—or failing to improve—Virginia's freight transportation system; and create a "return on investment" framework for decision-making.

- Form substantial, implementable recommendations and solutions for Commonwealth planning and programming.

- Address the critical roles that other levels of government and the private sector can and must play.

- Be grounded in a comprehensive outreach effort that reaches a full range of public and private stakeholders.

The Phase I report primarily addressed tasks related to outreach, data collection, baseline forecasting, system inventory/analysis, and freight improvement opportunities.

Two figures in the report that capture truck patterns in Virginia are inbound/outbound/internal truck tons and through truck tons, both for 2004. Figure 1 displays the inbound/outbound/internal truck tons for 2004. As expected, the truck tonnage was predominantly transported on the interstate and primary arterial system. Figure 2 shows that the through truck tonnage is heavily focused on north-south corridors with I-81 and I-95 being the primary corridors.

Executive Summary of VTrans2035 Report

VTrans2035 is the Commonwealth's statewide long-range multimodal transportation plan being developed by the Office of Intermodal Planning and Investment in partnership with the Department of Aviation, the Department of Rail and Public Transportation, VDOT, DMV, and VPA. The executive summary of the plan is provided in *Executive Summary of VTrans2035 Report* (Office of Intermodal Planning and Investment, 2010).

Corridors of Statewide Significance in VTrans2035

VTrans2035 used a concept of Corridors of Statewide Significance (CoSS) to review corridors and identify potential multimodal transportation improvement strategies to guide local land use planning and transportation investments. This is an ongoing process coordinated with local and regional transportation and land use planners. The CoSS represent multimodal connections to the Commonwealth's activity centers. This system consists of corridors to help people and goods move between Virginia's regions and to areas outside Virginia. The corridors are transportation facilities that must be protected to ensure appropriate levels of mobility to allow for long-distance travel.

There are 11 designated CoSS throughout Virginia.

1. Crescent Corridor (I-81)
2. Washington to North Carolina Corridor (I-95)
3. East-West Corridor (I-64)
4. Northern Virginia Connector (I-66)
5. Western Mountain Corridor (I-77)
6. Seminole Corridor (US 29)

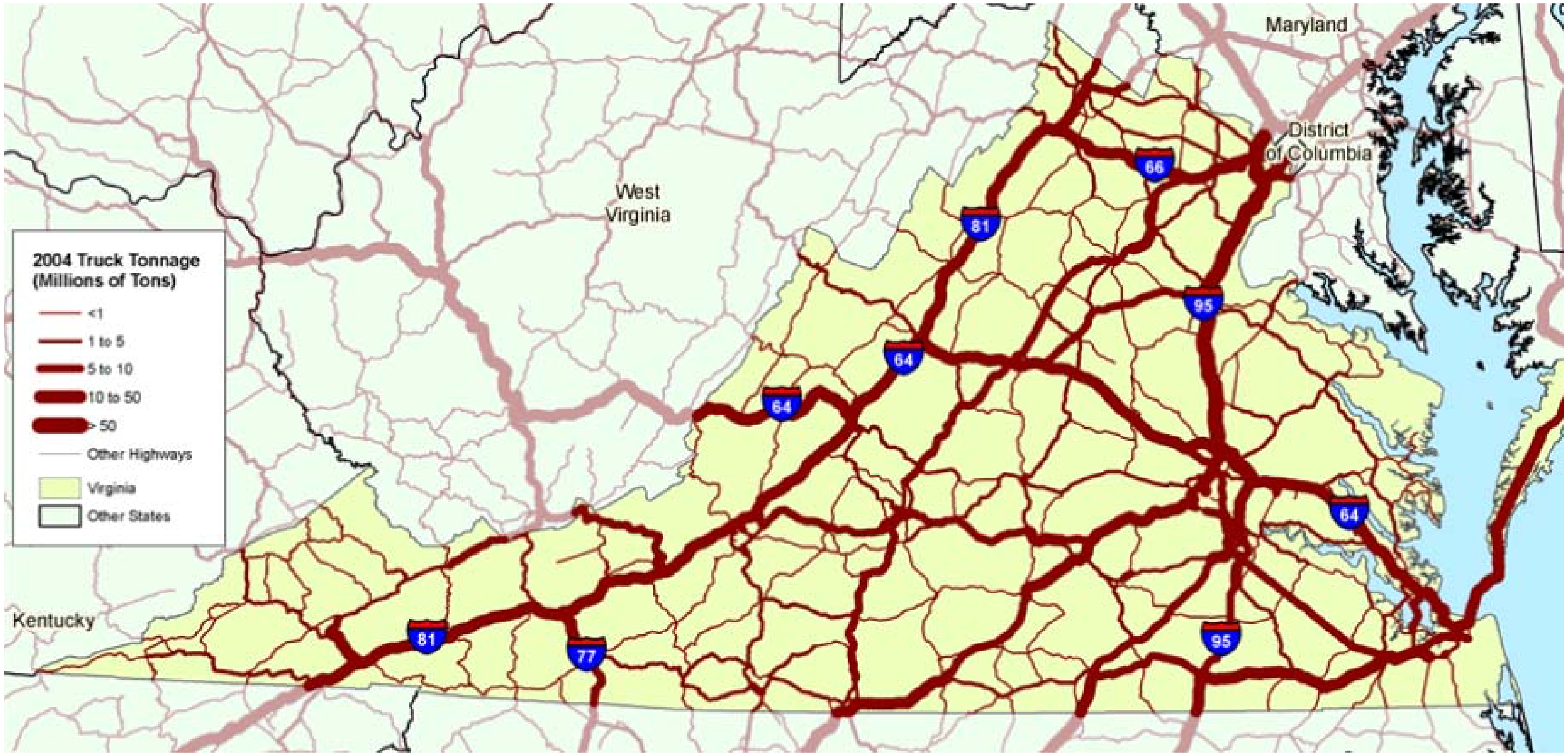


Figure 1. Virginia's Inbound/Outbound/Internal Truck Tons in 2004. *Source:* Cambridge Systematics, Inc., *Virginia Statewide Multimodal Freight Study, Phase I Report*, Richmond, VA, 2008.

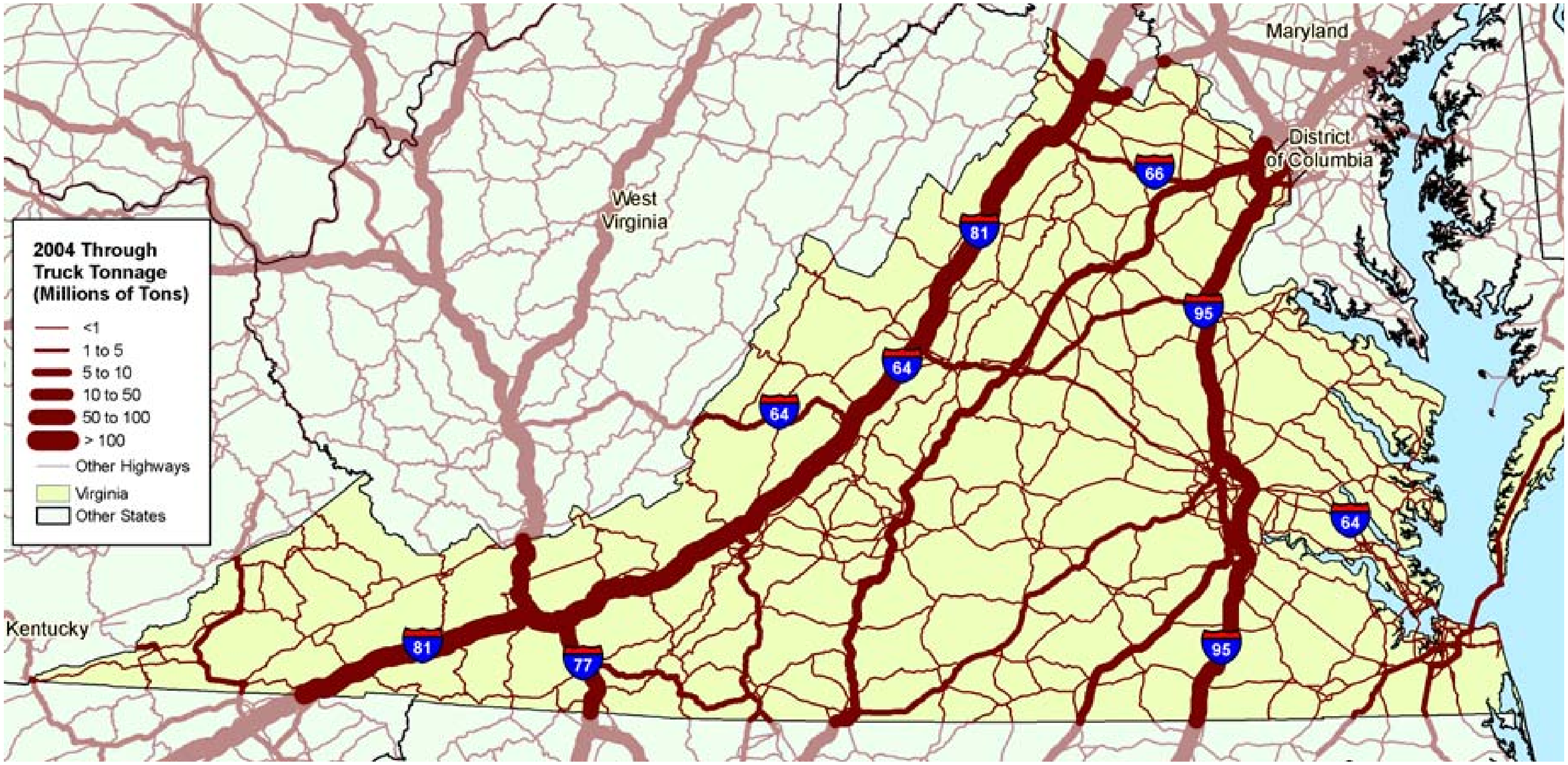


Figure 2. Virginia's Through Truck Tons in 2004. *Source:* Cambridge Systematics, Inc., *Virginia Statewide Multimodal Freight Study, Phase I Report,* Richmond, VA, 2008.

7. Southside Corridor (US 58)
8. Heartland Corridor (US 460)
9. Tidewater Corridor (US 17)
10. Eastern Shore Corridor (US 13)
11. North Carolina to West Virginia Corridor (US 220).

Some may be added or deleted in the future. The purpose of designating CoSS was to provide a multimodal statewide perspective to guide localities in their land use and transportation plans. VTrans2035 states that Virginia must take steps now to ensure the appropriate balance of development, transportation capacity, and natural resources. The designation of CoSS is the first step in ensuring that these corridors are invested in and protected for the future benefit of the entire Commonwealth, as called for in HB 2019 passed by the Virginia General Assembly in 2009. The extent to which a locality's land use plan protects the functionality of the corridor will be considered as part of the funding process. A map showing the 11 CoSS is provided in *Executive Summary of VTrans2035 Report* (Office of Intermodal Planning and Investment, 2010).

Potential corridor strategies were developed for each corridor. The common strategies across all corridors relate to improving transit and rail and improving the efficiency of the existing system with intelligent transportation systems, access management, improved land use patterns, and transportation demand management measures. As such, the corridor strategies promote mobility, environmental quality, and sustainable transportation. They will improve accessibility, reduce greenhouse gases and other emissions, improve quality of life with more transportation choices, and support the major population and commercial centers throughout the Commonwealth (Office of Intermodal Planning and Investment, 2010).

The next step in the CoSS process is the development of corridor master plans that turn the strategies into specific improvements. Because Virginia's landscape is constantly changing, new corridors may emerge that might meet the CoSS criteria. Therefore, the CoSS should be reviewed periodically and the need to add or delete corridors based on the established criteria considered.

Since the CoSS is a focus of VDOT's long-range plan, it is suggested that CoSS be considered for future WIM sites. VDOT currently collects WIM data on 7 of the 11 CoSS. (Williams, 2011). Possible ways to consider more WIM systems on CoSS are discussed in the section "Revise VDOT's Traffic Data Plan for MEPDG."

The Port of Virginia and Other Ports

The vision for the Port of Virginia is for the port to be the primary gateway for international cargo transported through the Mid-Atlantic and Midwest regions of the United States (The Port of Virginia, 2010). The VPA promotes economic development and stimulates job growth in Virginia through international trade. The VPA is Virginia's leading agency for international transportation and maritime commerce and has a long history of generating business through The Port of Virginia. The Port of Virginia consists of five state-owned facilities: the Newport News Marine Terminal, Norfolk International Terminals, the

Portsmouth Marine Terminal, the Virginia Inland Port in Front Royal, and APMT Virginia; combined, these five facilities make up the Port of Virginia. Much of the traffic that leaves and enters the ports is by truck on I-64 for all facilities except the inland port. As port activity grows, truck traffic on the CoSS is likely to grow.

In response to the new APMT Virginia terminal in Portsmouth and The Craney Island Eastward Expansion, which will provide land for the construction of a new marine terminal in Hampton Roads Harbor, staff of VDOT's Hampton Roads District requested and VDOT installed a WIM system on SR 164 in June 2007. This WIM site was intended to measure the increased truck traffic from these terminals Most of these trucks use the interstate system to access the terminals. The impact of port facilities and other truck-generating locations is incorporated in the two studies described.

Analysis of TWGs

WIM Systems

A list of the 22 WIM sites in Virginia and a map showing the locations of the WIM sites studied are provided in Table 5 and Figure 3, respectively.

Table 5. WIM Site Information

Site ID	Link ID	Lane No.	Route	Direction	Location	Agency	TWG[a]
1	10009	1,2	US 58	East	Lee County	VDOT	2
2	10009	3,4	US 58	West	Lee County	VDOT	2
3	30166	1	US 60	East	Cumberland County	VDOT	2
4	30166	2	US 60	West	Cumberland County	VDOT	2
5	30387	1,2	US 29	North	Danville	VDOT	2
6	30387	3,4	US 29	South	Danville	VDOT	2
7	40289	1,2	SR 288	North	Midlothian	VDOT	2
8	40289	3,4	SR 288	South	Midlothian	VDOT	2
9	50617	1,2	SR 164	East	Portsmouth	VDOT	2
10	50617	3,4	SR 164	West	Portsmouth	VDOT	2
11	90333	1,2	SR 234	North	Prince William County	VDOT	2
12	90333	3,4	SR 234	South	Prince William County	VDOT	2
13	70268	1,2	US 17	North	Fauquier County	VDOT	1
14	70268	3,4	US 17	South	Fauquier County	VDOT	1
15	80372	1	I-81	North	Stephens City	DMV	1
16	180008	1	I-81	South	Stephens City	DMV	1
17	90305	1	I-95	North	Dumfries	DMV	1
18	190013	1	I-95	South	Dumfries	DMV	1
19	140318	1,2	I-95	North	Sussex County	VDOT	1
20	190050	1,2	I-66	West	Fauquier County	VDOT	1
21	920178	1	I-81	North	Troutville	DMV	1
22	820004	1	I-81	South	Troutville	DMV	1

VDOT = Virginia Department of Transportation; DMV = Department of Motor Vehicles.
[a] Truck weight group (1 = tractor-trailer trucks ≥ 1,000 per day; 2 = tractor-trailer trucks < 1,000 per day) (based on 2001 traffic counts).

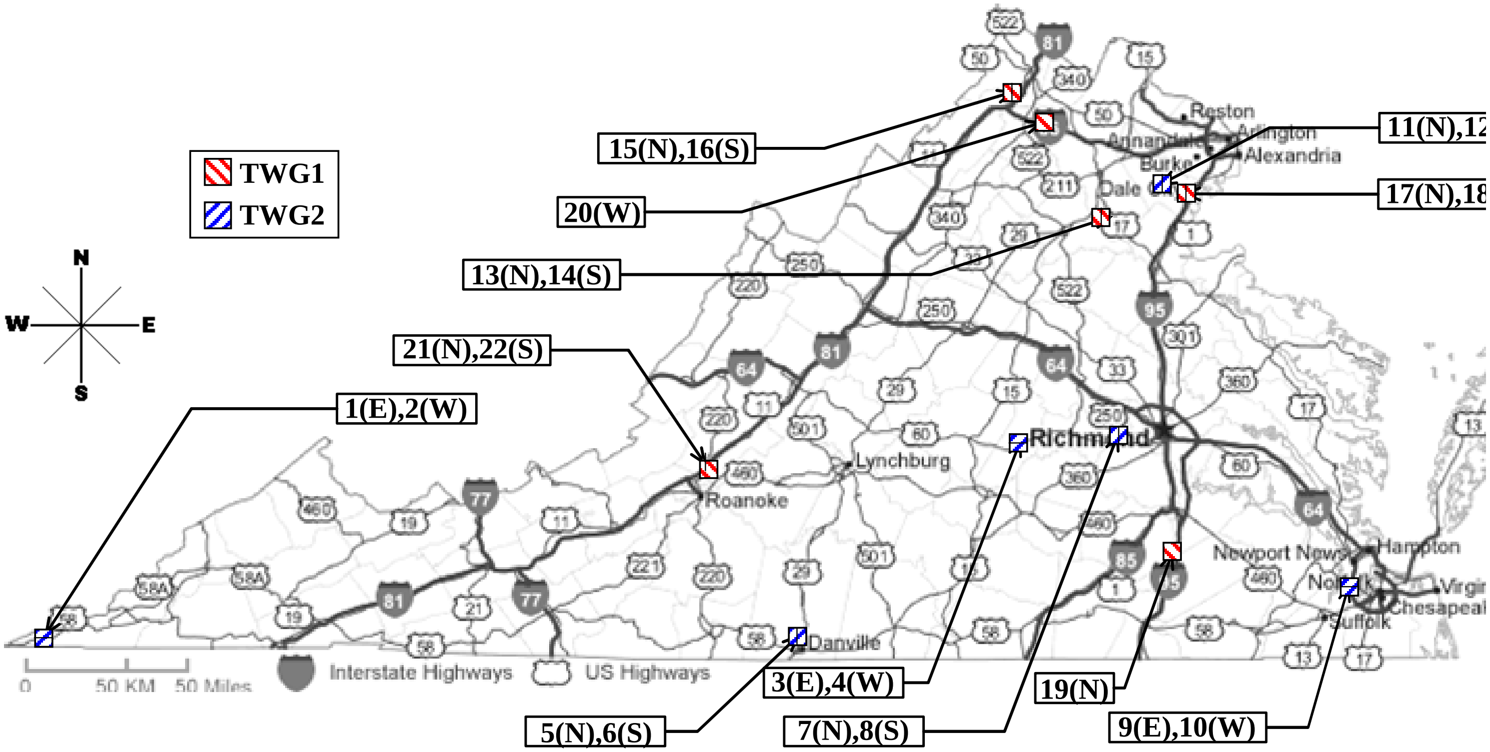


Figure 3. Site Locations With Truck Weight Group (TWG) Indications. Site ID (SID) and direction are indicated at each location. TWG1 = Truck Weight Group 1; TWG2 = Truck Weight Group 2; N/S/E/W = North/South/East/West.

WIM Data

Two years (2007 and 2008) of WIM data at the 22 sites were obtained from VDOT's TED. The WIM data consist of traffic counts and weight data for trucks only, i.e., FHWA Vehicle Classes 4 through 13. It should be noted that the WIM traffic volume data are different from traffic volume data obtained at the permanent vehicle classification count sites because (1) WIM data exclude FHWA Vehicle Classes 1 through 3, and (2) WIM sensors may not be installed on all lanes (e.g., all DMV sites have the WIM sensor only in the right lane).

Each vehicle record in the database has a field called "wimquality." When the WIM data are loaded into the WIM database, all of the vehicle records are assigned a default wimquality of "0," indicating valid data. The data review process consists of determining which of the vehicles have inaccurate weights and storing a "1" in the wimquality field for those records. VDOT staff reviews the gross vehicle weight distribution for FHWA Vehicle Class 9, which is relatively constant over time for a given lane. When this weight distribution changes, a sensor failure or other abnormal event (such as a snow storm) is likely to have occurred. All questionable vehicle records are given a wimquality of "1." After this process, any records with a wimquality of "0" that remain in the database are assumed to have accurate weights. Although all of the original vehicle records remain in the database, those with a wimquality of "1" are excluded from any data exports for users of the data. For 2007 and 2008, 83% and 94% of the data, respectively, passed the data quality test.

For each vehicle with valid WIM data detected, an ESAL value was calculated and placed in the study WIM database. For the interstate sites, the ESAL value was based on flexible pavement, Structural Number 6, and Terminal Serviceability 3. For non-interstate sites, the ESAL value was based on flexible pavement, Structural Number 4.75, and Terminal Serviceability 2.85. When there was no ESAL value on a certain day, that day was defined as a day without valid WIM data. It should be noted that some sites had WIM sensors installed in the middle of 2007 or lost WIM sensors attributable to construction projects and only the data that passed VDOT's WIM data quality control process were included in the study database. The number of days without valid WIM data varied by site, ranging from 0 (i.e., complete 2-year records) to 343 days (i.e., almost 1 year of data); Table B-1 in Appendix B presents the number of days without valid WIM data per month for each site.

In order for a consistent analysis to be performed across all 22 sites, months with fewer than 14 days (i.e., 2 weeks) of valid WIM data in 1 month were removed from the analysis. The time period of 14 days was chosen in order to obtain a sample of at least 50% of the days in each month to represent truck traffic characteristics for each month reliably and to include as many months as possible for data analysis. "Trailer trucks" used in this study were defined as vehicles in FHWA's Vehicle Class 8, 9, or 10. This definition is consistent with that used in the previous study by Cottrell et al. (2003) and VDOT's practice of grouping FHWA Vehicle Classes 8, 9, and 10 into one tractor-trailer group. The size of the 2-year raw data file was slightly larger than 7 gigabytes.

Monthly Truck Traffic Volumes

Daily truck volume and daily trailer-truck volume averaged over the study period (2007-2008) were used for analysis of the WIM data. To avoid potential confusion of these volumes with annual average daily traffic and annual average daily truck traffic including vehicles from all lanes, such terms were not used. Instead, all trucks per lane per day (ATplpd) and tractor-trailer trucks per lane per day (TTTplpd) were used to reference the volumes in this study.

ATplpd and TTTplpd were calculated for each month of the 2-year study period. Some WIM sites had stable patterns over several months in the same calendar year, and others had considerable fluctuation. Figure 4 shows ATplpd and TTTplpd over the 2 years at four sites. These values seemed stable for Site ID (SID) 1 and SID 7 in a calendar year and seemed to decline systematically for SID 7 starting from the end of 2007. These values for SID 12 and SID 20 fluctuated considerably over some months.

SID 20 showed substantial declines in August and September 2007, but these were found to be attributable to a failure of the WIM sensors. Only the data that passed VDOT's WIM data quality control process remained in the WIM database. This means that vehicles producing inaccurate axle weights were not stored in the study database, making those vehicles disappear from the traffic count and therefore lowering the monthly total traffic volume. A similar WIM sensor failure explained the volume decline in June 2008. This monthly volume concern was cited for 3 of the 22 WIM sites (14%).

VDOT has a comprehensive system of more than 300 continuous vehicle classification stations across the state that provides a more comprehensive picture of traffic volumes. This more robust dataset makes it preferable to volume data from WIM sites (where in some locations sensors are placed only in one lane) for calculating the monthly traffic input for the MEPDG. As Figure 5 shows, total daily VMT for the entire state and by operational region based on data obtained at permanent vehicle classification count sites revealed stable seasonal patterns over a number of years. Unless there are factors affecting traffic volume trends and patterns systematically, 1 year of such data might be enough to calculate traffic-related input values for the MEPDG. However, using more than 1 year of data could lead to inputs more reliably representing sites.

Monthly ESALs

To evaluate the reliability of the truck weight data from the WIM sites, monthly ESAL values were calculated for each site. Specifically, 85th percentile, average, and median ESAL values for each month were calculated. Figure 6 shows monthly ESAL values for the four sites shown in Figure 5.

When Figures 4 and 6 are compared, monthly ESAL values appeared stable over the 2 years compared to the month-to-month fluctuations in truck traffic volumes (Figure C-1 in Appendix C shows monthly ESAL values for each of the 22 sites). For example, at SID 20, monthly ESAL values in August and September 2007 were slightly lower than those in previous months whereas truck traffic volumes as recorded by the WIM sensors in those 2 months were

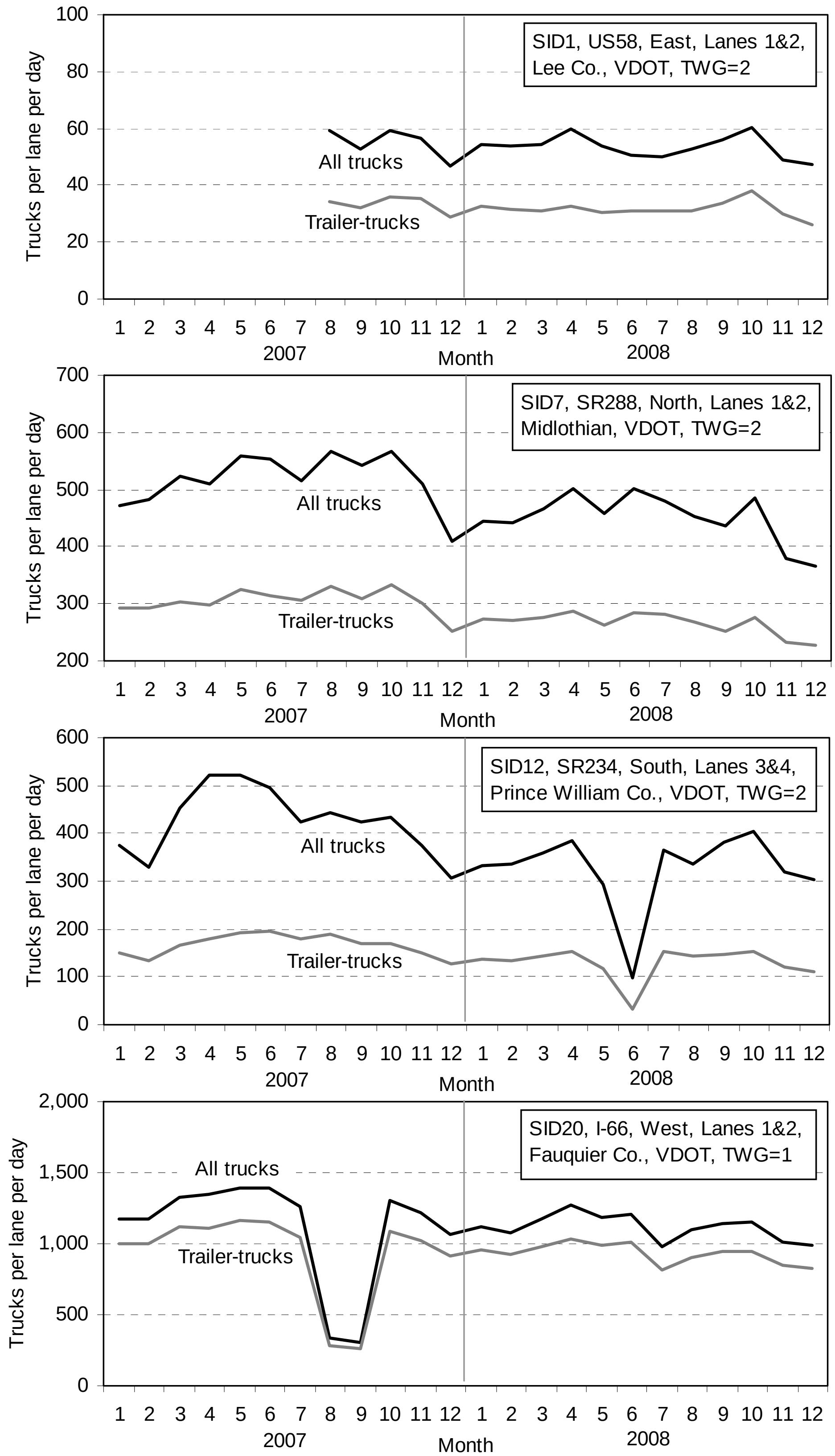


Figure 4. Monthly Truck Traffic Volume per Lane per Day. SID = Site ID; TWG = 1 if tractor-trailer trucks in 2001 $\geq$ 1,000 per day and 2 if < 1,000 per day.

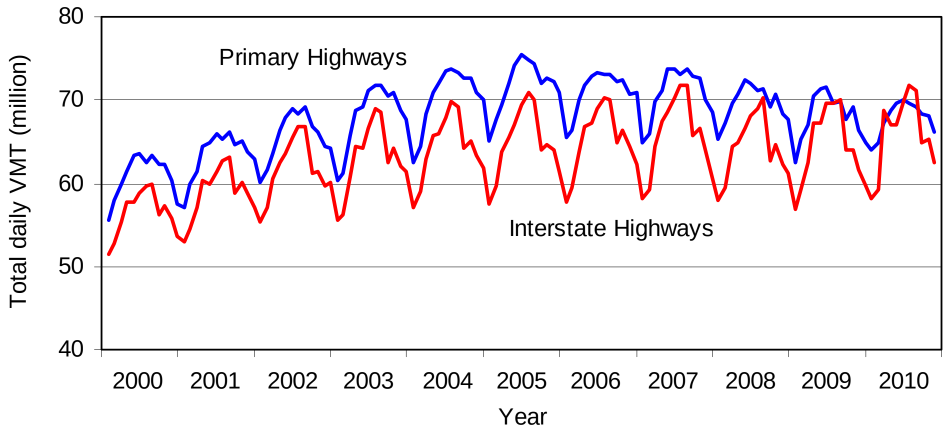


Figure 5. Statewide Monthly Total Daily Vehicle Miles Traveled (VMT) in Virginia

substantially lower. This indicates that a WIM sensor failure affected the data for all trucks rather than a specific class or weight group of trucks. Since occasional sensor failures did not seem to affect monthly weight statistics, temporary sensor failures were not considered detrimental to the calculation of weight input values for the MEPDG.

Analysis of ESALs by Truck Weight Group

Basic statistics of traffic volume and ESAL data are presented in Tables 6 and 7 for all trucks and for tractor-trailer trucks by site, respectively. ESAL statistics were based on calculated ESAL values of individual trucks provided by VDOT's TED. Because WIM sensors were installed in one or two lanes depending on the site, volume per lane (rather than total volume over all lanes) was appropriate for comparison across the sites. However, some bias might be introduced when averaged volume across lanes is used for comparison purposes, especially at DMV sites where WIM sensors are installed only in the right lane. In many cases, the truck volume in the right lane is higher than the truck volume in the left lane. As a consequence, the use of volume from the right lane as the average across all lanes could lead to substantial overestimations of total truck volumes for the segment. According to Tables 6 and 7, in general and as expected based on the TWG scheme, the sites on interstate highways carry many more trucks and tractor-trailer trucks than those on primary highways, and they all belong to TWG1.

Comparison by Truck Weight Group and Road Classification

The distributions of vehicle classifications, daily average volume per lane, and average ESAL of tractor-trailer trucks were compared by TWG and road classification. Table 8 presents the distribution of vehicle classifications, TTTplpd, and ESAL statistics of trailer trucks by TWG and road classification. When all 22 sites were combined, FHWA Vehicle Class 9 (five-axle single-trailer truck) was the majority (76%), followed by Class 5 (two-axle six-tire single-unit truck) (5.1%) and Class 6 (three-axle single-unit truck) (4.8%). TWG1 and interstate sites have higher percentages in Classes 8, 10, 11, and 12; higher average ESAL values; and much higher TTTplpd than do TWG2 and primary highway sites.

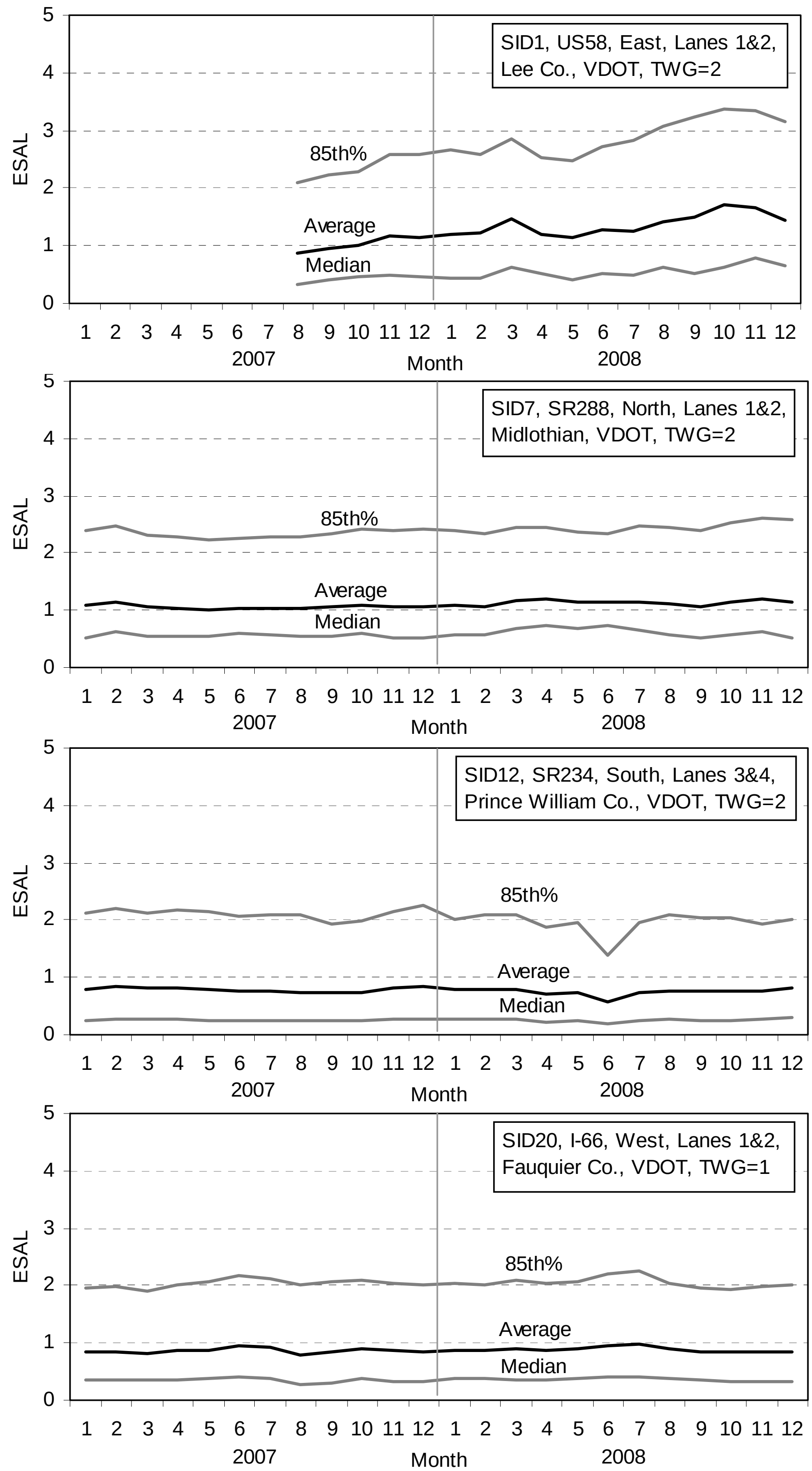


Figure 6. Monthly Equivalent Single-Axle Load (ESAL) Values for Selected WIM sites. SID = Site ID; TWG = 1 if tractor-trailer trucks in 2001 ≥ 1,000 per day and 2 if < 1,000 per day.

Table 6. Truck Traffic and ESAL Statistics of All Trucks[a] by Site

Site ID	Site			Truck Traffic			ESAL	
	No. of lanes[b]	TWG[c]	Road class	Total truck volume	ATpd[d]	ATplpd[e]	Avg.	Std. dev.
1	2	2	Primary	55,170	108	54	1.15	1.45
2	2	2	Primary	62,233	122	61	0.61	0.95
3	1	2	Primary	84,053	123	123	0.91	1.13
4	1	2	Primary	79,523	128	128	0.78	1.02
5	2	2	Primary	393,927	772	386	0.95	0.93
6	2	2	Primary	531,968	763	382	0.91	0.98
7	2	2	Primary	702,437	969	484	0.90	1.00
8	2	2	Primary	495,038	1,047	523	0.86	0.98
9	2	2	Primary	365,418	923	461	0.72	1.01
10	2	2	Primary	490,736	910	455	0.59	0.79
11	2	2	Primary	595,672	823	411	0.69	0.77
12	2	2	Primary	544,246	752	376	0.76	0.95
13	2	1	Primary	946,992	1,299	650	0.98	0.98
14	2	1	Primary	1,006,288	1,380	690	1.02	1.02
15	1	1	Interstate	3,507,141	5,585	5,585	1.10	0.92
16	1	1	Interstate	3,774,354	5,163	5,163	0.98	0.87
17	1	1	Interstate	3,425,754	4,693	4,693	1.02	0.93
18	1	1	Interstate	1,825,162	4,880	4,880	0.88	0.91
19	2	1	Interstate	2,047,055	2,967	1,483	1.14	0.93
20	2	1	Interstate	1,620,871	2,223	1,112	0.81	0.90
21	1	1	Interstate	2,288,841	5,450	5,450	0.98	0.80
22	1	1	Interstate	3,267,968	5,171	5,171	0.93	0.85

ESAL = equivalent single-axle load; TWG = truck weight group; ATpd = all trucks per day; ATplpd = all trucks per lane per day.

[a] FHWA Vehicle Classes 4-13.

[b] Number of lanes equipped with WIM system.

[c] TWG = 1 if tractor-trailer trucks in 2001 ≥ 1,000 per day; TWG = 2 if < 1,000 per day.

[d] ATpd = Trucks per day = Total truck volume ÷ Number of valid WIM data days in 2007 and 2008.

[e] All ATplpd = Trucks per lane per day = All trucks per day ÷ Number of lanes.

The statistics in Table 8 are presented in Figures 8 and 9 for visual comparison. In Figure 7, TWG1 and interstate sites have a similar distribution and the same is true for TWG2 and primary highway sites. Such similarity occurs because all TWG1 sites except for two (on primary highways) are on interstate highways and all TWG2 sites are on primary highways. The TWG1 and interstate sites have a higher percentage of vehicles in FHWA Vehicle Class 9 than do the TWG2 and primary highway sites and have a lower percentage of vehicles in Classes 5 and 6.

Figure 8 provides visual comparisons of average ESAL and TTTplpd for TWG1 versus TWG2 and interstate versus primary road sites. With regard to TTTplpd, the TWG1 and interstate sites have many more trailer trucks than do the TWG2 and primary highway sites. Average ESAL values show similar patterns, with smaller differences between the groups. The TWG1 and interstate sites have higher average ESAL values than the TWG2 and primary highway sites.

Table 7. Traffic and ESAL Statistics of Tractor-Trailer Trucks[a] by Site

Site ID	Site Information			Tractor-trailer Truck Traffic			ESAL	
	No. of lanes[b]	TWG[c]	Road Class	Total truck volume	TTTpd[d]	TTTplpd[e]	Avg.	Std. dev.
1	2	2	Primary	32,801	64	32	1.28	1.58
2	2	2	Primary	40,163	78	39	0.66	1.02
3	1	2	Primary	51,729	76	76	1.18	1.22
4	1	2	Primary	50,769	82	82	0.88	1.09
5	2	2	Primary	303,602	595	298	1.01	0.94
6	2	2	Primary	412,395	592	296	1.01	1.03
7	2	2	Primary	413,782	571	285	1.09	1.08
8	2	2	Primary	295,777	625	313	0.94	1.00
9	2	2	Primary	240,526	607	304	0.89	1.12
10	2	2	Primary	319,066	592	296	0.67	0.84
11	2	2	Primary	229,134	316	158	0.92	0.94
12	2	2	Primary	214,420	296	148	0.77	0.97
13	2	1	Primary	743,362	1,020	510	1.09	1.02
14	2	1	Primary	801,105	1,099	549	1.10	1.06
15	1	1	Interstate	3,033,622	4,831	4,831	1.11	0.90
16	1	1	Interstate	3,223,196	4,409	4,409	1.00	0.86
17	1	1	Interstate	2,901,056	3,974	3,974	1.10	0.94
18	1	1	Interstate	1,529,139	4,089	4,089	0.96	0.94
19	2	1	Interstate	1,763,856	2,556	1,278	1.24	0.94
20	2	1	Interstate	1,356,988	1,861	931	0.88	0.93
21	1	1	Interstate	1,952,852	4,650	4,650	0.99	0.79
22	1	1	Interstate	2,699,671	4,272	4,272	0.96	0.84

ESAL = equivalent single-axle load.
[a] FHWA Vehicle Classes 8, 9, and 10.
[b] Number of lanes equipped with WIM system.
[c] Truck weight group (= 1 if tractor-trailer trucks in 2001 ≥ 1,000 per day and = 2 if < 1,000 per day).
[d] Tractor-trailer trucks per day = Total trailer truck volume ÷ Number of valid WIM data days in 2007 and 2008.
[e] Tractor-trailer trucks per lane per day = Tractor-trailer trucks per day ÷ Number of lanes.

Figure 9 shows ESAL distribution by TWG and road classification. ESAL values are distributed skewed to the lower values in general, influencing the selection of statistical techniques for data analysis. As expected, the TWG1 and interstate highway sites had a similar distribution as did the TWG2 and primary highway sites.

The TWG1 and interstate sites were found to carry heavier trucks than the TWG2 and primary highway sites, as shown in Figures 7 and 8, respectively. To confirm this finding, a statistical test was performed for group comparison. As seen in Figure 9, ESAL values were non-normally distributed, and this was confirmed by the Kolmogorov-Smirnov test at an 0.01 significance level (i.e., 99% confidence level). Other tests such as the Cramer-von Mises and Anderson-Darling tests were also performed and led to the same results. For non-normally distributed values, a typical *t*-test cannot be applied. Thus, a non-parametric test was employed, specifically, the Wilcoxon rank sum test. Other tests such as the Kolmogorov-Smirnov, median scores, and Van der Waerden tests were also performed and led to the same results. The Wilcoxon rank sum test confirmed that trucks passing the TWG1 and interstate highway sites were heavier than those passing the TWG2 and primary highways, respectively, at the 0.01

Table 8. Vehicle Classification, Volume, and ESAL Statistics of Trucks by Groups

Variable		All Sites[a]	TWG		Road Classification	
			1[b]	2[c]	Interstate[d]	Primary[e]
% Trucks by FHWA Vehicle Class	4	3.54	3.12	5.81	3.05	5.23
	5	5.09	3.66	12.8	3.42	10.82
	6	4.82	2.67	16.4	2.48	12.85
	7	0.94	0.37	3.98	0.19	3.49
	8	3.08	2.74	4.97	2.62	4.67
	9	76.3	80.8	52.2	81.5	58.6
	10	1.00	0.82	2.01	0.71	2.03
	11	3.59	4.00	1.35	4.12	1.77
	12	1.29	1.48	0.26	1.56	0.38
	13	0.01	0.01	0.01	0.01	0.01
	15	0.29	0.32	0.17	0.33	0.16
TTTplpd[f]		1,023	2,235	200	2,993	261
ESAL[g]	Avg.	0.96	0.99	0.80	0.99	0.86
	Std. Dev.	0.91	0.90	0.95	0.89	0.97

TWG = truck weight group.
[a] 22 directional sites at 12 locations.
[b] 10 directional sites at 6 locations.
[c] 12 directional sites at 6 locations.
[d] 8 directional sites at 5 locations.
[e] 14 directional sites at 7 locations.
[f] Tractor-trailer trucks per lane per day (2007-2008).
[g] Equivalent single-axle load of tractor-trailer trucks (FHWA Vehicle Classes 8, 9, and 10).

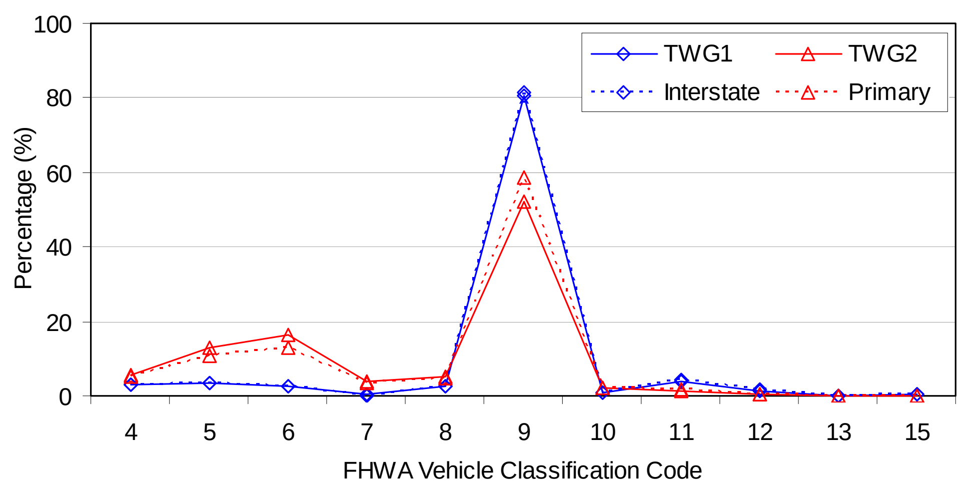


Figure 7. Distribution of FHWA Vehicle Classifications by Truck Weight Group (TWG) and Road Classification. TWG1=Truck weight group 2 (tractor-trailer trucks in 2001 ≥ 1,000 per day) and TWG2 = Truck weight group 2 (tractor-trailer trucks in 2001 < 1,000 per day).

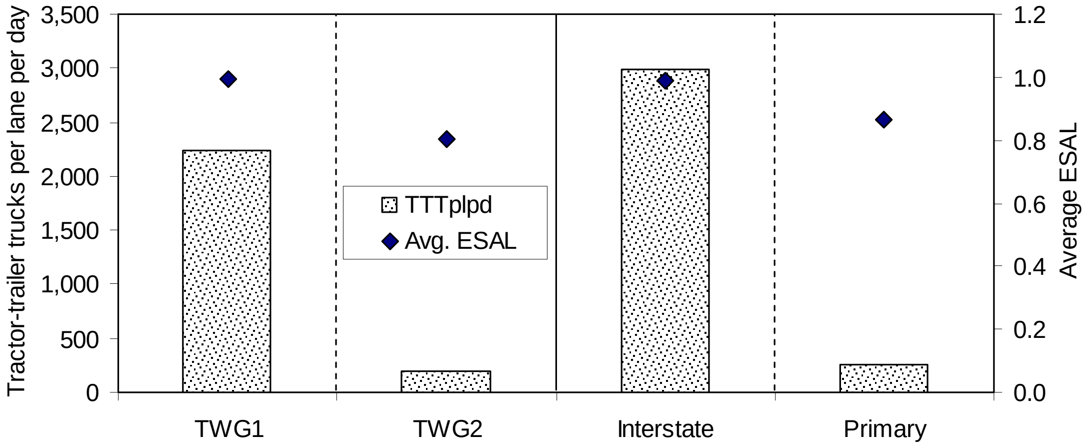


Figure 8. Tractor-trailer Trucks per Lane per Day (TTTplpd) and Average Equivalent Single-Axle Load (ESAL) by Truck Weight Group (TWG) and Road Classification. TWG1=Truck weight group 1 (tractor-trailer trucks in 2001 ≥ 1,000 per day) and TWG2 =Truck weight group 2 (tractor-trailer trucks in 2001 < 1,000 per day).

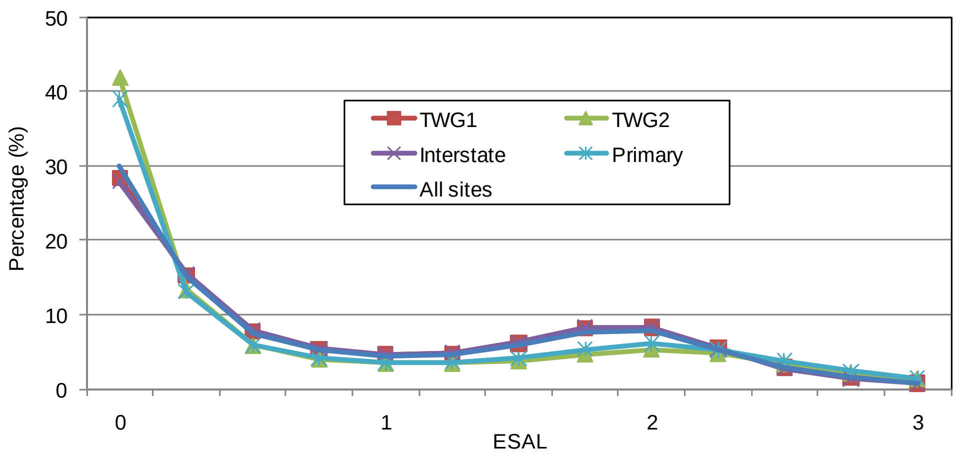


Figure 9. Distribution of Equivalent Single-Axle Load (ESAL) Values by Truck Weight Group (TWG) and Road Classification. TWG1=Truck weight group 1 (tractor-trailer trucks in 2001 ≥ 1,000 per day) and TWG2=Truck weight group 2 (tractor-trailer trucks in 2001 < 1,000 per day).

significance level (99% confidence level). In order to remove possible influences because of the administering agency (i.e., DMV or VDOT) (e.g., that truck weight data collected at the DMV sites could be different than data from similar sections of the same roadway because overweight trucks might avoid enforcement sites), the test was performed on the data from only the sites operated by VDOT, and the result led to the same conclusion.

In summary, TWG1 and interstate sites had higher percentages of trucks in FHWA Vehicle Class 9, lower percentages of trucks in Classes 5 and 6, higher average ESAL values, and much higher TTTplpd values than those for TWG2 and primary highway sites. Since Class 9 trucks have longer hauls and larger cargo spaces than those in Classes 5 and 6, they are likely to use interstate highways more often and carry heavier loads. The similarity with regard to distribution of FHWA vehicle classes and average ESAL values between TWG1 and interstate highway sites and between TWG2 and primary highway sites occurs because all TWG1 sites except two are on interstate highways and all TWG2 sites are on primary highways; thus, the comparison results between TWG1 and TWG2 are similar to those between interstate and primary highway sites.

Assessment of DMV WIM Data

Virginia's DMV has been maintaining WIM sites primarily for truck weight limit enforcement purposes. Thus, there has been a concern among traffic and pavement engineers that truck weight data collected at the DMV sites could be different than data from similar sections of the same roadway because overweight trucks might avoid enforcement sites. If this is the case, truck weights collected at the DMV sites may be lower than those collected at "non-enforcement" sites (i.e., VDOT sites). As a consequence, including weight data from the DMV sites may lead to insufficient pavement designs.

To compare data collected at VDOT and DMV sites, SID 17 and SID 19 were selected because both are located on northbound I-95. Although other differences between the two sites may exist because of geographical differences, the influence of three factors (road classification, direction, and route) on the comparison results between VDOT and DMV sites were mitigated to some extent. SID 17, located in the northern part of Virginia (Dumfries), is maintained by DMV, and SID 19, located in the southern part of Virginia (Sussex County), is maintained by VDOT. To assess truck weight data from the DMV sites, three variables collected from the WIM system were compared between the two sites: distribution of FHWA vehicle classifications, TTTplpd, and average ESAL. Table 9 presents the three variables by agency and road classification. It also presents ESAL values for interstate WIM sites grouped by VDOT and DMV. The average ESAL for all trucks and the percentage of FHWA Vehicle Class 9 trucks were the same for the two sites although the TTTplpd was quite different.

Values shown in Table 9 are presented in Figures 10 and 11 for visual comparison. In Figure 10 it can be seen that the VDOT sites have a lower percentage of vehicles in FHWA Vehicle Class 9 and a higher percentage of vehicles in Classes 4 and 5 than do the DMV sites. Figure 11 shows that the DMV sites have higher TTTplpds than do the VDOT sites. The patterns for average ESAL values are similar to those with TTTplpd yet the difference between the comparing groups is smaller. The DMV sites have higher ESAL values than the VDOT sites, which was confirmed by the Wilcoxon rank sum test. All 6 DMV sites are on interstate highways, whereas only 2 of the 16 VDOT sites are on interstate highways. Thus, the differences between the VDOT and DMV sites are likely to be attributable to the road classification (i.e., interstate versus primary highways) rather than to the administering agencies (i.e., enforcement versus non-enforcement sites). Ideally, for comparison purposes (not for pavement design purposes), all conditions (e.g., route, road geometry, traffic volume and patterns, and land use) except for the administering agency should be identical for the two groups of sites so that any difference could be attributable to the agencies. However, such sites do not currently exist in Virginia.

Table 9. Vehicle Classification, Volume, and ESAL Statistics of Trucks

Variable		All Sites[a]	Agency		SID 19	SID 17	Road Classification		Interstate	
			VDOT[b]	DMV[c]	VDOT	DMV	Interstate[d]	Primary[e]	VDOT[f]	DMV[g]
% Trucks by FHWA Vehicle Class	4	3.54	4.72	2.88	3.82	4.21	3.05	5.23	3.85	2.88
	5	5.09	8.81	3.03	5.27	3.87	3.42	10.82	5.33	3.03
	6	4.82	9.12	2.44	2.39	2.92	2.48	12.85	2.68	2.44
	7	0.94	2.3	0.19	0.05	0.29	0.19	3.49	0.23	0.19
	8	3.08	3.98	2.59	2.32	3.53	2.62	4.67	2.79	2.59
	9	76.3	67.0	81.5	83.1	80.4	81.5	58.6	81.5	81.5
	10	1.00	1.59	0.68	0.76	0.80	0.71	2.03	0.83	0.68
	11	3.59	1.83	4.56	1.37	2.83	4.12	1.77	1.95	4.56
	12	1.29	0.49	1.73	0.74	1.12	1.56	0.38	0.68	1.73
	13	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
	15	0.29	0.17	0.36	0.19	0.07	0.33	0.16	0.20	0.36
TTTplpd[h]		1,023	388	4,364	1,278	3,974	2,993	261	1,100	4,364
ESAL[i]	Avg.	0.96	0.91	0.99	1.02	1.14	0.99	0.86	0.99	0.99
	Std. dev.	0.91	0.96	0.88	0.93	0.93	0.89	0.97	0.93	0.88

SID 19 = VDOT WIM site on I-95 North in Sussex County; SID 17 = DMV WIM site on I-95 North in Dumfries; VDOT = Virginia Department of Transportation; DMV = Virginia Department of Motor Vehicles.
[a] 22 directional sites (12 locations).
[b] 16 directional sites (9 locations).
[c] 6 directional sites (3 locations).
[d] 8 directional sites (5 locations).
[e] 14 directional sites (7 locations).
[f] 2 directional sites (2 locations).
[g] 6 directional sites (3 locations).
[h] Tractor-trailer trucks per lane per day in 2007-2008.
[i] Equivalent single-axle load of tractor-trailer trucks (FHWA Vehicle Classes 8, 9, and 10).

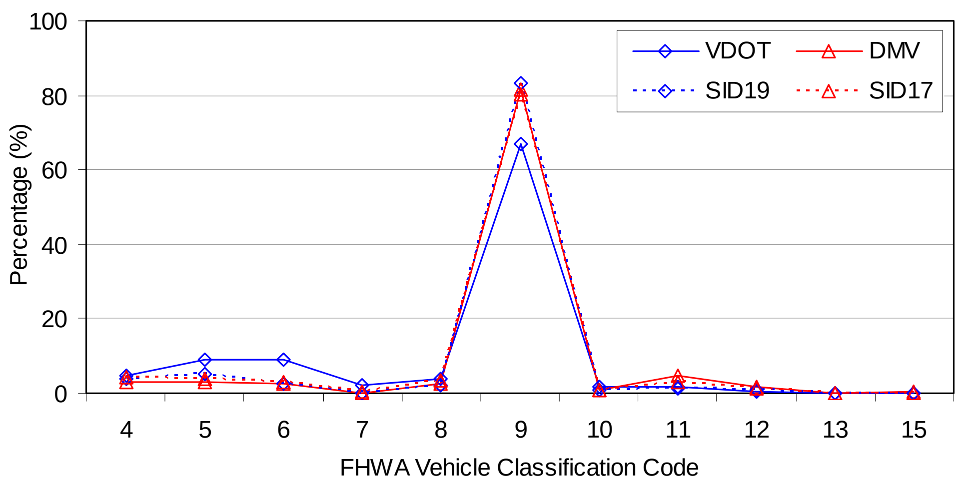


Figure 10. Distribution of FHWA Vehicle Classes by Agency and Site VDOT = Virginia Department of Transportation; DMV = Department of Motor Vehicles; SID 17 = DMV WIM site on I-95 North in Dumfries; SID 19 = VDOT WIM site on I-95 North in Sussex County.

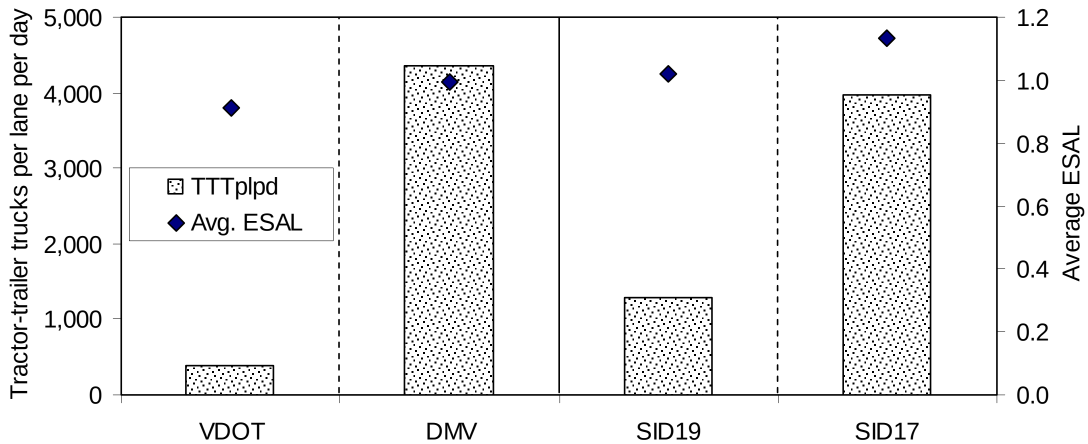


Figure 11. Tractor-Trailer Trucks per Lane per Day (TTTplpd) and Average Equivalent Single-Axle Load (Avg. ESAL) for All Vehicles by Agency. VDOT = Virginia Department of Transportation; DMV = Department of Motor Vehicles; SID 17 = DMV WIM site on I-95 North in Dumfries; SID 19 = VDOT WIM site on I-95 North in Sussex County

As described previously, to mitigate the possible influences of road classification, direction, and route so that a more fair comparison between the VDOT and DMV sites could be made, SID 17 and SID 19 were selected because both are located on northbound I-95. SID 17 (DMV) and SID 19 (VDOT) were similar with regard to the distribution of FHWA vehicle classes, as shown in Figure 10. This means when the three factors are controlled, the difference in the distribution of FHWA vehicle classes between the DMV and VDOT sites disappeared. However, SID 17 had a higher average ESAL and a much higher TTTplpd than did SID 19, as shown in Figure 12. The difference in ESAL values between the two sites was confirmed by the Wilcoxon rank sum test. Thus, the concern with regard to using truck loads collected from the DMV sites (enforcement sites) seems to be precautionary. However, although three factors (i.e., road classification, direction, and route) were controlled for in this comparison, the comparison results between the two sites could not be generalized because of the distance between the sites.

Update on DMV Activity and Perspective

In the early 1990s, VDOT's truck weight enforcement staff were concerned about trucks avoiding weigh stations and actively sought to deter it. Cottrell (1992) attempted to investigate this issue. The primary objective of the research was to examine the avoidance of weigh stations in Virginia by overweight trucks. Secondary objectives were (1) to determine the magnitude of overweight truck activity on selected routes and (2) to compare traffic loading data collected using static scales with enforcement with data collected using weigh-in-motion without enforcement. Two weigh stations on I-81 were studied for weigh station avoidance. It was found that 11% and 14 % (respectively) of the trucks on routes used to bypass the Stephens City and Troutville stations were overweight. At the Stephens City station, 50% percent of the runbys (which are trucks that travel past the weigh station without being weighed because the entrance lane to the station is filled with a queue of trucks) were overweight on Sunday night. Based on the number and percentage of overweight runbys, there is a need to increase the truck weighing capacity of this weigh station. From 12% to 27% of the trucks on two primary routes and one interstate route were overweight. Traffic loadings collected with WIM without enforcement are

30% to 60% higher than loadings collected using static scales and enforcement. If scale avoidance is a substantial problem, the DMV truck weight data may be biased. Currently, there appears to be little concern by the staff regarding scale avoidance. Virginia's truck weight enforcement staff, now part of DMV, stated that the truck traffic and flow are different than they were 20 years ago ((J. Bishop, personal communication, October 2, 2009). The addition of mainline WIM and intermittent weight enforcement activity on bypass routes has helped to mitigate scale avoidance concerns. Violations on bypass routes are not exorbitant in weight; they are typical violations. In the opinion of DMV staff, a negligible percentage of trucks bypass mainline weigh stations (J. Bishop, personal communication, October 2, 2009). DMV believes that the WIM information is solid and accurate and may be used for pavement design (J. Bishop, personal communication, October 2, 2009). [Note that this is based on subjective experience rather than supporting data.] PrePass (2010) has also helped improve truck flow. PrePass is an automatic vehicle identification system that enables participating transponder-equipped commercial vehicles to be pre-screened throughout the nation at designated weigh stations, port-of-entry facilities, and agricultural interdiction facilities (PrePass, 2010). Cleared vehicles are able to "bypass" the weigh station while traveling at highway speeds, eliminating the need to stop. Trucks using PrePass are required to travel in the right lane where the DMV mainline WIM sensor is located. About 20% of the truck traffic on I-81 uses PrePass (J. Bishop, personal communication, October 2, 2009). Thus, the use of DMV WIM data for pavement design is viewed as appropriate because scale avoidance is no longer an issue.

Assessment of the Current VDOT Truck Weight Data Plan for the MEPDG

This task determined how well the current plan (Cottrell, et al, 2003) satisfies VDOT's truck weight data needs for the MEPDG. Questions to be answered included:

1. Are the current WIM sites located in the right areas?
2. Is a regional factor needed?
3. If so, is there adequate regional coverage to determine a regional factor?
4. Should unique truck loading situations such as the coal loading in VDOT's Bristol District be part of VDOT's truck weight data plan?

A cluster analysis was applied to assess current truck weight groupings in Virginia for MEPDG implementation. Average ESAL, three traffic volume statistics, and vehicle classification were used as clustering criteria. The cluster analysis was used (1) to compare the current two groups (TWG1 and TWG2) with groups formed based on the average ESAL values, and (2) to explore better grouping schemes. In this manner, the current grouping scheme based on tractor-trailer truck volumes was assessed with regard to its ability to differentiate heavy load sites and light load sites Table 10 summarizes 2007-2008 ESAL and traffic volume data for tractor-trailer trucks for a cluster analysis.

Table 10. Summary Statistics of Tractor-Trailer Trucks[a] for Cluster Analysis

Site ID	No. of Lanes	No. of Valid Days	Average ESAL[c]	Total Volume[d]	TTTpd[d]	TTTplpd[f]
1	2	512	1.28	32,801	64	32
2	2	512	0.66	40,163	78	39
3	1	682	1.18	51,729	76	76
4	1	622	0.88	50,769	82	82
5	2	510	1.01	303,602	595	298
6	2	697	1.01	412,395	592	296
7	2	725	1.09	413,782	571	285
8	2	473	0.94	295,777	625	313
9	2	396	0.89	240,526	607	304
10	2	539	0.67	319,066	592	296
11	2	724	0.92	229,134	316	158
12	2	724	0.77	214,420	296	148
13	2	729	1.09	743,362	1,020	510
14	2	729	1.10	801,105	1,099	549
15	1	628	1.11	3,033,622	4,831	4,831
16	1	731	1.00	3,223,196	4,409	4,409
17	1	730	1.10	2,901,056	3,974	3,974
18	1	374	0.96	1,529,139	4,089	4,089
19	2	690	1.24	1,763,856	2,556	1,278
20	2	729	0.88	1,356,988	1,861	931
21	1	420	0.99	1,952,852	4,650	4,650
22	1	632	0.96	2,699,671	4,272	4,272

[a] FHWA Vehicle Classes 8, 9, and 10.
[b] Number of days with valid WIM data excluding months with fewer than 14 valid data days per month in 2008-2009.
[c] Equivalent single-axle load.
[d] Total tractor-trailer trucks passing the site during the valid days in 2007-2008.
[e] Tractor-trailer trucks per day = Total tractor-trailer truck volume ÷ Number of valid WIM data days in 2007-2008.
[f] Tractor-trailer trucks per lane per day = Tractor-trailer trucks per day ÷ Number of lanes.

Preliminary Visual Analysis

Before the cluster analysis was performed, two groups were formed based on a visual examination of the two statistics, i.e., TTTplpd and average ESAL; Figures 12 and 13 present the resulting groups. As shown, two sites were not assigned to any cluster because their group membership could not be clearly determined by visual examination; the values for SID 19 and SID 20 were between those for the high and low TTTplpd groups. It is clearly shown that the resulting groups based on TTTplpd and average ESAL did not match with the group based on average ESAL.

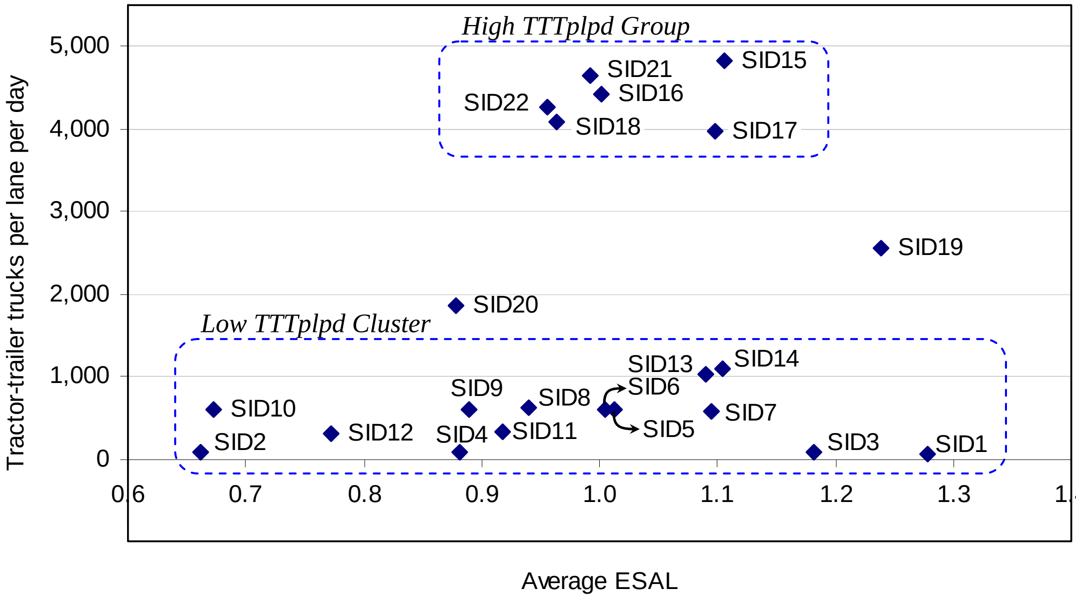


Figure 12. Clustering Results by Visual Examination Based on Tractor-Trailer Trucks per Lane per Day (TTTplpd). ESAL = equivalent single-axle load; SID = site ID. The sites are described in Table 5.

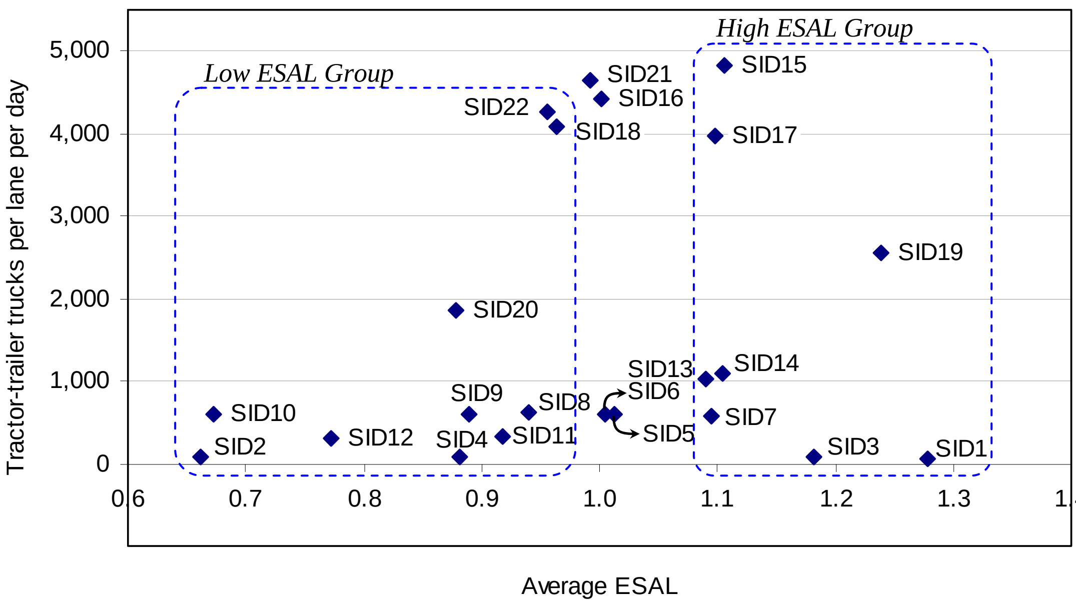


Figure 13. Clustering Results by Visual Examination Based on Average Equivalent Single-Axle Load (ESAL) for Tractor-Trailers. SID = site ID. The sites are described in Table 5.

Cluster Analysis

Table 11 presents two clusters formed by five criteria: (1) 2-year total tractor-trailer truck volume, (2) TTTpd, (3) TTTplpd, (4) average ESAL, and (5) vehicle classifications. Ward's method (Ward, 1963) was employed for cluster analysis, and the resulting two clusters were determined based on a dendrogram, a graphical output of the cluster analysis (see Appendix D for an example of a dendrogram). A brief description of Ward's method is presented in Appendix E.

Table 11. Resulting Clusters by Different Criteria Using Ward's Method

Site ID	TWG	Criterion Tot.Truck	TTTpd	TTTplpd	Avg.ESAL	Veh.Class
1	2	A[a]	A	A	A	A
2	2	A	A	A	B[b]	A
3	2	A	A	A	A	A
4	2	A	A	A	B	A
5	2	A	A	A	B	A
6	2	A	A	A	B	A
7	2	A	A	A	A	A
8	2	A	A	A	B	A
9	2	A	A	A	B	A
10	2	A	A	A	B	A
11	2	A	A	A	B	A
12	2	A	A	A	B	A
13	1	A	A	A	A	A
14	1	A	A	A	A	A
15	1	B	B	B	A	B
16	1	B	B	B	B	B
17	1	B	B	B	A	B
18	1	B	B	B	B	B
19	1	B	A	A	A	B
20	1	B	A	A	B	B
21	1	B	B	B	B	B
22	1	B	B	B	B	B

TWG = truck weight group; Tot.Truck = total tractor-trailer truck volume for valid WIM data period in 2007-2008; TTTpd = tractor-trailer trucks per day; TTTplpd = tractor-trailer trucks per lane per day; ESAL = equivalent single-axle load; Veh.Class = FHWA Vehicle Class.
[a] Cluster A.
[b] Cluster B.

The cluster analysis based on the four traffic characteristics (i.e., total tractor-trailer truck volume (Tot.Truck), TTTpd, TTTplpd, and FHWA vehicle class [Veh.Class.]) led to similar resulting clusters. The resulting clusters based on TTTpd and TTTplpd were identical. The resulting clusters based on Tot.Truck and Veh.Class corresponded with road classifications (i.e., interstate and primary highways). The sites in Cluster B by Tot.Truck and Veh.Class corresponded to the interstate highway sites, and the sites in Cluster A by Tot.Truck and Veh.Class corresponded to the primary highway sites. Cluster results based on average ESAL (Avg.ESAL) were very different from those based on traffic volume and vehicle classification. For five of the locations with a WIM site in both directions (US 58, US 60, SR 288, I-81 Stephens City, and I-95 Dumfries), these matching WIM sites were split between the two ESAL-based groups.

Figures 14 and 15 present the resulting clusters based on TTTplpd and Avg.ESAL. In comparison with Figures 12 and 13 based on visual examination, cluster memberships were similar and the sites indeterminate in group membership in Figures 12 and 13 were assigned to clusters. As anticipated from the visual grouping results in Figures 12 and 13, the resulting clusters by TTTplpd and Avg.ESAL were very different in terms of cluster membership. This means grouping the sites based on TTTplpd did not differentiate heavy load sites from light load sites. The 2003 study by Cottrell et al. assumed that a site recording more tractor-trailer trucks

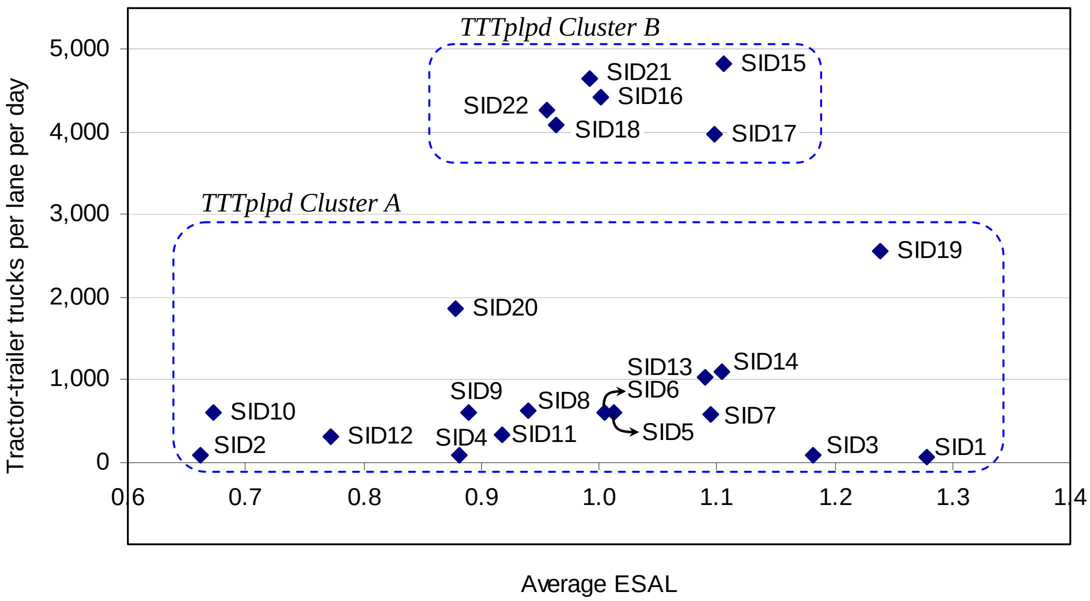


Figure 14. Clustering Results Based on Tractor-trailer Trucks per Lane per Day (TTTplpdESAL = equivalent single-axle load; SID = site ID. The sites are described in Table 5.

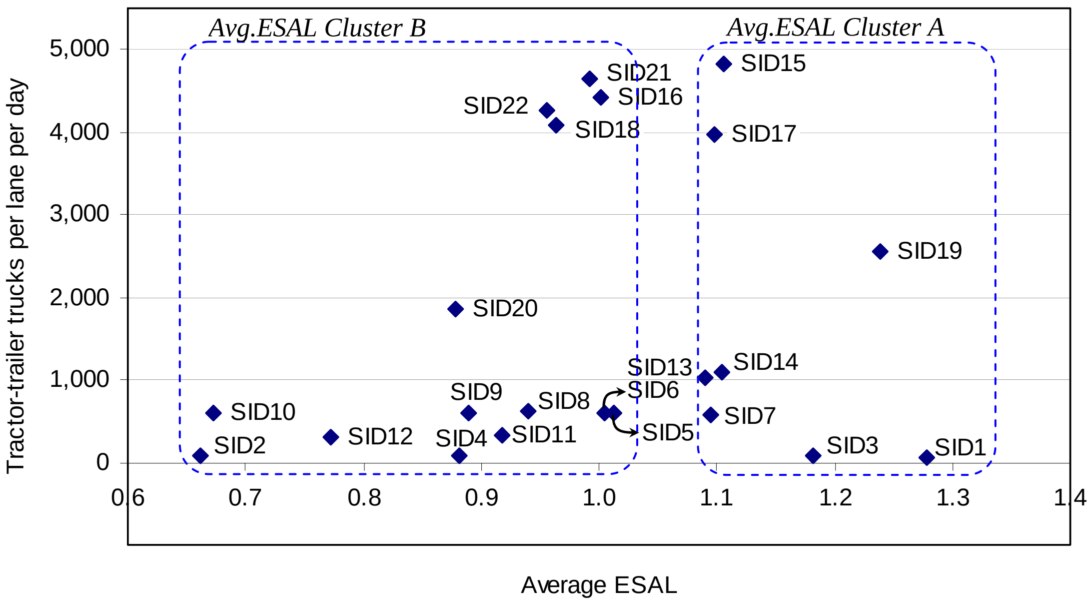
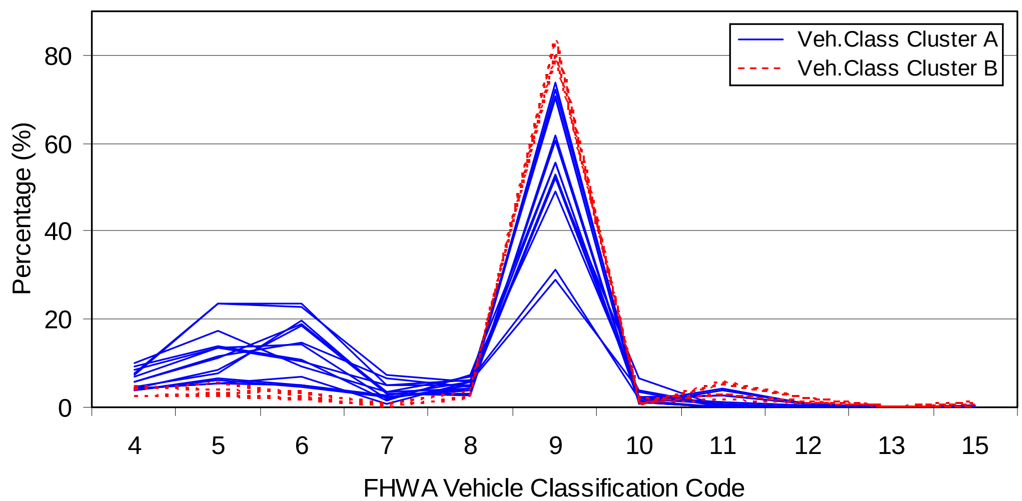


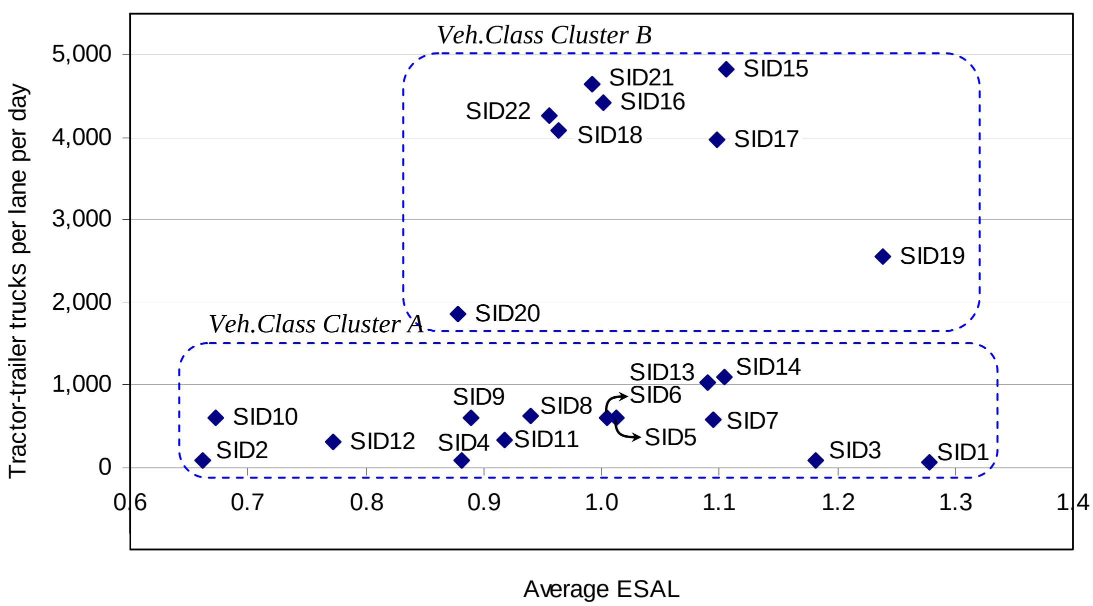
Figure 15. Clustering Results Based on Average Equivalent Single-Axle Load (ESAL) for Tractor-Trailers. SID = site ID. The sites are described in Table 5.

was likely to be used by more heavy trucks. Based on this assumption, the 2003 study suggested grouping the WIM sites based on tractor-trailer truck volumes in 2001, thus assigning the sites into two groups: TWG1 (tractor-trailer trucks ≥ 1,000 per day) and TWG2 (tractor-trailer trucks < 1,000 per day). The clustering results in the current study revealed that this assumption was invalid; sites with larger truck volumes were not also likely to have heavier truck weights (ESAL values).

Figure 16 presents vehicle classification profiles of the 22 sites by the resulting clusters. According to Figure 16(a), Cluster A has a higher percentage of vehicles in Class 9 and a lower percentage in Classes 4 through 8 than does Cluster B. Figure 16(b) overlays the clustering results on the TTTplpd–Avg.ESAL plot to show cluster membership based on vehicle classification. As mentioned earlier, the cluster memberships based on vehicle classification largely coincided with those based on TTTplpd. The only difference was cluster membership with regard to SID 19 and SID 20; SID 19 and SID 20 belonged to Cluster A by TTTplpd and to Cluster B by FHWA vehicle class.



(a) Vehicle classification profile



(b) Cluster membership based on vehicle classifications

Figure 16. Clustering Results Based on Vehicle Classifications. ESAL = equivalent single-axle load; SID = site ID. The sites are described in Table 5.

In summary, the clustering results based on two traffic characteristics, i.e., TTTplpd and FHWA vehicle class (Veh.Class), were generally in agreement with the current TWG. The current TWG and the clustering results based on TTTplpd and Veh.Class were generally in line with sites grouped by road classification (interstate and primary highways). However, the clustering results based on average ESAL (Avg.ESAL) were considerably different from the TWGs and clusters based on TTTplpd, Veh.Class, or a combination of the two variables. A study appears to be needed to replace the current grouping scheme devised using tractor-trailer truck volume criteria. The intent would be to identify a readily available variable for most roadways statewide that would result in a TWG cluster scheme that correlated with traffic loadings. For example, a recent study (Mihai et al., 2010) was conducted in Australia to provide reliable loading classification of a site using only vehicle classification data. Using data from the WIM system, the Kolmogorov-Smirnov statistic from the cumulative distribution function was found to be robust in correctly identifying sites with high loading conditions.

Recommendation of the Optimal Number of Clusters

Although the number of clusters was initially set at two to be consistent with the current TWG system, there is a possibility that a larger number of clusters might result in groups where sites within each group becomes more similar in truck volume than the current two TWGs. The number of clusters can be determined based on three goodness-of-fit measures of cluster analysis: (1) cubic clustering criterion (CCC), (2) pseudo *F* statistic (PSF), and (3) pseudo t^2 statistic (PST2). The general rules for determining the optimal number of clusters (Bauserman et al., 2007) are as follows:

1. CCC values greater than 2 or 3 correspond to an appropriate number of clusters.

2. Local peak PSF values correspond to an appropriate number of clusters.

3. Local peak PST2 values correspond to an appropriate number of clusters – 1. Thus, an appropriate number is the one corresponding to the peak PST2 plus 1.

Based on TTTplpd, these three rules led to (2, 3, or 4), (21), and (2, 6, 9, or 20) as the potential appropriate numbers of clusters, respectively. A large number of clusters is not useful unless a detailed classification is required. Thus, some of the PSF and PST2 results (e.g., 9, 20, and 21 clusters) were not useful for this study. Ideally, all three rules would lead to the same number of clusters. In cases where they lead to different numbers, the smallest number of clusters with a reasonable agreement across the results from the three rules would be the best. Following this guide 2 appeared to be a reasonable number of clusters for these data because 2 clusters were recommended by the two rules using CCC and PST2, and the optimal number of clusters based on TTTplpd for this study was 2 for the current volume-based TWGs.

When determining what variables to consider for developing TWGs, it is important to consider the availability of such variables for other sites. For example, to determine what traffic loadings to consider for Site X on Route YY, the first question is: "Is the site similar to those in TWG1 or TWG2?" To answer this question, information on some site characteristics for Site X needs to be available. Traffic loading data will not be available. Smith and Diefenderfer (2010) used the grouping of interstate and primary road classes in their study *Analysis of Virginia-Specific Traffic Data Inputs for Use with the Mechanistic-Empirical Pavement Design Guide.* As noted earlier, with the exception of the sites on US 17, i.e., SID 13 and SID 14 in TWG1, the TWGs are grouped by interstate (TWG1) and primary routes (TWG2).

Regional Factor Consideration

To evaluate needs for regional factors, sites within the same geographical areas were compared. VDOT's Bristol District was thought to be a candidate for an area deserving a regional factor because of its unique coal mining industry. The two sites in the Bristol District were compared to determine if the sites in the same region showed similarities. VDOT's Hampton Roads and Northern Virginia districts may also be viewed as potential areas for separate regional factors because their traffic characteristics are thought to be different from those of other areas. Hampton Roads could be different with regard to truck traffic characteristics because of the presence of the port. Northern Virginia could be different because it abuts Washington, D.C., and its large metropolitan area. Thus, sites in these districts were included for comparison. Table 12 presents the distribution of FHWA vehicle classes, TTTplpd, and average ESAL by three geographical areas. For visual comparisons by geographical areas, the values in Table 12 are presented in Figures 18 through 21.

Figure 17 presents the distribution of vehicle classes at the four sites in the Bristol and Hampton Roads districts. SID 1 and SID 2 in Bristol are on the eastbound and westbound lanes, respectively, at the same location on US 58 in Lee County. SID 1 had a lower percentage of vehicles in Class 9 and a slightly higher percentage in Class 5 than did SID 2. SID 9 and SID 10 in Hampton Roads are on the eastbound and westbound lanes, respectively, at the same location on SR 164 in Portsmouth. These two sites had a similar distribution with regard to FHWA vehicle class. All four sites had a smaller percentage of vehicles in Class 9 and a higher percentage in Classes 5 and 6 than the average of all sites combined.

Figure 18 presents the distribution of FHWA vehicle classes at the six sites in Northern Virginia. SID 11 and SID 12 are in the northbound and southbound lanes, respectively, at the same location on SR 234 in Prince William County, and they had a much lower percentage of vehicles in Class 9 and a higher percentage in Classes 5 and 6 than the other four sites in the area. The four sites were SID 13 and SID 14, northbound and southbound, respectively, at the same location on US 17 in Fauquier County, and SID 17 and SID 18, northbound and southbound, respectively, at the same location on I-95 in Dumfries. They were similar with regard to the distributions and similar to all sites combined. Although SID 11 and SID 12 are physically close to SID 17 and SID 18, they were very different from them with respect to the distribution of FHWA vehicle classes.

Figure 19 presents TTTplpd and average ESAL at the four sites in the Bristol and Hampton Roads districts in comparison to the average of all sites in Virginia. SID 1 and SID 2 in Bristol had very low trailer-truck volumes. SID 1 (eastbound) had a much higher average ESAL than that of SID 2 (westbound) and the average of all the sites. At the two sites in the Bristol District, trailer trucks heading east appeared to have much heavier loads, on average, than those traveling west. SID 9 and SID 10 in Hampton Roads had lower trailer-truck volumes than

Table 12. Vehicle Classification, Volume, and ESAL Statistics of Trucks by Geographical Areas

Variable		All Sites[a]	Bristol[b] SID 1	Bristol[b] SID 2	Hampton Roads[c] SID 9	Hampton Roads[c] SID 10	Northern Virginia[d] SID 11	SID 12	SID 13	SID 14	SID 17	SID 18
% Trucks by FHWA Vehicle Class	4	3.54	10.1	9.15	4.20	4.45	7.23	7.66	3.90	3.91	4.21	4.62
	5	5.09	17.3	13.71	8.35	7.89	23.5	23.4	6.56	6.13	3.87	3.93
	6	4.82	9.46	10.97	18.5	19.6	22.8	23.5	4.97	4.62	2.92	2.94
	7	0.94	3.29	1.38	3.04	2.91	7.25	5.09	2.49	2.32	0.29	0.61
	8	3.08	6.89	7.24	2.88	3.28	5.68	6.31	3.75	4.23	3.53	3.30
	9	76.3	49.0	55.73	61.8	60.7	28.9	31.3	72.3	73.6	80.4	78.7
	10	1.00	3.55	1.57	1.16	1.04	3.84	1.80	2.43	1.76	0.80	1.74
	11	3.59	0.01	0.00	0.01	0.00	0.58	0.59	2.80	2.61	2.83	2.68
	12	1.29	0.00	0.01	0.00	0.00	0.04	0.04	0.65	0.67	1.12	0.99
	13	0.01	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.01
	15	0.29	0.39	0.23	0.10	0.14	0.16	0.22	0.13	0.14	0.07	0.45
TTTplpd[e]		1,023	32	39	304	296	158	148	510	549	3,974	4,089
ESAL[f]	Avg.	0.96	1.28	0.66	0.89	0.67	0.92	0.77	1.09	1.10	1.10	0.96
	Std. dev.	0.91	1.58	1.02	1.12	0.84	0.94	0.97	1.02	1.06	0.94	0.94

[a] 22 directional sites at 12 locations.
[b] SID 1 and SID 2 are at same location on US 58 in Lee County: SID 1 is on eastbound and SID 2 is on westbound.
[c] SID 9 and SID 10 are at same location on SR 164 in Portsmouth: SID 9 is on eastbound and SID 10 is on westbound.
[d] SID 11 and SID 12 are at same location on SR 234 in Prince William County; SID 13 and SID 14 are at same location on US 17 in Fauquier County; and SID 17 and SID 18 are at same location on I-95 in Dumfries.
[e] Tractor-trailer trucks per lane per day.
[f] Equivalent single-axle load of tractor-trailer trucks (FHWA Vehicle Classes 8, 9, and 10).

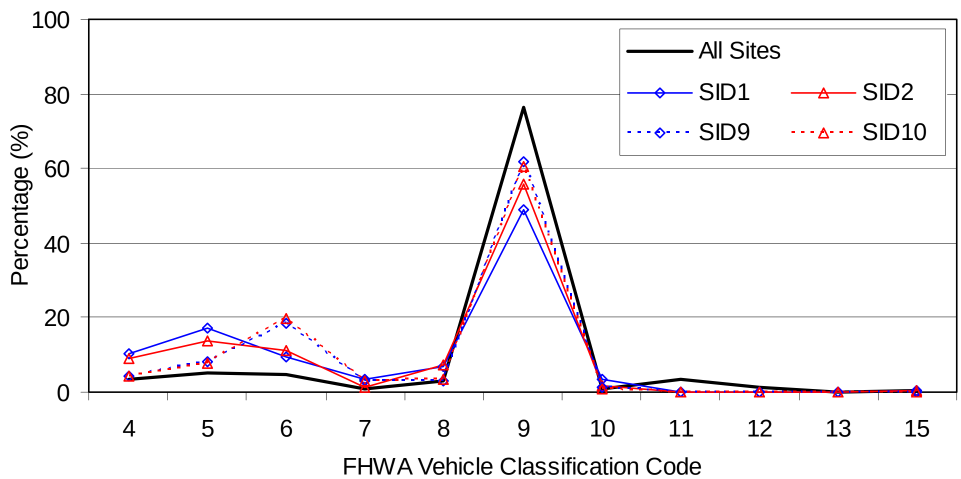


Figure 17. Distribution of FHWA Vehicle Classes at Sites in Bristol and Hampton Roads Districts. SID 1 and SID 2 are in the Bristol District, and SID 9 and SID 10 are in the Hampton Roads District. The sites are described in Table 5.

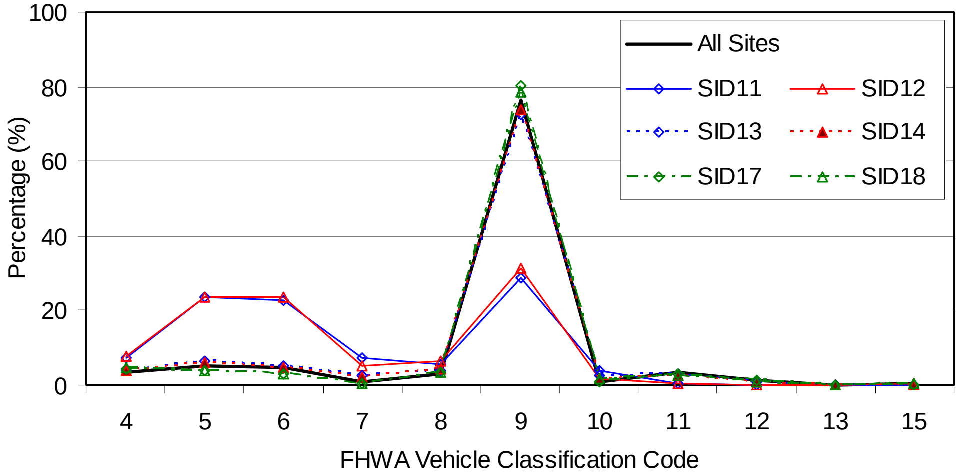


Figure 18. Distribution of FHWA Vehicle Classes at Sites in Northern Virginia District. SID = site ID. The sites are described in Table 5.

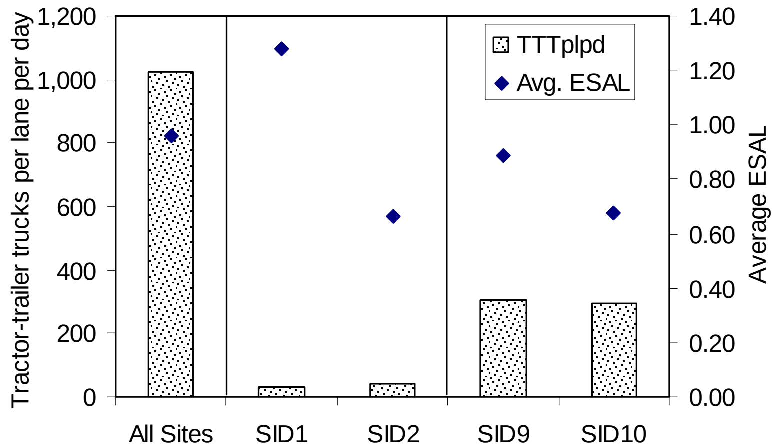


Figure 19. Tractor-trailer Trucks per Lane per Day (TTTplpd) and Average Equivalent Single-Axle Load (ESAL) at Sites in Bristol District (SID 1 and SID 2) and Hampton Roads District (SID 9 and SID 10). SID = site ID. The sites are described in Table 5.

the average of all the sites in Virginia. SID 9 (eastbound) had a higher average ESAL than that of SID 10 (westbound) but a lower average than the average of all 22 sites. A significant directional difference might exist for other highways and potential WIM sites just as SID 1 and SID 2 showed a considerable difference in average ESAL. This may have implications with regard to using a single average ESAL value (or a single set of load spectra values for the MEPDG) for both directions at one location for pavement design.

Figure 20 presents TTTplpd and average ESAL at the six sites in Northern Virginia. SID 11 and SID 12 on SR 234 and SID 13 and SID 14 on US 17 had lower trailer-truck volumes than the average of all 22 sites, and SID 17 and SID 18 on I-95 had much higher trailer-truck volumes than the average. In terms of average ESAL, SID 13 and SID 14 were similar to SID 17 (northbound). In terms of average ESAL, SID 11 and SID 18 were closer to all 22 sites combined and SID 12 was lower. Thus, in general, SID 13 and SID 14 were similar to SID 11 and SID 12 in TTTplpd and similar to SID 17 and SID 18 in average ESAL.

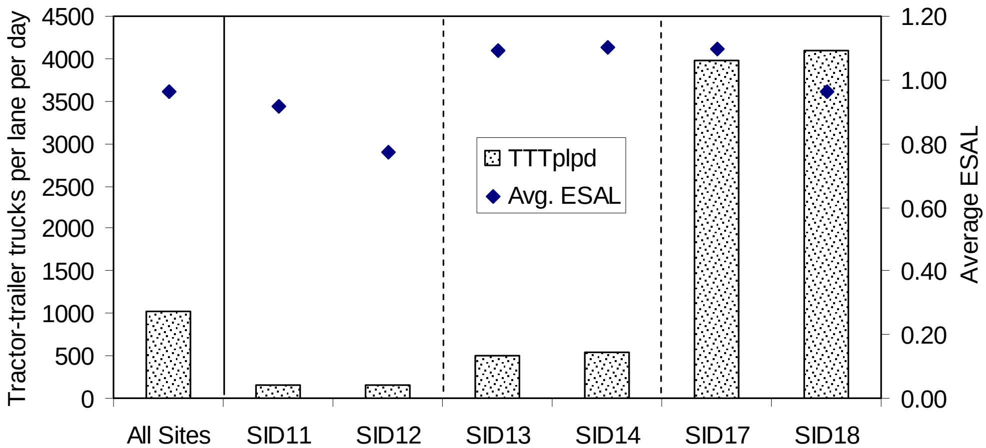


Figure 20. Tractor-trailer Trucks per Lane per Day (TTTplpd) and Average Equivalent Single-Axle Load (ESAL) at Sites in Northern Virginia District. SID = site ID. The sites are described in Table 5.

In summary, considerable differences were found within the same areas in terms of distribution of FHWA vehicle classes. Smaller differences were found in TTTplpd and average ESAL. This means a regional factor calculated based on loading conditions of sites in the region may not serve as a stable adjustment for the region. At one location, significant directional differences were found in the distribution of vehicle classes and average ESAL values. Thus, using an average ESAL value or axle load spectra values for the MEPDG for both directions at one location might lead to an insufficient or overly conservative pavement design, depending on the direction. The use of average values in general carries this risk.

Unique Truck Loading Situations

The coal hauling roads in Southwest Virginia are most often cited as comprising a unique truck loading situation. For the most part, VDOT field crews/staff understand and are knowledgeable regarding the unique conditions. Through experience, they have learned to accommodate the conditions through pavement design adjustments and/or increased maintenance activity. It is possible that the heavier traffic loadings may reduce the service life of the WIM system. Because of the cost to install a WIM system and the effort to maintain it, the researchers think that a WIM system for a unique truck loading situation is not justifiable. There may be extenuating circumstances that warrant WIM for some unique situations, but these are expected to be rare.

Examination of Use of WIM Data and Performance of WIM Systems

Information on the use of data and performance of VDOT's WIM system was provided by VDOT's TED (Williams, 2010a,b). The following is a list of VDOT WIM data users:

- *FHWA:*

  – LTTP: Long-Term Pavement Performance Program
  – HVTIS: Heavy Vehicle Travel Information System

- *VCTIR:* various purposes including the current study and two studies by Smith and Diefenderfer (2009, 2010)

- *Koch Industries:* Route 288 pavement warranty

- *Wayne State University:* Center for Advanced Bridge Engineering

- *VDOT's Transportation and Mobility Planning Division:* freight studies

- *VDOT's TED:* such tasks as revising the vehicle classification table to improve the data.

Once the MEPDG is implemented (currently planned for December 2013), requests by VDOT for WIM data will likely increase substantially.

The performance objective for WIM data quality is to achieve the accuracy specified in ASTM E1318-02, Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM, 2002) for a Type I WIM system (i.e., 95% of vehicles have a gross weight within 10% of their actual weight). The following data are for VDOT WIM sites in 2008:

- *Number of sites:* 11
- *Number of days in year:* 366
- *Maximum possible site-days of data (11 x 366):* 4,026
- *Actual number of days of data:* 4,012 (99.7%)
- *Number of days with at least 1 non-error vehicle:* 3,991 (99.1%)
- *Number of days with <200 error vehicles:* 3,882 (96.4%).

Error vehicles are vehicles that are not completely detected by all of the sensors in a lane. This can make it impossible to determine the vehicle's speed, weight, number of axles, etc. Error vehicles can be caused by equipment malfunctions, but they are usually caused by the vehicle being partially in the lane or changing lanes while over the sensor array.

The maintenance needs for the sites with Kistler sensors include calibration (typically on an annual basis) and periodic grinding over the sensors to smooth out the effects of pavement rutting. There have been few sensor failures. Depending on the mode of failure, failed sensors are either repaired in place or removed and replaced with new sensors. Pavement deterioration will eventually cause the sensors to become loose and will necessitate their removal. This has not happened yet at any VDOT site. The FHWA LTPP contractor is currently handling the calibration and maintenance needs for the one site with bending plate sensors (US 29 South in Danville) (Williams, 2010a).

Answers to the Four Review Questions Regarding VDOT's Truck Weight Data Plan

The answers to the four questions asked at the beginning of the study are as follows:

1. *Are the current WIM sites located in the right areas?* Based on the information available for this analysis, this question could not be answered conclusively.

2. *Is a regional factor needed?* Based on the WIM data analysis, it appears that geographic location is not an indicator of traffic loadings. There are similar characteristics of the two TWGs. There was considerable variation in the traffic loadings among sites in the same region, meaning a regional factor would not likely represent the loading conditions of a region. Based on this analysis, there is no evidence to suggest that a regional factor is needed.

3. *If so, is there adequate regional coverage to determine a regional factor?* This is not applicable since no regional factor seems to be needed.

4. *Should unique truck loading situations such as the coal loading in the Bristol District be part of VDOT's Truck Weight Data Plan?* No. Consideration of unique loading situations should be considered on a case-by-case basis when engineers design pavement.

Revising VDOT's Truck Weight Data Plan for the MEPDG

Before discussing any necessary revisions to VDOT's truck weight data plan for the MEPDG, it is useful to provide an update on the VDOT WIM program.

Update on VDOT WIM Program

Since this study began, five sites in three locations (there are WIM sites in both directions at two sites) were added to the VDOT WIM program. The three locations and their TWG groups are as follows:

1. *US 29 south of Charlottesville in Albemarle County:* TWG2 (<1,000 tractor-trailers per day per direction) (added July 2009)

2. *I-66 E near mile marker 16 in Fauquier County:* TWG1 (>1,000 tractor-trailers per day per direction) (added October 2009)

3. *US 13, Accomac County:* TWG2 (added August 2010) (US 13 is a CoSS).

The addition of the 5 sites to the former 22-site WIM program represents a 23% increase in the number of sites.

Necessary Revisions to VDOT's Truck Weight Data Plan for the MEPDG

Challenge of WIM Program Development

The development of a WIM program is more art than science. The challenge with regard to developing a WIM program is how to develop TWGs that represent all Virginia roads without truck weight data representative of all roads. Traditional sample size selection procedures begin with known data for the population (all sites) to be sampled and stratified. The evaluation of VDOT's WIM program is limited by the availability of data to determine with any statistical significance whether the current program is adequate. This limitation is difficult to overcome. The approach used here was to provide suggested revisions to the extent possible given the existing limitations.

Revisions to Consider

The analysis conducted in this study suggests that until a better means than that used in this study is available for defining TWGs, TWG1 and TWG2 as defined in VDOT's current truck weight data plan (Cottrell et al, 2003) should be used. If there is a concern that a particular site or route may have characteristics that do not fit the profile of the selected group, secondary factors such as functional classification should be considered in selecting a TWG.

Future WIM Locations to Consider

In the absence of a definitive approach to quantifying what would represent an adequate number of WIM sites and where they should be located, it is suggested that VDOT continue installing WIM systems as resources and opportunities allow and that the CoSS and truck traffic patterns be considered when candidates for future WIM sites are selected. There are several DMV WIM sites such as the one on I-77 (also a CoSS) where WIM data do not meet VDOT data quality standards (see "Examination of Use of WIM Data and Performance of WIM Systems"). The data for these DMV sites are available in the DMV database but have not been loaded into VDOT's database. The primary issue with the data quality is that the pavement is not smooth enough to yield the desired WIM data accuracy. Route 460 and Route 220, both CoSS, could be considered for future WIM sites by VDOT if there are suitable locations.

On average, VDOT has been installing about two WIM sites per year since 2005. Currently VDOT is not actively looking for new sites. As WIM sites are removed from service because of pavement deterioration, VDOT will consider adding replacement sites. WIM sites can be installed in grades up to 2%. There are no WIM sites with a TTTplpd between 1,500 and 3,500. To expand the WIM data pool, sites in this range would be good candidates for new installation of WIM systems. The most difficult aspect of new site selection has always been locating new, smooth pavement.

CONCLUSIONS

- *There is very little literature that provides specific information on the structure of a truck weight data plan for the MEPDG.* There is much flexibility in the development of such a plan. Most states are working to develop this plan, and there is much variation in the existing plans of state DOTs.

- *The Corridors of Statewide Significance (CoSS) in Virginia's statewide long-range multimodal transportation plan represent the routes where truck traffic is most prominent.*

- *The sites in TWG1, the higher trailer-truck volume group, carry heavier trucks in terms of site average ESAL values than those in TWG2, the lower trailer-truck volume group. In addition, TTTplpd (tractor-trailer trucks per lane per day) and distribution of vehicle classes were different between the two groups. TWG1 sites correspond to the sites on interstate highways, and TWG2 sites correspond to the sites on (non-interstate) primary highways.*

- *Volume data from WIM sites could be significantly different from those from continuous count classification stations because of the number of lanes with sensors and other factors. Thus, for calculating traffic-related inputs such as monthly traffic factors, volume data from continuous count classification stations are preferred.*

- *There were considerable differences in truck and tractor-trailer truck volume, distribution of FHWA vehicle classes, and/or average ESAL of tractor-trailer trucks across some sites in the same area and between two directions at the same site. This means that the average input values from the WIM sites in a certain area (or region) may not accurately represent the input conditions of all roads in the area.*

- *Enforcement (DMV) sites carry heavier trucks than pavement data collection (VDOT) sites. Thus, the concern that truck weights collected at the enforcement sites might be inappropriate to use for pavement design because of scale avoidance by heavy trucks seems unwarranted. However, because of several factors and limitations, a definitive conclusion regarding this comparison result could not be drawn.*

- *Grouping the sites based on average ESAL resulted in TWGs that were considerably different than the current TWGs and TWGs based on traffic characteristics including TTTplpd and distribution of FHWA vehicle classes.*

RECOMMENDATIONS

1. *Staff of VDOT's TED Traffic Monitoring Program should continue using VDOT's current truck weight data plan for the MEPDG.* If there is concern that a particular site or route may have characteristics that do not fit the profile of the selected TWG, secondary factors such as functional classification should be considered in selecting a TWG.

2. *VDOT's MEPDG Traffic Data Team and staff of VDOT's TED Traffic Monitoring Program should work together to develop a strategic plan for the continuing incremental expansion of the WIM program.* The plan should include consideration of the resources needed to administer an expanded WIM program.

3. *As VDOT moves forward in its implementation of the MEPDG, it should continue to add WIM sites as opportunities and funding permit.* Installing WIM sites on all CoSS should be considered as a goal. VDOT's Chief Engineer and Chief of System Operations should encourage the addition of WIM sites when major projects are planned in locations that are part of the strategic plan for WIM. Site characteristics required for acceptable WIM sensor performance should be specified by VDOT's MEPDG Traffic Data Team.

4. *Staff of VDOT's TED Traffic Monitoring Program should continue monitoring data quality at the DMV WIM sites through periodic contact with DMV staff.* If there are changes to a DMV WIM station such as a pavement resurfacing that may improve the quality of the data to acceptable levels, VDOT should consider re-evaluating that DMV site for inclusion in its truck weight data plan.

5. *VDOT'S MEPDG Traffic Data Team should continue to monitor activities in other states to determine if others have adopted truck weight data plan strategies that may be beneficial to VDOT.*

BENEFITS AND IMPLEMENTATION PROSPECTS

With its current truck weight data plan, VDOT is positioned to implement the MEPDG. The WIM data are an input to the MEPDG process that is expected to provide VDOT with more accurate pavement designs based on traffic loadings in Virginia. The implementation of the recommendations in this study will assist VDOT in using the MEPDG to advance pavement design and improve its cost-effectiveness.

It is difficult to estimate the magnitude of potential benefits because data are not available regarding the frequency of under- and over-designing pavement. However, the magnitude of the potential savings can be illustrated with the following example of over-designing road sections. If the pavement on 10% of the more than 1,000 miles of pavement VDOT places annually could be reduced by ½ in (10% of 1,000 miles times $15,000 per mile), VDOT could save $1.5 million per year. With 5%, the potential savings would be $750,000 per year.

ACKNOWLEDGMENTS

The authors thank Hamlin Williams of VDOT's TED for providing WIM data; Trenton Clark of VDOT's Materials Division for information and insights on MEPDG implementation; Brian Diefenderfer of VCTIR for assistance with pavement design issues; In-Kyu Lim of VDOT's TED for assistance in data conversion; VDOT's MEPDG Traffic Data Team (Trenton

Clark, chair; Tom Schinkel; Hamlin Williams; Richard Bush; Brian Diefenderfer; William Hughes; Affan Habib; and Mohamed Elfino, chair of the overall VDOT effort to implement the MEPDG); Catherine McGhee of VCTIR for serving as the technical review panel; and Linda Evans of VCTIR for editing the report.

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APPENDIX A

SURVEY INSTRUMENT AND ACCOMPANYING EMAIL

Greetings,

The Virginia Department of Transportation is reviewing its truck weight program for traffic monitoring. As part of this effort, I am requesting information on the programs of other state DOTs.

The same form that is below is attached as a Word document in the event that your email software loses the format.

I am requesting that the completed survey and attachments be returned to me by Friday, May 22, 2009.

If you have questions, please contact me.

Thank you.

Ben Cottrell
Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903-2454
(434) 293-1932 FAX (434) 293-1990
Ben.Cottrell@VDOT.Virginia.gov
http://www.vtrc.virginiadot.org

Survey on State DOT Truck Weight Programs

Name ________________________________
State ______________________________
Email____________________________
Phone No.________________________

1. Do you have weigh in motion (WIM) systems? ☐ yes ☐ no If yes, please list how many of each type in the table below. If available, please provide a map displaying your WIM locations.

Type of WIM	**Number of WIM sites**
Load Cells	
Bending Plate	
Piezoelectric	
Quartz Piezoelectric	
Other (describe)	
Total	

2. Did you follow the FHWA's Traffic Monitoring Guide's truck weight section in developing your WIM program? ☐ yes ☐ no

If yes, please provide a list and description of your truck weight groups. Please describe how the groups were developed. If no, how was your program developed?

3. For the mechanistic-empirical pavement design guide, MEPDG, there are three input levels. For Level 1 input, all project-specific data will be collected, including axle load spectra information (and axle loadings by vehicle classification) and vehicle classification counts at the project location. For Level 2 input, regional and project-specific data will be applied. For Level 3 input, estimated project-specific and statewide average or default data will be used in the analysis.
What input level(s) is your state using or plan to use? ☐ 1 ☐ 2 ☐ 3 ☐ don't know (please check all that apply).

For level 2 input, please describe the regions (for example, geographic, climatic, urban and rural, roadway functional classification, etc.) that have been defined for your state. Please provide information on how the regions were determined. If available, please include a map of the regions.

4. Do you use any truck weight data collected by your state's truck weight enforcement program? ☐ yes ☐ no If yes, please provide the number of sites used.

5. How do you determine where (locations) WIM systems are installed?

6. Is your program completed or expanding? ☐ completed ☐ expanding If expanding, please provide the plans for expansion.

7. When a WIM system has served its useful life and needs to be replaced, what do you do?

☐ Replace the WIM system,
☐ Terminate operations,
☐ Relocate the system elsewhere to increase data pool,
☐ Other, please explain. ____________________

8. Do you perform WIM data quality testing to check data accuracy? Please explain the process and frequency.

Thank you.

Please return the completed survey by Friday, May 22 to:
ben.cottrell@vdot.virginia.gov

Ben Cottrell
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(434) 293-1932 FAX (434) 293-1990

APPENDIX B

NUMBER OF DAYS WITHOUT VALID WIM DATA BY MONTH

For each vehicle with valid WIM data detected, an ESAL value was calculated and placed in the study WIM database. When there was no ESAL value on a particular day, that day was defined as a *WIM data missing day*. It should be noted that some sites had WIM sensors installed in the middle of 2007 or lost WIM sensors because of construction projects and only the data that passed VDOT's WIM data quality process were included in the study database. Thus, a large number of days without valid WIM data for a particular WIM site does not necessarily mean that the site had many days of recording WIM data that did not pass the quality process.

Table B-1. Number of Days per Month Without Valid WIM Data

Site ID	Year	Month												Annual Total	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Count**	**%**
1	2007	**31**	**28**	**31**	**30**	**31**	**30**	**31**	**7**	0	0	0	0	219	60
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2007	**31**	**28**	**31**	**30**	**31**	**30**	**31**	7	0	0	0	0	219	60
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2007	0	0	0	0	1	10	31	7	0	0	0	0	49	13
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2007	0	0	0	0	0	10	31	7	0	0	0	0	48	13
	2008	0	0	0	0	18	30	0	0	0	0	0	0	48	13
5	2007	**31**	**28**	**31**	**30**	**31**	**30**	**24**	6	3	0	0	0	214	59
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	2007	7	0	0	15	12	0	0	0	0	0	0	0	34	9
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	0	6	0	0	0	0	0	0	0	6	2
8	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	13	31	30	31	31	30	31	30	31	258	70
9	2007	**31**	**28**	**31**	**30**	**31**	**21**	0	0	21	31	30	31	285	78
	2008	22	0	0	0	1	0	0	0	0	0	0	0	23	6
10	2007	**31**	**28**	**31**	**30**	**31**	**19**	0	0	0	6	4	0	180	49
	2008	0	0	0	0	0	0	1	0	0	0	0	0	1	0
11	2007	0	0	0	0	1	0	0	4	0	0	0	0	5	1
	2008	0	0	0	0	0	2	0	0	0	0	0	0	2	1
12	2007	0	0	0	0	1	0	0	4	0	0	0	0	5	1
	2008	0	0	0	0	0	2	0	0	0	0	0	0	2	1
13	2007	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	2008	0	0	0	0	0	1	0	0	0	0	0	0	1	0
14	2007	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	2008	0	0	0	0	0	1	0	0	0	0	0	0	1	0
15	2007	0	0	0	0	0	0	0	0	4	31	30	31	96	26
	2008	0	0	0	0	0	0	0	0	7	0	0	0	7	2
16	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2008	1	0	0	0	0	0	0	0	0	0	0	0	1	0

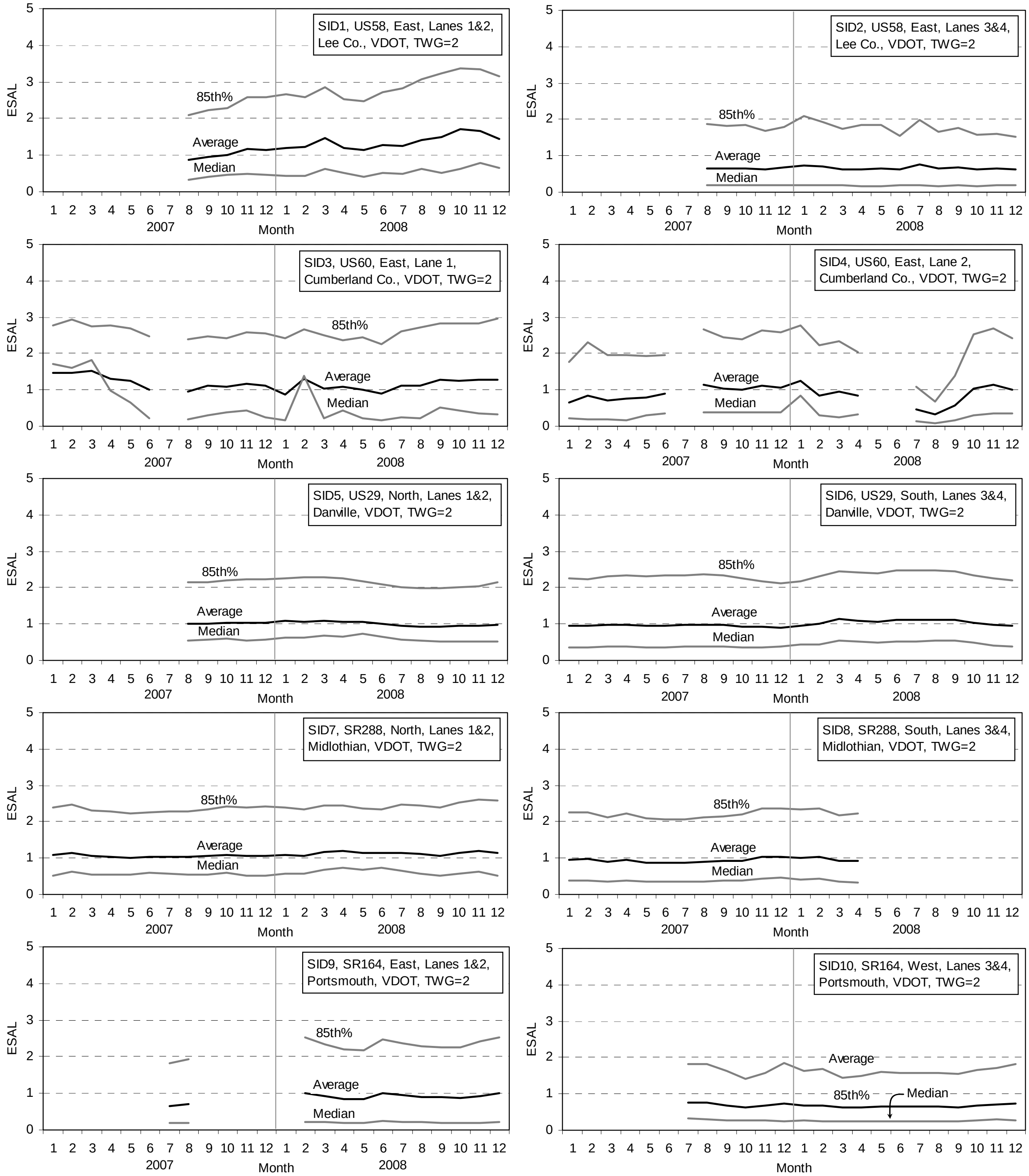
18	2007	**31**	**28**	**31**	**30**	**31**	**30**	**31**	**31**	**30**	**16**	0	0	289	79
	2008	1	0	0	0	0	0	0	0	6	24	23	0	54	15
19	2007	0	0	0	0	0	10	30	0	0	0	0	0	40	11
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	0	0	0	2	0	0	0	0	0	2	1
21	2007	**31**	**28**	**31**	**30**	**31**	**30**	**31**	**31**	**19**	0	0	22	284	78
	2008	0	0	0	0	0	7	0	0	0	0	0	0	7	2
22	2007	0	0	0	0	0	0	0	1	6	29	30	31	97	27
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Numbers in bold represent the number of days in 2007 before the WIM system was operating.

APPENDIX C

MONTHLY ESAL VALUES

Figure C-1 shows the 85th percentile, average, and median ESAL values for each month.



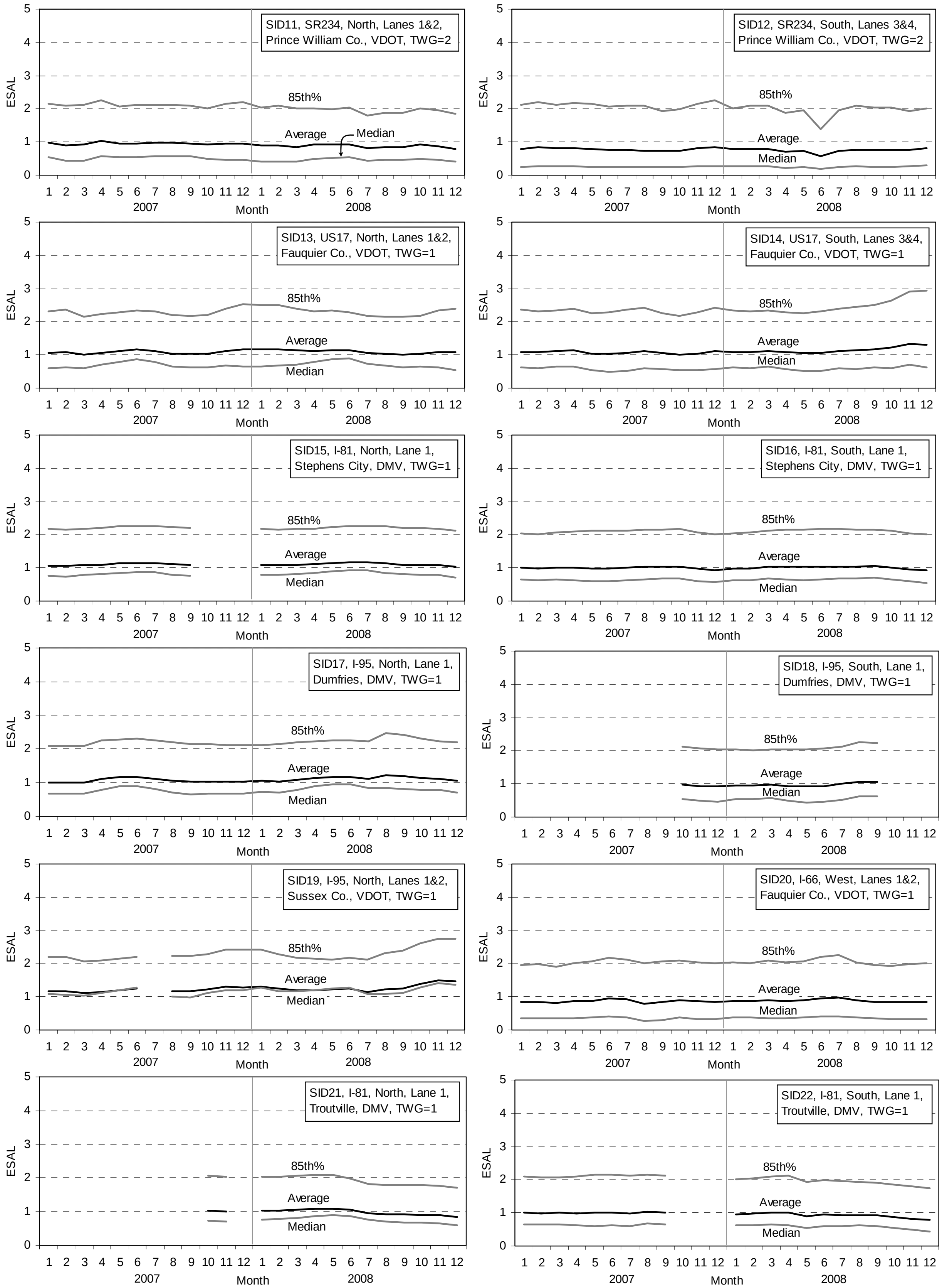


Figure C-1. Monthly Equivalent Single-Axle Load (ESAL) Values. The sites are described in Table 5.

APPENDIX D

EXAMPLE OF DENDROGRAM

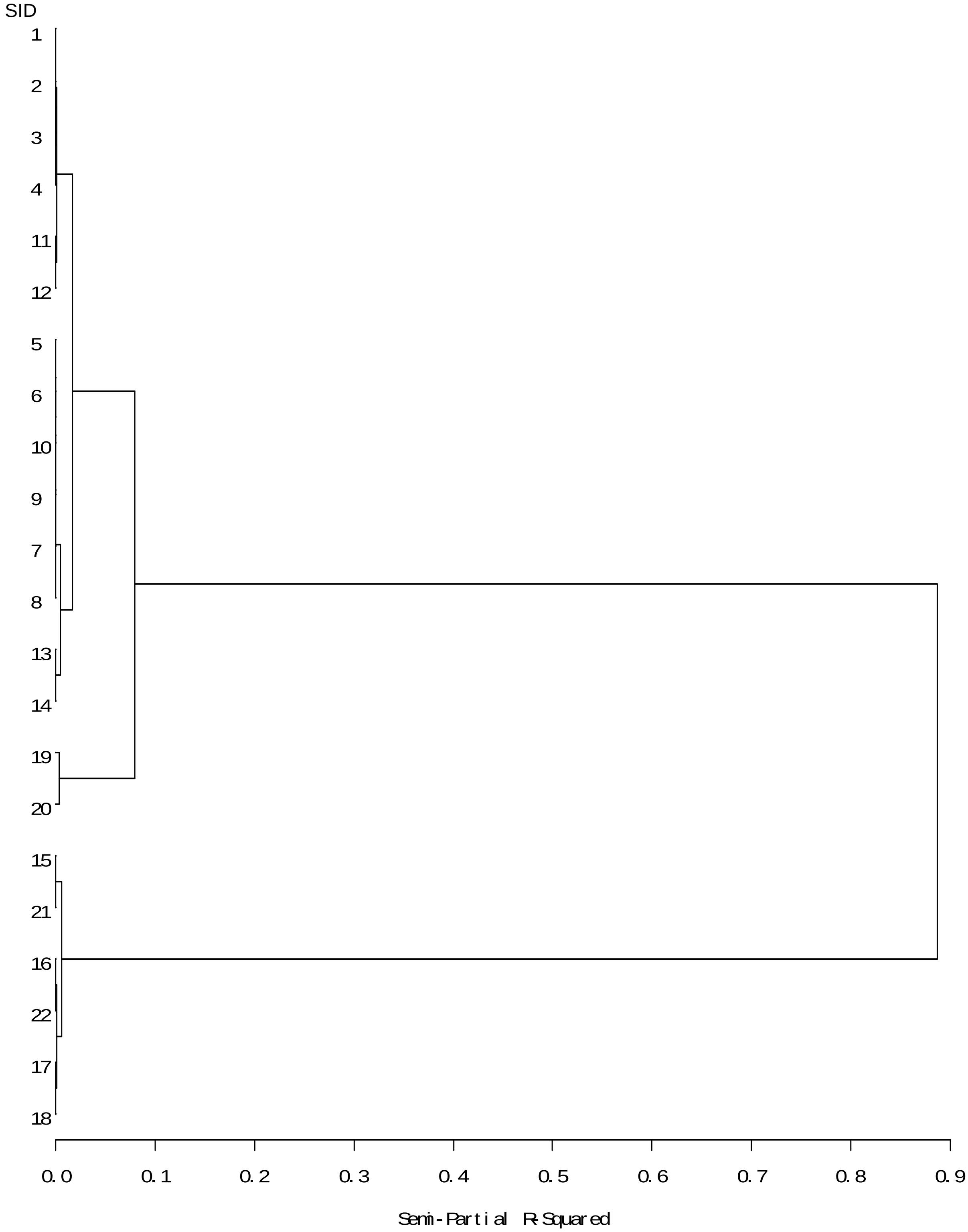


Figure D-1. Dendrogram by Ward's Method Based on Tractor-trailer Trucks per Lane per Day (TTTplpd)

APPENDIX E

WARD'S MINIMUM VARIANCE METHOD

Ward's minimum variance method (called Ward's method) was proposed by Ward (1963) and is one of the divisive hierarchical clustering methods designed to minimize the variance of members within clusters. The divisive methods begin with placing all members in one cluster and dividing the cluster until each member belongs to a cluster where no members other than itself are left, resulting in as many clusters as members. The method tends to produce clusters of near equal size, having hyperspherical shapes. The following descriptions are from SAS Institute Inc. (2008).

In Ward's method,

> the distance between two clusters is the ANOVA sum of squares between the two clusters added up over all the variables. At each generation, the within-cluster sum of squares is minimized over all partitions obtainable by merging two clusters from the previous generation. The sums of squares are easier to interpret when they are divided by the total sum of squares to give proportions of variance (squared semipartial correlations) (SAS Institute Inc., 2008).

The distance between two clusters is defined by

$$D_{AB} = \frac{\left\| \bar{\mathbf{x}}_A - \bar{\mathbf{x}}_B \right\|^2}{\frac{1}{N_A} + \frac{1}{N_B}}$$

where A and B = two clusters
$\bar{\mathbf{x}}_A$ = a vector of sample mean for Cluster A,
N_A =number of members in Cluster A, and
$\| \;\; \|$ =Euclidean distance.

Ward's method is one of the most frequently employed methods, and the average linkage and Ward's method show the best overall performance according to simulation studies (SAS Institute Inc., 2008). The method tends to join clusters with a small number of observations, and it is strongly biased toward producing clusters with roughly the same number of observations. It is also very sensitive to outliers (Milligan, 1980).