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EVALUATION OF TRUCK LANE RESTRICTIONS IN VIRGINIA

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Supplementary Notes

Abstract

A number of states have implemented truck lane restrictions in an attempt to improve safety and mobility on freeways. These restrictions typically prohibit trucks from traveling in the median lane, potentially increasing passing opportunities and reducing negative interactions between slow-moving trucks and other vehicles. Virginia currently has two forms of truck restrictions in place. The first type of restriction prohibits trucks from the median lane of interstates that have three or more lanes by direction, provided certain criteria on speed limit and location are satisfied. The second type of restriction prohibits trucks from traveling more than 15 mph below the posted speed limit in the left lane of two-lane directional interstate segments.

This report documents the results of a safety and operational evaluation of Virginia's truck lane restrictions. Crash data were examined at a total of 43 sites with restrictions and 16 similar sites without restrictions. Likewise, operational data were collected at 7 sites with restrictions and 6 similar sites without restrictions. The results of the analysis showed that the restrictions on two-lane sites appeared to be having a positive impact on operations and safety. At these sites, crashes were reduced by 23 percent, and speeds were estimated to have increased by 5.5 mph. At the three-lane sites, no statistically significant increase in speed was observed. A breakpoint in crash performance appeared to occur at approximately 10,000 vehicles per day per lane. Roads below this threshold experienced significantly fewer crashes than anticipated, whereas roads above this level had significantly more crashes than expected.

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ABSTRACT

A number of states have implemented truck lane restrictions in an attempt to improve safety and mobility on freeways. These restrictions typically prohibit trucks from traveling in the median lane, potentially increasing passing opportunities and reducing negative interactions between slow-moving trucks and other vehicles. Virginia currently has two forms of truck restrictions in place. The first type of restriction prohibits trucks from the median lane of interstates that have three or more lanes by direction, provided certain criteria on speed limit and location are satisfied. The second type of restriction prohibits trucks from traveling more than 15 mph below the posted speed limit in the left lane of two-lane directional interstate segments.

This report documents the results of a safety and operational evaluation of Virginia's truck lane restrictions. Crash data were examined at a total of 43 sites with restrictions and 16 similar sites without restrictions. Likewise, operational data were collected at 7 sites with restrictions and 6 similar sites without restrictions. The results of the analysis showed that the restrictions on two-lane sites appeared to be having a positive impact on operations and safety. At these sites, crashes were reduced by 23 percent, and speeds were estimated to have increased by 5.5 mph. At the three-lane sites, no statistically significant increase in speed was observed. A breakpoint in crash performance appeared to occur at approximately 10,000 vehicles per day per lane. Roads below this threshold experienced significantly fewer crashes than anticipated, whereas roads above this level had significantly more crashes than expected.

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INTRODUCTION

Large trucks and passenger vehicles can have dramatically different performance characteristics even though they travel on the same roads. Disparities in acceleration performance can create situations where there are large differences in the travel speeds of different vehicle types especially on roads in mountainous regions that have steep grades. Differences in speeds have the potential to impact both the safety and operations, and a number of transportation agencies have sought to mitigate these problems using a variety of techniques. One potential method to address speed differentials is to restrict trucks from traveling on certain lanes on a highway. This may help reduce the number of interactions between slow-moving trucks and passenger vehicles by creating passing opportunities for faster-moving passenger vehicles.

The Virginia Department of Transportation (VDOT) was charged with implementing the truck lane restrictions that are included in the Code of Virginia. These restrictions were enacted in 1997 and subsequently expanded in 2000 and 2004. The full text of the relevant section of the Code is included in Appendix A. The specific restrictions in the Code are:

- When the posted speed limit is 65 mph, commercial motor vehicles are prohibited from the left-most lane of any interstate highway having more than two lanes in each direction. This was enacted in 1997.

- In the Eighth Planning District (analogous to VDOT's Northern Virginia District) and on I-81, commercial motor vehicles are prohibited from the left-most lane of any interstate highway having more than two lanes in each direction, regardless of the posted speed limit. This was enacted in 2000.

- Every commercial motor vehicle must keep to the right-most lane when operating at a speed of 15 mph or more below the posted speed limit on an interstate highway with two lanes in each direction. This portion of the Code took effect in July 2004.

These provisions do not apply to buses, when a commercial vehicle is entering or exiting a highway using a left side ramp, or for vehicles being used to perform maintenance or construction work. Violations of these restrictions are classified as traffic infractions and are subject to a fine of up to $250 and 3 points on the driver's license. Representatives of the Virginia State Police have indicated that enforcement of these restrictions has not been a priority due to manpower limitations.

Virginia's restrictions can be broadly separated into the restrictions for three or more lane facilities and the speed-dependent two-lane restrictions. These different types of restrictions will be referred to as "three-lane" and "two-lane" restrictions, respectively, in the remainder of this report. For the three-lane restrictions, trucks are prohibited from the left lane. Figure 1 shows the regulatory signs posted at all three lane sites where restrictions apply. These restrictions are relatively straightforward, and the restrictions exist only on roads where signs are posted.

Figure 1. Truck Restriction Signs Used on Interstates with 3 or More Directional Lanes

The two-lane restrictions are a relatively recent addition to the Code. These restrictions were enacted to provide a low-cost substitute for truck climbing lanes. In fact, the 15 mph threshold was derived from warrants used to determine when a truck climbing lane should be provided.[1] The two-lane restrictions are intended to force slow-moving trucks to travel in the right lane, thereby allowing faster vehicles to pass. These restrictions apply to all two-lane interstates segments, but VDOT has installed signs only at the base of steep upgrades where trucks are most likely to decelerate substantially below the speed limit. Figure 2 shows the signs posted at two-lane sites with steep grades. The appropriate VDOT district traffic engineer (DTE) was responsible for determining the location of these problem areas in conjunction with the Virginia State Police.[2]

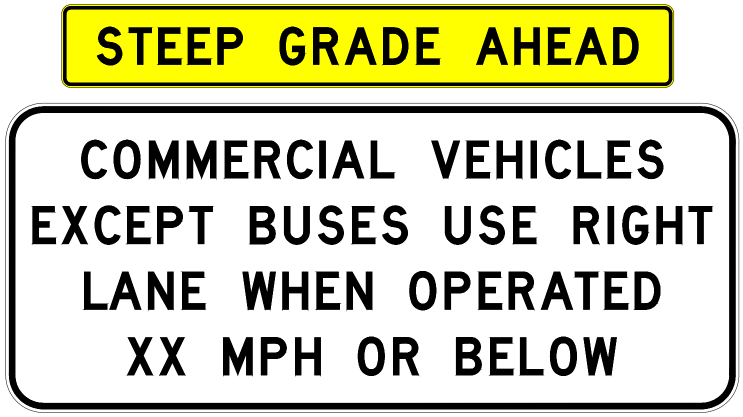

Figure 2. Truck Restriction Signs Used on Interstates with 2 Directional Lanes

Although some truck restrictions have been in effect for nearly a decade, there has not been a formal evaluation of the safety or mobility impacts of the restrictions. Furthermore, studies in other states have produced results that are often inconclusive or based on limited data sets. Given that a number of years have passed since restrictions were first installed, it should be possible to determine whether Virginia's restrictions have been having a positive impact on safety and mobility. This report assesses whether the restrictions have had a positive impact since they were installed.

PURPOSE AND SCOPE

The purpose of this project was to examine the impact of truck lane restrictions on traffic operations and safety on interstate highways. The specific objectives of the project were:

1. Assess the level of compliance with Virginia's truck lane restrictions.

2. Determine the safety impact of truck lane restrictions on Virginia interstates.

3. Examine the operational impact of truck lane restrictions on traffic operations on interstate highways.

4. Identify potentially beneficial modifications to the Code of Virginia, if warranted.

The three-lane and two-lane restrictions were evaluated. The scope of this project was limited to access-controlled freeways, and truck restrictions on signalized arterials were not explicitly examined.

METHODOLOGY

The methodology used in this research consisted of five major tasks. First, the literature was reviewed to identify other studies that have examined the safety or mobility impacts of truck lane restrictions. The second and third tasks involved identifying sites with lane restrictions and then collecting detailed geometric and traffic data. Fourth, traffic operations and safety at the sites with truck restrictions were examined, and, fifth, the impact of the restrictions was estimated.

Literature Review

The VDOT Research Library, the University of Virginia library, and relevant Transportation Research Board databases were used to identify research that examined the operational and safety effects of truck lane restrictions. Field studies and simulation evaluations were examined to determine potential impacts of truck lane restrictions.

Site Identification

The next major task was to identify locations on Virginia interstates that had truck lane restrictions in place. VDOT DTEs were asked to identify interstate segments that have truck lane restrictions. The DTEs provided information on:

- the start and end point of posted truck lane restrictions
- the number of directional lanes on the segment
- the posted speed limit
- the date the restrictions were installed.

The DTEs were also asked to list any major construction or maintenance projects that occurred in the vicinity of the sites. Since long-term work zones or changes in traffic control could have a significant impact on crash history, those sites were not used in the safety or operational analysis. VDOT's Traffic Monitoring System (TMS) was used to determine traffic volumes and truck percentages at the sites provided by the DTEs.

Collection of Geometric Data

After the districts identified sites with truck lane restrictions, it was necessary to collect detailed geometric data from those sites. Site geometry, especially the grade of the road, can significantly impact the operations of large trucks, so it was critical to have consistent, accurate data for all of the sites identified.

A site visit was made to each location that was identified by the districts, and a global positioning system (GPS) unit was used to collect the horizontal and vertical profile of the road. A vehicle was driven over the route being studied while the GPS collected data every second. The vehicle was driven at approximately 60 mph, so a location reading was collected approximately every 88 feet. The vertical accuracy of the GPS unit used was about 10 meters. Although the GPS unit's vertical accuracy was not as good as its horizontal accuracy, errors in grade estimation could be minimized by examining a series of vertical position estimates.

Regression was used to smooth these position estimates and develop a vertical profile of the road that could be used estimate the average sustained grade. An example of the raw and smoothed elevation information is shown in Figure 3. Figure 3 shows that the original raw data possesses some minor fluctuations due to positioning error. The data have been processed to produce a smooth linear approximation of the roadway grade. Although horizontal curvature data were collected with the GPS, it was used only to develop the roadway grade estimates. Horizontal curvature was not explicitly examined in the analysis. This process was completed for each of the sites identified by the DTEs.

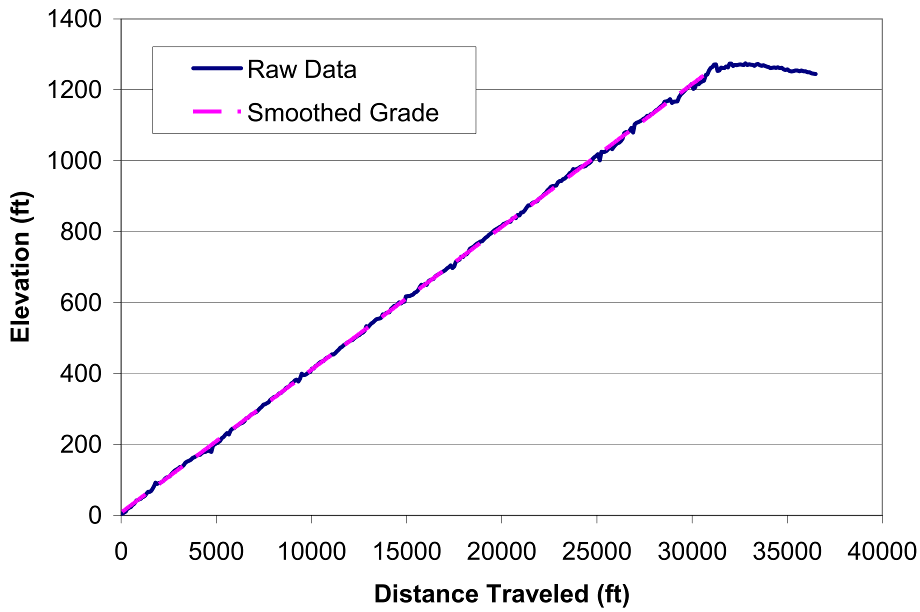

Figure 3. Raw and Smoothed Grade Data for I-77 Northbound

While the GPS data were being collected, a distance measuring instrument (DMI) was used to identify the location of significant traffic control and geometric features. Speed limit signs, freeway ramps, truck restriction signs, and changes in cross section were noted using the DMI measurements. DMI measurements were estimated to be accurate to within 1 foot of reality. The locations of these features were then related to the GPS data so that the location of major features could be related to the vertical profile of the road.

Safety Analysis of Sites with Truck Restrictions

One of the intended purposes of truck lane restrictions is to improve safety by reducing interactions between slow-moving trucks and passenger vehicles. A number of studies have shown high speed variance can be a significant factor in dictating the number of crashes that occur on a road.[3,4,5,6,7] It seems plausible that truck lane restrictions could improve safety by reducing the speed variance between trucks and passenger vehicles in the median lane of highways. As a result, the potential safety impacts of the restrictions were evaluated to determine whether any tangible improvements in safety were created by implementing the restrictions.

The safety analysis of the three-lane and two-lane sites had to be tailored to fit the available data and the manner in which the restrictions were implemented. In the case of the three-lane sites, 3 to 9 years of data were available from the period after the lane restrictions were installed. There were also similar comparison sites available where restrictions were not installed. This allowed for a robust analysis of the safety impacts of the restrictions on those facilities. For the two-lane sites, only one year of crash and traffic volume data was available from the time the restrictions were installed. Furthermore, there were no directly comparable sites that did not have restrictions since the restrictions were implemented on all interstates simultaneously. Given these distinctions, the methodologies used to analyze the safety effects of the three-lane and two-lane restrictions varied. The two approaches are discussed in the following sections.

Three-Lane Sites

The crash data from the three lane sites were analyzed using the Empirical Bayes (EB) approach. The EB method uses crash data from sites with and without truck lane restrictions to develop crash estimation models. The crash estimation models serve to predict the number of crashes that would have occurred at sites that have restrictions had the restriction not been implemented. This method requires data from sites with restrictions ("test sites") and from similar sites that did not have restrictions installed ("comparison sites"). This method controls for regression-to-the-mean bias, and explicitly accounts for the impact of a number of factors that we expected to influence crash frequency, such as traffic volume. Another advantage of the EB method is that it can easily examine a large number of sites where the treatment being evaluated was installed at different times. The procedures developed by Hauer[8] were used to conduct the EB analysis.

Crash data were obtained for the years 1998 through 2005. Personnel in the VDOT Traffic Engineering Division indicated that the average annual daily traffic (AADT) estimates for the years prior to 1998 could be inconsistent with later estimates, so the data analysis was limited to the years where the AADT estimates were deemed to be reasonable. A custom spreadsheet developed by the Virginia Transportation Research Council (VTRC) was used to perform the EB analysis.

Identification of Test and Comparison Sites

The first major task in the EB analysis was to identify test and comparison sites. The test sites consisted of the locations identified earlier by the DTEs that did not have major work zones during the study period. Major interchange reconstruction projects, major bridge rehabilitation projects, and roadway widening are examples of work zone activities that caused sites to be eliminated from the analysis. To conduct the EB analysis, comparison sites that were similar to the test sites had to be identified so that the crash estimation models developed would be valid.

The VDOT TMS was used to identify interstate highways with three or more lanes and AADT values within 10,000 vehicles per day of the test sites. This value was selected to generate a reasonably large pool of candidate sites, while simultaneously ensuring that the traffic volumes of the test and comparison sites were relatively similar. Furthermore, comparison sites needed to be similar in length to the test sites and no major work zones could have been in effect during the study period. Given that restrictions had been extended to all of I-81 and Northern Virginia, most comparison sites were located around Richmond or Hampton Roads. Relevant traffic and crash data were collected for all comparison sites identified.

Construction of the Crash Estimation Model

Data from periods when sites did not have restrictions installed were used to create a crash estimation model that predicts the number of crashes as a function of a variety of factors. These data came from the comparison sites, as well as the time periods at the test sites when no restrictions were present. The crash estimation model used takes the form:

$$Crashes = \alpha_y \left(Factor_1\right)^b \left(Factor_2\right)^c \ldots \left(Factor_n\right)^n$$

The factor α_y is a parameter that varies according to the specific year being predicted, and *Factor* is the variable being used to predict crash frequency. The α_y factor indirectly controls for a number of variables that cannot be directly accounted for, such as the influence of weather, changes in the vehicle fleet, and improvements to guardrail design or emergency medical response. The specific factors that were examined in the model included:

- average segment AADT
- average segment truck AADT
- length of segment (in miles)
- number of basic freeway lanes in the segment
- number of interchanges in segment
- posted speed limit in segment.

An iterative process was used to examine all of these factors using the VTRC spreadsheet. This process identified which variables were significant through iteration, with non-significant factors having coefficients of zero. The model that produced the best fit was then used to perform the evaluation.

Safety Evaluation

The EB method was used to generate predictions of the number of crashes that would have occurred at the test sites had no truck lane restrictions been installed. The predicted crashes are developed using the crash estimation model and applying relevant correction factors. Comparing the actual crashes that were observed at the site to the predicted crashes allows the estimated impact of the restrictions to be assessed. Four types of crashes were examined to determine the impact of the truck lane restrictions on safety:

1. total number of crashes
2. number of injury and fatal crashes
3. total number of crashes involving large trucks
4. number of injury and fatal crashes involving large trucks.

A crash was determined to have involved a truck if any one of the vehicles involved was a truck. This does not imply that the truck caused the crash. Rather, it simply means that one of the vehicles involved in the crash was a truck.

For each crash type, two measures of effectiveness were used. First, the estimated change in the number of crashes was determined by comparing the predicted number of crashes to the actual number of crashes at the sites with truck lane restrictions. Second, the index of effectiveness, θ, was calculated. The θ value shows the ratio of the crashes that actually occurred to what was predicted. A θ less than 1.0 shows a positive safety benefit, and those greater than 1.0 indicate that more crashes occurred than were predicted based on the control data and pre-existing conditions. A 95^{th} percentile confidence interval was constructed for both of these measures to determine whether the estimated changes were statistically significant.

Two-Lane Sites

Since the restrictions were implemented on a statewide basis on the interstate system, there were few relevant comparison sites. As a result, a robust method like EB analysis could not be used to analyze these data. The sites with two-lane restrictions that were identified by the DTEs were subjected to a two stage analysis. First, crash rates and crash frequencies were compared without using any formal statistical analysis. Second, a naïve before-and-after study using the methodology suggested by Hauer[8] was performed on the crash frequency. This methodology was used to compare data from 4 years prior to the installation of the two-lane restrictions to the year after installation. The following crash statistics were analyzed using the before-and-after design:

- total number of crashes
- number of injury and fatal crashes
- total number of crashes involving large trucks
- number of injury and fatal crashes involving large trucks.

The naïve before-and-after analysis of crash frequency has some limitations. First, it contains the underlying assumption that the same crash trends in the before period will continue during the after period. Thus, detailed crash estimation models are not developed, and it is simply assumed that crash trends at the sites would have been the same during the "before" and "after" periods had the truck restrictions not been installed. This may not be accurate, as it does not account for random variation or systematic differences due to factors like the weather. Furthermore, it does not directly account for regression-to-the-mean bias. Part of the reason for limiting the "before" period to 4 years was to reduce some of the impacts of changing traffic volume or other large-scale, systemic changes that could impact the crash estimates. Despite these limitations, this study design appears to be the best option available given that there were not enough comparison sites to perform a more robust study design. Once again, the differences in predicted versus observed crashes and the index of effectiveness were used to evaluate the effect of truck lane restrictions.

Operational Data Collection and Analysis

A field evaluation was also conducted to determine the operational impact of Virginia's truck lane restrictions. Unfortunately, the three-lane and two-lane restrictions were implemented without any detailed operational data being collected prior to the installation of the restrictions. Thus, the data do not exist to do a direct before-and-after comparison of operations at a specific site. To overcome this limitation, operations at sites with restrictions had to be compared to other sites without restrictions that had similar geometric and traffic characteristics to estimate the likely impact of the restrictions. The methods used to collect operational data at the three-lane and two-lane sites were very similar, but different analytical methods were required due to the characteristics of the two types of restrictions.

Site Identification

The initial task in the operational analysis was to identify sites with restrictions that were comparable to sites that did not have restrictions. For the three-lane sites, the traffic volumes, truck percentages, and geometry were examined for the sites with restrictions. The VDOT TMS was then used to identify other interstate locations without restrictions that had similar traffic characteristics. The comparison sites were further narrowed to roads that had similar cross sections to the test sites.

Identification of comparison sites for the two-lane restrictions was more complicated. Since the two-lane restrictions were applied to all interstates in 2004, it was necessary to search for comparison sites on the primary system. Initially, the VDOT TMS was searched to identify segments of primary road where the traffic volumes and truck percentages were comparable to the interstate sites. Next, the list of candidate sites was narrowed to roads in the VDOT Staunton, Salem, and Bristol districts to make it more likely that the road would be located in mountainous terrain that would be more likely to have long, steep grades. Next, the VDOT geographic information system (GIS) Integrator video log was used to perform a virtual "drive through" of the sites. The purpose of the drive through was to screen out sites that did not appear to function in a manner similar to a limited access facility or had speed limits below 55 mph. Roadways with frequent driveways and traffic signals were eliminated from further consideration. This left a list of candidate primary road segments that were either limited access or had little or no access points.

GPS data were then collected on these candidate segments to determine the horizontal and vertical profile of the roads. These data were collected in the same manner as the data on the test site profiles that were collected earlier. GPS data were collected on more than 336 miles of primary roads in Virginia. DMI data on the locations of major geometric features and traffic control elements were also collected. The elevation data were processed to determine specific locations on the candidate segments that had grades that were comparable to what was observed for the two-lane sites with restrictions. In the end, comparison sites were selected that had traffic volumes and grades that were similar to the sites with restrictions.

Data Collection

The VTRC Smart Travel Van (STV) was used to collect data on individual vehicle performance at the three-lane and two-lane sites. The STV uses video detection to collect traffic characteristics of vehicles as they pass by the STV. The STV set up proved to play a critical role in collecting accurate traffic data. The STV was typically parked on the right shoulder of a highway close to the right edge line. The STV was positioned to balance the goals of getting as close to the edge line as possible, while simultaneously providing enough space between the STV and traffic to ensure safety and minimize the impact on lane choice. If not positioned properly, large trucks can occlude the view of vehicles on the lanes further from the STV. These large trucks would block the view of vehicles in neighboring lanes, resulting in the STV undercounting traffic or creating errors in speed estimation. The STV camera was oriented as close to straight down as possible to minimize occlusion effects.

The STV location varied according to site characteristics. When data were being collected in urban areas, the STV was located at least 0.5 mile from any entrance or exit ramps so that ramp impacts could be minimized. In locations where there was a steep grade (as in all of the two-lane sites) the STV was located as close to the top of the grade as possible. This created a "worst case scenario" for the trucks where they had the potential to decelerate significantly.

Prior to recording any data, the speed data collected by video detection system were compared to measurements collected by the data collection team using a lidar speed detection unit. A lidar unit functions in the same manner as a radar unit, only it uses lasers to measure vehicle speeds instead of radio signals. The lidar allows for more precise speed measurements and can more accurately detect speeds of individual vehicles in traffic than a radar unit. Calibration factors in the STV were then modified to ensure that the video detection system produced speed estimates that were in agreement with the lidar data. The STV produced a text file with traffic data, and the video feed was also recorded to videotape. The data collected included:

- vehicle speed (mph)
- vehicle lane number
- length of vehicle (ft)
- the time the vehicle was detected.

These data were collected for a minimum of 4 to 8 hours at each site during daylight conditions. The quality of the data collected by the STV was checked once data collection was complete by comparing the videotape to the text data file. False activations or cases of occlusion were identified, and the text data file was modified to ensure that only correct data were retained.

The STV offers the ability to collect detailed, individual-level vehicle information in a non-intrusive manner. Although the STV enables data to be collected quickly and safely on high-volume roads, it does have some limitations. One potential concern is that the STV may have some influence on traffic behavior. Traffic control for a shoulder closure had to be set up while the STV was being operated, and the presence of the STV could potentially impact speed or lane choice decisions. The data collection technician visually observed the oncoming traffic to determine whether the van appeared to be impacting lane choice decisions. Specifically, the technician looked for vehicles moving out of the right lane in the upstream of the van. The technician did not observe any obvious impact on lane choice at any of the sites. Although the STV had the potential to influence lane choice, the van did not appear to produce any significant effect during data collection.

Three-Lane Data Analysis

The data analysis for the three-lane sites focused on three areas. First, the proportion of trucks traveling in the left lane was compared between sites with and without restrictions. Second, the proportion of trucks in the left lane that were impeding traffic was investigated. Third, the impact of the restrictions on overall travel speed was examined.

Compliance with Restrictions

The first major task was to assess whether trucks were complying with the posted restriction. The percentage of trucks traveling in the left lane was compared between the sites with and without restrictions. A Chi-square analysis was performed to determine whether there was a significant difference in the lane distribution of trucks between the sites with and without restrictions. Analysis of variance (ANOVA) was used to determine whether fewer trucks were traveling in the left lane at the sites with restrictions. This analysis was intended to determine whether the restrictions were creating a significant difference in lane distribution.

Trucks Impeding Flow

An underlying premise behind implementing truck lane restrictions is that many slow-moving trucks are traveling in the left lane, reducing the travel speed of passenger cars behind them. Whether a vehicle is impeding traffic was determined by examining headways. When a vehicle had a headway value of at least 3 seconds, it was considered to be traveling in an unimpeded manner. Thus, if a leading vehicle in a platoon was traveling with a headway of at least 3 seconds and was followed by other vehicles with headways less than 3 seconds, the lead vehicle was considered to be impeding the flow of the trailing vehicles. The 3-second headway criterion for free flow was derived from the *Highway Capacity Manual*.[9] The number and percentage of trucks impeding flow in the left lane were determined in order to identify the magnitude of this problem.

Impact on Speeds

Finally, analysis of covariance (ANCOVA) was used to assess whether the truck lane restrictions were having an impact on average travel speed. The following factors were analyzed using ANCOVA:

- presence or absence of restriction (categorical variable)
- 15-minute truck flow
- 15-minute overall flow.

ANCOVA allows the speed analysis to control for flow rates which could cause speeds to decline. Since all of the three-lane sites examined were located on level terrain, grade was not included as a factor. This analysis was used to examine overall speed on the road, as well as the speed differential between the left and center lane. This speed differential was analyzed to determine if there was the potential for significant speed variance between neighboring lanes.

Two-Lane Analysis

The operational analysis for the two-lane sites differed somewhat from the three-lane analysis. Since the restriction is speed dependent, the analysis focused on those extremely slow speed vehicles that were traveling in the left lane. The methods used to analyze the two-lane sites are described here.

Compliance with Restrictions

For the two-lane sites, a variety of factors could impact compliance with the restrictions. In contrast to the three-lane sites, the two-lane sites all involved steep upgrades. As a result, stepwise regression was used to analyze compliance as a function of:

- presence or absence of restrictions (categorical variable)
- hourly truck volume
- hourly total volume
- roadway grade
- length of grade.

The interaction of these factors was also examined to determine whether the presence of restrictions impacted the number of slow moving trucks in the left lane.

Trucks Impeding Flow

The number of trucks impeding flow was analyzed in the same manner as it was for the three-lane sites. The number and percentage of trucks impeding flow were examined to determine the extent to which slow-moving trucks were reducing the speed of other traffic. The number of non-trucks traveling at slow speeds in the left lane was also examined to determine whether trucks were the primary cause of delays.

Impact on Speeds

Finally, ANCOVA was again used to assess whether the truck lane restrictions were having an impact on average travel speed. The following factors were analyzed using ANCOVA:

- presence or absence of restriction (categorical variable)
- 15-minute truck flow

- 15-minute overall flow
- length of grade
- magnitude of grade.

This analysis allowed for geometric and traffic conditions to be controlled so that the potential impact of the truck lane restriction could be isolated.

RESULTS

The results of the literature review, safety analysis, and operational analysis are discussed in this section. The safety and operational analysis for the three-lane and two-lane restrictions are discussed separately.

Literature Review

Studies of truck lane restrictions can be generally categorized into field tests and simulation studies. Field tests provide insight into actual performance observed under real world conditions, but location-specific characteristics can limit the extent to which the findings can be generalized to other situations. Simulation studies can provide valuable insights into general trends in the performance of restrictions, but they sometime suffer from simplifications in model formulation. Major studies of the impact of truck lane restrictions are briefly reviewed in this section.

Field Tests

A survey conducted by FHWA in 1988 found that 26 states used some form of truck restrictions.[10] The objectives of those restrictions varied, but they were usually implemented to improve operations, reduce crashes, or preserve deteriorating pavement. Although the use of truck lane restrictions is widespread, in most cases no objective data on the impact of the restrictions on operations or safety were collected. In many cases, the restrictions were implemented for political reasons and lacked any type of formal analysis of their impact following installation. In cases where evaluations were performed, the amount of data used to assess the impact of the restrictions was often limited. Cases where an evaluation did occur are briefly summarized in the following sections.

Broward County, Florida

In 1988, Broward County conducted a 6-month experiment that restricted trucks from the left lane on a three-lane directional segment of I-95 between 7 A.M. and 7 P.M.[10] The truck restrictions were implemented in conjunction with a coordinated enforcement and education campaign, and signs noting the restrictions were posted every mile. Compliance with the restrictions was high, with 2 percent of trucks traveling in the restricted lane. Crash data from the period where truck restrictions were in effect showed that the overall crash rate increased by 6.3 percent, and the crash rate involving trucks with 3 or more axles declined by 3.3 percent.

These crash results should be viewed with caution, however, given that they were based on only 6 months of data.

I-75 in Florida

Trucks were restricted from the left lane in each direction over 139 miles of I-75 in an attempt to improve operations and safety.[11] This stretch of I-75 was a six-lane facility. The researchers examined 1 day of data at a station in the corridor to examine compliance and speeds. The analysis showed that approximately 1 percent of the trucks were in violation of the restriction. Data also showed that the restrictions did not produce any statistically significant effect on truck speeds or travel times within the corridor.

Louisiana

In 1982, Louisiana installed 6 truck restriction signs on 190 miles of I-20.[10] These were advisory signs that asked trucks to drive in left lane due to pavement deterioration in right lane. The signs were only posted at truck weigh stations along I-20, so only long-distance truck drivers were likely to see the signs. Data showed that between 16 and 21 percent of trucks shifted from the right to the left lane. The impact on safety was inconclusive. Crashes on I-20 were found to have increased but the total vehicle miles of travel (VMT) also increased, making it difficult to determine if the change in crashes was due to increased exposure or actual negative safety effects of the restrictions.

Washington, D.C., Beltway

In 1984, Virginia implemented truck restrictions on I-95 between I-395 and the Woodrow Wilson Bridge.[10] These restrictions were specific to the Beltway and were not part of the wider truck restriction legislation that was enacted later. All trucks were restricted from the left lane, and trucks transporting hazardous materials were restricted to the right two lanes. An analysis of this section conducted in 1985 showed a slight overall decline in crash rate and crash severity. An additional study of this section was later conducted using 2 years of data before the restriction was implemented and 2 years after it was installed. That analysis showed that crash rate increased by 13.8 percent following the installation of the restriction, but the severity of crashes did not change. A third study in 1988 confirmed that truck crash rate increased in the sections where restrictions were present, and recommended removal of the restrictions.

Texas

Truck restrictions were implemented and tested on three six-lane freeways in Texas.[12] In all cases, the trucks were restricted from the left lane. The sites evaluated included:

- a 5-mile segment of I-10 near Houston with an AADT of 32,000
- a 9-mile segment of I-20 near Fort Worth with an AADT of 39,000
- a 9-mile segment of I-35E near Dallas with an AADT of 87,000.

Table 1 shows the percentage of trucks that were traveling in the left lane before and after the restrictions were enacted. Between 1 and 6 percent of all trucks were not complying with the restrictions. There was a statistically significant decrease in the percentage of truck traffic in the left lane following the implementation of the restrictions for all sites except I-10 WB. The researchers also examined time gaps and speeds to try to ascertain the impact of the restrictions on operations. No statistically significant impact on the time gap between vehicles was found. The impact on travel speeds was also minimal, with speeds changing by less than 1 mph following implementation of the restrictions.

Table 1. Trucks in the Left Lane Before and After Restrictions in Texas

Site	Time Period	% in Left Lane Before	% in Left Lane After	Difference (%)
I-10 WB	All	3.8	2.5	-1.3
I-10 EB	All	5.2	1.3	-3.9
I-20 WB	Peak	8.9	3.2	-5.7
	Non-peak	5.3	1.3	-4.0
I-20 EB	Peak	11.7	4.4	-7.3
	Non-peak	7.9	2.9	-5.0
I-35E NB	Peak	14.3	2.4	-11.9
	Non-peak	8.2	3.1	-5.1
I-35E SB	Peak	8.5	5.9	-2.6
	Non-peak	8.6	3.3	-5.3

The researchers conducted a series of driver surveys at the I-20 site to gauge whether the public would accept the truck restrictions. Prior to installation of the restrictions, 60 percent of passenger vehicle drivers were in favor of the restrictions, whereas only 28 percent of the truck drivers were. A follow-up survey was conducted after the truck restriction was installed.[12] The survey showed that 68 percent of the drivers surveyed and 76 percent of the truck drivers noticed the restrictions. Perceptions of the effectiveness of the restrictions were mixed. For passenger vehicle drivers, 45 percent said that the restrictions improved operations, 43 percent were not sure, and 12 percent said they degraded operations. Truck drivers generally had a less positive view of the restrictions, with 20 percent saying that operations had improved, 28 percent unsure, and 52 percent saying that operations were worse.

A more recent study examined safety and operations on freeways in the Houston area with truck lane restrictions.[13] This study examined four freeways in the Houston area: U.S. 290, Texas State Highway 225, I-10, and I-45. The sections studied were up to 20 miles long, and all had at least 3 lanes by direction. Trucks were restricted from the median lane at all sites. The percentage of trucks traveling in the left lane was between 0.6 and 2.8 percent of all trucks, indicating that compliance with the restrictions was reasonably good. Although compliance with the restrictions was good, the researchers did not find any significant improvement in travel speeds.

Seattle Area

A 1993 study examined the operational impact of truck restrictions at 3 sites in the Seattle area.[14] All sites had a posted 55 mph speed limit, and trucks comprised between 2 and 3 percent of the traffic stream. The sites examined included:

- a 3-mile segment of I-5 SB that had 5 lanes and a grade of +4 percent
- a 1.4-mile segment of I-5 SB that had 4 lanes and a grade of +3 percent
- a 1-mile segment of SR 520 WB that had 3 lanes and a grade of +5.1 percent.

For the 3- and 4-lane segments, trucks were restricted from the far left lane. For the 5-lane segment, trucks were restricted from the leftmost 2 lanes.

In general, the impact of the restrictions on operations was found to be limited. The researchers found that the proportion of trucks traveling in the restricted lanes remained the same before and after the restrictions were implemented. About 2.1 percent of trucks traveled in the restricted lanes in both cases, although non-compliance increased during congestion. The mean speed of non-truck traffic increased by 0.7 mph. This was found to be statistically significant, but may not have a large degree of practical significance.

Wisconsin and Chicago Area

A before-and-after with control sites evaluation was conducted at three sites near Chicago and in Southern Wisconsin.[15] The sites evaluated were:

- I-55 EB. Trucks were restricted from the left lane of a three-lane facility. The road had an AADT of 23,500 with 21 percent trucks.

- I-290 EB. Trucks were restricted from the left lane of a three-lane facility. The road had an AADT of 78,500 with 13 percent trucks.

- I-90/94 EB. Trucks were restricted from the right lane of a two-lane facility due to pavement deterioration. The road had an AADT of 4478 with 13.4 percent trucks.

The research looked at the percentage of trucks that were in violation of the lane restrictions, and found that non-compliance varied among the sites. At I-55, 0.9 percent of trucks were traveling in the restricted lane, as compared to 5.7 percent on I-290. Non-compliance was highest at I-90/94, where 10.2 percent of trucks were traveling in the restricted lane.

The researchers also looked at the percentage of trucks that were impeding car traffic at the sites. The results varied among the sites, ranging from 12 percent more trucks impeding flow at I-290 to 1.7 percent less trucks impeding flow at I-90/94. At both of the three-lane sections, more trucks did impede traffic, however. The researchers also examined the speeds in adjacent lanes at the sites. They found no significant differences between adjacent lane speeds between the control and test sites.

New Jersey

Another study examined the potential safety impact of having mixed traffic lanes versus passenger vehicle-only lanes using data from the New Jersey Turnpike.[16] Although this configuration is not the same as what is being used in Virginia, it does offer some possible insights into the safety benefits of separating trucks and cars. The researchers examined one year of crash data from 2002 for two sections of the Turnpike, one that was 2.5 miles long and another than was 5.3 miles long. AADTs ranged from 55,000 to 65,000 for the passenger vehicle-only lanes and from 42,000 to 52,000 for the mixed traffic lanes. The mixed traffic lanes contained between 30 and 47 percent heavy vehicles. The researchers found that the crash rate in the mixed traffic lanes was approximately double that in the passenger vehicle-only lane. Although the researchers concluded that the passenger vehicle-only lanes offered some safety benefit, they also hypothesized that property damage crashes involving a large truck would be more likely to be reported than those involving two passenger vehicles. This may skew some of the crash numbers if it is true.

Simulation Studies

There have also been several attempts to define the impact of truck lane restrictions through simulation. A study by Garber and Gadiraju attempted to assess the impact of truck lane restrictions through a simulation-based analysis.[17] Differential speed limits and truck restrictions were simulated at 9 sites that had 2, 3, or 4 lanes. The simulation results showed a statistically significant decrease in headways in right lane following implementation of truck restrictions at some sites. This decrease usually occurred at locations with a high AADT and high percentage of trucks. The simulation results also implied that lane restrictions could create problems when there is a 3 or 4 lane segment with an AADT greater than 75,000 and a truck percentage greater than 3.6. In these situations, a “barrier” effect could be created where trucks impede merging operations.

The safety impact of the truck lane restrictions was also estimated based using the simulation results. The estimated number of overall and truck-involved crashes was expected to increase by a statistically significant margin when truck restrictions were implemented. These estimates were based purely off of simulation results, however, and it is unknown whether they conform to what would actually occur at a site.

Another simulation study used the model FRESIM to analyze the impact of truck restrictions on traffic density, speed differentials, and the number of lane changes.[18] The study evaluated truck restrictions using a series of scenarios that examined the impacts of volume, truck percentage, grade, and lane distribution. This was followed up with 3 case studies of real world locations.

The research found that restricting trucks from the left lane on steep grades generally increases speed differentials between lanes, but reduces traffic density and number of lane changes. The researchers recommended that truck restrictions be considered when grades are greater than 4 percent. The implications of these findings on safety are unclear; however, as decreased lane changes may be indicative of improved safety whereas increased speed differentials may be associated with increases in crashes.

This second study had some limitations which may affect the extent to which it can be extended to real world sites. At the time this work was done, FRESIM did not incorporate the concept of a maximum crawl speed for trucks traveling up a grade. Acceleration rates were reduced going up a grade, but there was nothing to limit a truck from eventually reaching its desired maximum speed. As a result, truck performance in the model was probably overestimated. Also, the statistical analysis of the results was limited to paired t-tests. A formal experimental design was not used, so there was no attempt made to assess whether factor interactions were significant. As a result, it was not possible to determine a true response surface for lane restrictions across a variety of factors.

Summary of Studies

The review of studies shows some common trends in the performance of truck lane restrictions. On multilane freeways, four separate studies have shown no practically significant improvements in overall travel speeds. Likewise, three studies have shown increased crash rates following installation of restrictions. One study did show a reduction in truck crash rate, however.

There are several common limitations in these studies, especially in the safety analysis. First, crash analysis was frequently performed using a limited amount of data. Likewise, the crash analysis did not attempt to control for regression-to-the-mean or use control sites to correct for systematic trends. Although the trends from these studies do not show a significant benefit to installing truck lane restrictions, some of the results may be attributed to inadequate study designs.

Table 2. Summary of Field Test Results

Site	Operational Impacts	Safety Impacts
Broward County, Florida	N/A	Overall rate up 6.3%, truck rate down 3.3%
I-75 in Florida	No significant change in speed or travel time	N/A
I-20 in Louisiana	N/A	Crashes increased, but may be due to increased exposure
Washington, D.C., Beltway	N/A	13.8% increase in crashes, no change in severity
Texas	Speed change < 1 mph	N/A
Seattle	Speeds increased by 0.7 mph	N/A
Wisconsin and Chicago	No significant change from control sites	N/A

Safety Analysis

The first major task in this study was to assess the impact of Virginia’s truck restrictions on safety. Findings from the analysis of sites with three or more lanes by direction are reviewed, followed by a summary of the results from the two-lane segments.

Sites with Three or More Lanes by Direction

Site Identification

Initially 33 sites with truck lane restrictions were identified through the survey of DTEs. Ten of these locations either contained or were in close proximity to a major work zone that was active during the study period, so they were eliminated from the analysis. As a result, 23 sites representing more than 240 directional miles of road were used to perform the safety analysis of three-lane segments. These sites ranged in length from about 2.2 miles to more than 18.5 miles. Some of the roadways that were eliminated from the analysis included I-395, I-495, and I-95 near the Springfield interchange and a portion of I-295 where major bridge work was underway during the analysis period. Table B-1 in Appendix B summarizes the location and traffic characteristics of sites that were used in the analysis. Table B-1 shows that these sites were primarily located in Richmond, Northern Virginia, and along I-81.

A total of 16 comparison sites were identified that had characteristics similar to the sites with restrictions. The summary of comparison sites can be found in Table B-2. The comparison sites represent 154 directional miles of road, and were primarily located in Hampton Roads and Richmond. The sites ranged in length from 3 miles to 22 miles. Although the AADTs of these sites were consistent with the sites that have restrictions, the percentage of trucks in the comparison sites tends to be lower, particularly as compared to the sites on I-81. On average, the comparison sites had 6.2 percent trucks, whereas the sites with restrictions had 15.3 percent trucks.

The first step in the analysis was to perform a high-level examination of the trends in crash rate at the sites with restrictions. The overall crash rate and the fatal/injury crash rate for each site with restrictions is summarized in Table 3. The crash rates have been subdivided into rates from the period before the restrictions were put in place and rates from after the restrictions were installed. It should be noted that the "before" and "after" periods do not represent the same amount of time for all sites. Since data from 1998 through 2005 were used, the "before" period was calculated using between 1 and 5 years of data, whereas the "after" data were calculated using between 3 and 7 years of data. Table 3 shows that there is a general trend in increasing crash rate at all of the sites with truck restrictions. Only 7 sites (30.4 percent) showed a reduction in overall crash rate during the after period, and 8 (34.8 percent) showed a reduction in fatal and injury crash rate. Looking at crash rates in this manner can be misleading, however, since there is a systematic trend in increasing crash rate that would cause these increases to appear less severe. As a result, the EB analysis was expected to shed further light on what was really happening at these sites.

Table 3. Three-Lane Site Crash Rate Summary (Crash Rate Expressed as Crashes per 100 million VMT)

Interstate	Start MP	End MP	Overall Crash Rate		Fatal and Injury Crash Rate	
			Before	After	Before	After
I-64 EB	177.25	179.51	64.8	89.0	21.9	21.2
I-64 EB	194.9	198.29	60.7	85.8	20.8	28.0
I-64 WB	17.25	179.51	50.6	145.7	15.3	40.8
I-64 WB	194.9	198.29	47.2	70.8	21.2	25.7
I-66 EB	47.6	64	89.1	86.1	28.4	31.0
I-66 WB	47.6	64	83.2	113.3	28.0	41.5
I-77 NB	1.18	7.52	40.7	52.7	13.6	22.5
I-81 NB	0	3	25.0	23.0	8.3	7.0
I-81 NB	3	8.1	70.5	68.5	26.1	22.2
I-81 SB	0	3	27.9	19.5	11.1	10.2
I-81 SB	3	8.1	60.2	36.8	26.0	12.3
I-95 NB	89.24	101.33	41.9	43.3	15.8	14.2
I-95 NB	101.33	116.87	29.9	37.7	11.9	12.1
I-95 NB	116.87	132.44	35.7	56.5	10.9	15.5
I-95 NB	132.44	148	32.8	50.2	10.4	13.5
I-95 SB	89.24	101.33	39.4	53.7	13.1	17.7
I-95 SB	101.33	117.07	30.7	44.1	13.2	14.6
I-95 SB	117.07	132.68	38.0	45.0	11.4	12.6
I-95 SB	132.68	148	46.0	75.1	12.3	20.0
I-295 EB	0	8.51	29.7	42.6	12.3	12.4
I-295 EB	25.41	43.94	37.1	33.1	17.2	11.3
I-295 WB	0	8.51	45.1	59.0	17.0	19.7
I-295 WB	25.41	43.94	39.7	29.4	15.4	9.6
Average of All Sites (Weighted Equally)			**46.3**	**59.2**	**16.6**	**18.9**

Model Development

Crash frequency estimation models were developed separately for all crashes, fatal/injury crashes, truck-involved crashes, and fatal/injury crashes involving trucks. Initially, all test and comparison sites were used to develop these models. Examination of the models produced revealed, however, that the performance of the crash estimation models appeared to vary significantly between high-volume and low-volume sites. High-volume sites consistently had more crashes than were predicted, whereas the lower volume sites had fewer crashes than were predicted. This breakpoint seemed to occur at a volume of approximately 10,000 vehicles per day per lane. As a result, the data set was divided into two groups based on the observed traffic volumes to ensure that the models developed were, in fact, most appropriate for the given conditions. Table 4 summarizes the models that were developed, with the factor values listed representing the exponents in the model for each factor. In addition to the factors in Table 4, VMT, truck percentage, speed limit, and number of interchanges were examined. None of those factors improved the quality of the models developed, and so they were not used.

Table 4 reveals several interesting features of the crash estimation models. First, every crash estimation model included the length of the segment as a factor, and the vast majority included total AADT and the number of lanes as a factor. The crash estimation model for the total number of crashes at low-volume sites did not contain any measure for traffic volume. A possible explanation for this is that all sites had volumes that were between 17,000 and 40,000 vehicles per day. Since AADTs were grouped relatively tightly, it may not have had a strong predictive power for the model. A second interesting feature of the models developed is that only the models for the truck-involved crashes at low-volume sites included the truck AADT as a significant factor. There are a couple of potential explanations for this. First, it is possible that the truck AADTs were close enough together that they did not strongly distinguish the sites from one another. This would make the number of crashes roughly proportional to the overall AADT, which was a significant factor in nearly all cases. Another potential explanation is that the quality of the truck AADTs was generally poorer in the early years covered in this model. If the truck AADTs were off in the years before 2000, then they may have created enough problems in the construction of the crash estimation model that it was not included as a factor.

Table 4. Crash Estimation Models Developed

Measure	Sites Used	No. of Test Sites	No. of Comparison Sites	Factor			
				AADT	Truck AADT	Length	No. of Lanes
Overall crashes	All	23	16	0.785	-	0.662	2.168
	High Volume	11	10	0.906	-	0.670	2.901
	Low Volume	12	6	-	-	0.236	1.64
Fatal/Injury Crashes	All	23	16	0.712	-	0.644	2.200
	High Volume	11	10	0.770	-	0.638	2.794
	Low Volume	12	6	0.615	-	0.462	1.265
Truck Involved Crashes	All	23	16	0.824	-	0.900	-
	High Volume	11	10	0.798	-	0.892	0.806
	Low Volume	12	6	0.641	0.436	0.893	-
Truck Involved Fatal/Injury Crashes	All	23	16	0.787	-	0.825	-
	High Volume	11	10	0.748	-	0.743	1.061
	Low Volume	12	6	0.707	0.354	0.863	-

Safety Evaluation

Table 5 shows the results of the EB analysis for all crashes. The "Index of Effectiveness" column shows that, on an aggregate basis, the number of crashes at sites with the truck restrictions was about 8 percent higher than would have been expected without the restrictions. When the sites were stratified into high and low-volume locations, very different safety performance was observed. Crashes at the low-volume sites were about 90 percent of what would have been expected without the restrictions, whereas the crashes at the high-volume sites were 12 percent higher than was expected. All of these results were statistically significant.

Interestingly enough, the high-volume results appear to be reasonably consistent with what was reported in the prior studies of the Washington Beltway and Broward County. The trends in the low-volume sites differ markedly from those prior studies, potentially indicating that there were differences in safety impacts depending on the volume of the sites.

Table 5. EB Analysis of All Crashes

Traffic Volumes	Actual Crashes	Predicted Crashes	Difference	95th% Confidence Interval	Index of Effectiveness	95th% Confidence Interval
All sites	11,188	10,372	+816	816 ± 251.7	1.08	1.08 ± 0.03
Low-volume sites	1,314	1,455	-141	-141 ± 98.1	0.90	0.90 ± 0.06
High-volume sites	9,874	8,810	+1064	1064 ± 232.97	1.12	1.12 ± 0.03

Table 6 shows the results for the EB analysis of fatal and injury crashes. The trends again were very similar to what was observed for the overall number of crashes. The low-volume sites had 17 percent fewer severe crashes than were expected, whereas the high-volume sites had 14 percent more crashes than were expected. All of these results were statistically significant.

Table 6. EB Analysis of Fatal and Injury Crashes

Traffic Volumes	Actual Crashes	Predicted Crashes	Difference	95th% Confidence Interval	Index of Effectiveness	95th% Confidence Interval
All sites	3,619	3,345	+274	274 ± 142.1	1.08	1.08 ± 0.04
Low-volume sites	443	536	-93	-93 ± 53.9	0.83	0.83 ± 0.09
High-volume sites	3,176	2,776	+400	400 ± 130.7	1.14	1.14 ± 0.05

Table 7 shows the crash analysis for crashes involving trucks. It would intuitively be expected that the truck lane restrictions would have a larger impact on crashes involving trucks than on the overall crash numbers. The number of crashes at low-volume sites was 29 percent lower than predicted, whereas the number of crashes involving trucks was 37 percent higher than expected at high-volume sites. All of these results were also statistically significant. These findings appear to deviate substantially from what was found during the limited safety analysis in Broward County.

Table 7. EB Analysis of Truck-Involved Crashes

Traffic Volumes	Actual Crashes	Predicted Crashes	Difference	95th% Confidence Interval	Index of Effectiveness	95th% Confidence Interval
All sites	1,725	1,368	+357	357 ± 91.8	1.26	1.26 ± 0.07
Low-volume sites	240	336	-96	-96 ± 38.8	0.71	0.71 ± 0.10
High-volume sites	1,485	1,087	+398	398 ± 84.1	1.37	1.37 ± 0.08

The EB analysis for the severe crashes involving trucks can be found in Table 8. Once again, the truck restrictions appear to be creating a positive effect at the low-volume sites, with 34 percent fewer crashes being observed than were predicted. Likewise, the high-volume sites had 27 percent more crashes than were predicted. All of these results were also statistically significant.

Table 8. EB Analysis of Fatal and Injury Truck-Involved Crashes

Traffic Volumes	Actual Crashes	Predicted Crashes	Difference	95th% Confidence Interval	Index of Effectiveness	95th% Confidence Interval
All sites	597	510	+87	87 ± 52.9	1.17	1.17 ± 0.06
Low-volume sites	86	130	-44	-44 ± 20.7	0.66	0.66 ± 0.08
High-volume sites	511	404	+107	107 ± 49.0	1.27	1.27 ± 0.13

Discussion of Safety Analysis

The results in Tables 5 through 8 all seem to indicate that the lower volume sites benefited from the installation of the restrictions, whereas the higher volume sites saw a negative safety impact. There are several potential explanations for these conflicting results:

- By restricting trucks from the left lane at high-volume sites, more trucks are driving in the center and right lane of the highway. At high-volume, urban sites, this would place more trucks in potential conflict with vehicles that are merging on and off of the highway. This has the potential to create a safety hazard, particularly during congested periods of the day. In contrast, the low-volume sites were unlikely to experience significant congestion, so there may be sufficient capacity to easily and smoothly accommodate merging operations. This hypothesis is supported by the simulation work performed by Garber and Gadiraju.

- The primary safety benefit of truck lane restrictions would be derived from a reduction in conflicts between slow-moving trucks and high-speed passenger vehicles. It is possible that the higher volume sites would still have congestion in the left lane, so the net safety benefit would be limited when combined with the potential "barrier" effect of the restrictions in a high-volume situation.

- Most of the high-volume sites were located in Northern Virginia, whereas the high-volume comparison sites were located in Richmond and Hampton Roads. Prior research to support the VDOT Highway Safety Corridor program showed that crash involvement in Northern Virginia is higher than other regions of the state. Although the comparison sites also represent high crash locations, the crashes frequencies were not as high as what is observed on some sections of interstate in Northern Virginia.[19] It is possible that the crash trends from the comparison sites were not sufficiently close to the Northern Virginia sites to create the best possible predictive models.

- As noted earlier, the truck percentage at the comparison sites tended to be lower than at the test sites. Since truck AADT was not a significant factor in any of the high-volume models, the total exposure of trucks at the sites was not directly accounted for. This may have influenced some of the higher estimates for truck involved crashes.

It is possible that any or all of these factors could play a role in the analysis results for the high-volume sites. The studies of the Beltway and in Broward County did show similar trends in performance, however, which may indicate that these results are valid. A detailed examination of the almost 10,000 crashes at the high-volume sites would be required to confirm this, but this was outside the scope of this study. A thorough analysis of those crashes may reveal whether merging or weaving operations interacted in a negative manner with the truck restrictions. Crash performance on basic freeway segments could be examined separately from crashes in the interchange area so that differences in impacts could be determined. Based on this analysis, however, it seems clear that lower volume sites saw a positive improvement in safety whereas the high-volume site results are either negative or inconclusive.

Sites with Two Lanes by Direction

The DTEs identified a total of 20 two-lane sites that had restrictions installed. The characteristics of those sites are summarized in Tables C-1 and C-2. Table 9 shows the crash rates that were observed at the two-lane sites before and after the truck restrictions were installed. Crash rates are based on 4 years of before data, and 1 year of after data. The crash rate analysis seems very positive, with overall crash rates declining at 13 sites (65 percent) and fatal/injury crash rates declining at 14 sites (70 percent). On average, the overall crash rate and fatal/injury crash rate declined by 19.4 and 33.1 percent, respectively, if all sites were weighted equally. Thus, the initial examination of the crash rate appears to indicate that the restrictions may have yielded a positive safety benefit.

Table 9. Summary of Crash Rates at Two-Lane Sites (Crash Rates Expressed as Crashes per 100 Million VMT)

Interstate	Direction	Start MP	End MP	Length (mi)	Crash Rate		Fatal/Injury Crash Rate	
					Before	After	Before	After
64	E	37.54	41.04	3.5	20.8	57.3	4.2	0.0
64	E	96.5	100	3.5	89.7	47.5	18.2	31.7
64	W	0	6.95	6.95	28.2	32.7	13.2	8.2
64	W	44.1	48.04	3.94	54.8	15.9	15.7	0.0
77	N	44.2	46.54	2.34	8.6	8.5	0.0	0.0
77	S	20	22	2.0	26.4	42.9	9.4	21.5
77	S	23	24	1.0	30.2	71.6	15.1	14.3
77	S	55.17	58.6	3.4	29.8	6.1	11.9	6.1
81	N	39.1	40.42	1.32	36.8	11.8	20.1	0.0
81	N	105.7	107.4	1.7	29.3	57.8	13.5	21.7
81	N	107.8	108.4	0.6	32.0	40.9	25.6	20.5
81	N	129.6	130.6	1.0	42.5	32.6	8.5	10.9
81	N	196.24	198.54	2.3	56.1	15.3	25.1	5.1
81	N	200.76	201.96	1.2	80.9	58.2	31.8	23.3
81	N	236.4	237	0.6	63.6	61.0	11.6	20.3
81	N	299.2	299.98	0.78	56.7	36.6	11.3	18.3
81	S	93.53	95.1	1.57	65.0	33.5	30.2	0.0
81	S	121.08	123.3	2.22	67.5	21.0	32.4	5.2
81	S	166.64	167.5	0.86	25.3	15.8	8.4	0.0
81	S	235.18	236.16	0.98	41.1	47.7	19.0	11.9
Average of Sites					**44.3**	**35.7**	**16.3**	**10.9**

As noted earlier, the analysis of the two-lane sites was limited by the lack of directly comparable comparison sites. As a result, a naïve before-and-after analysis was conducted using data from 2001 through 2006 at the two-lane sites. Data from the before period were limited to the 4 years prior to installation in order to control somewhat for the influence of increasing traffic volumes. Table 10 shows the results of this analysis. Unlike the three-lane sites, there were no obvious trends in crash performance relative to the volume on the road. This is likely due to the fact that the traffic volumes at the two-lane sites were very tightly grouped, ranging from 4,000 to 25,000 vehicles per day.

Table 10 shows the results of the before-and-after analysis. The total number of crashes and the number of severe truck-involved crashes were reduced by a statistically significant margin. The index of effectiveness for those two measures also decreased by a statistically significant margin, as did the θ for the total number of fatal and injury crashes. Generally speaking, the confidence intervals for the two-lane analysis were proportionately much wider than the three lane sites. This is driven, in part, by the fact that only a single year of data was available from after the restrictions were installed. The small amount of data means that few crashes are available for some of the analyses, most notably the severe truck-involved crashes.

Table 10. Two-Lane Before-and After Crash Analysis Results

Crash Type	Crash Frequency				Index of Effectiveness 95th % Confidence Interval
	Average Before	After	Difference	95th% Confidence Interval	
All Crashes	91.25	70	-21.25	-21.25 ± 18.89	0.77 ± 0.20
Fatal and Injury Crashes	34.5	24	-10.5	-10.5 ± 11.20	0.69 ± 0.30
All Truck-Involved Crashes	23.5	22	-1.5	-1.5 ± 10.35	0.93 ± 0.43
Fatal and Injury Truck Involved Crashes	10.5	5	-5.5	-5.5 ± 5.41	0.47 ± 0.42

The results from the first year of installation at the two-lane sites show positive trends, but the analysis could be improved if more data following installation of the restrictions existed. The two measures that did not have statistically significant frequency results could very well show significant reductions as more experience with the restrictions becomes available. At this point, however, the yearly variations in the historic crash data were such that the variance in the estimates was too high to indicate statistical significance in those measures. It does appear that the two-lane restrictions were having a positive impact on overall safety, however, and they should be retained.

Operational Analysis

This section describes the results of the operational analysis of the truck lane restrictions. The sites selected for detailed data collection are described, and levels of compliance with the restrictions are discussed. The impact of the restrictions on mobility is then estimated for the three-lane and two-lane segments.

Site Selection

Sites with restrictions and comparable control sites had to be identified before the operational data could be collected. First, sites with three or more lanes in each direction were examined. After comparing truck percentages, grades, and traffic volumes, three sites with restrictions in the Richmond area and three comparison sites in Hampton Roads were selected for data collection. Table 11 summarizes the characteristics of the test and control sites. At all of these sites, grades were negligible, AADTs were similar, and truck percentages were between 4 and 8 percent. Speed limits did differ between the two sites, but the actual operating speeds were similar at both locations. None of the sites with restrictions in Northern Virginia were analyzed since there were no viable comparison sites that had similar volumes.

Table 11. Three-Lane Sites Examined for Operational Analysis

Type of Site	Site Location	Posted Speed Limit (mph)	2005 AADT	Total Length of Restricted Segment (mi)	Truck %
Test Sites	I-295 EB, MP 6	65	27,627	8.5	8.0
	I-64 WB, MP 178.2	65	30,468	2.3	7.9
	I-64 EB, MP 196	65	22,971	3.4	6.9
Control Sites	I-264 WB, MP 4	55	34,998	4.0	5.0
	I-464 NB, MP 3	60	24,307	5.0	4.5
	I-464 SB, MP 3	60	21,853	5.0	5.3

Next, the two-lane sites were examined. As noted in the methodology, sites on primary roads had to serve as comparison locations for this analysis. The AADT, grade, and length of grade served as the primary factors used to select control sites. The identification of control sites on the primary system was relatively challenging since few of the primary sites examined had high volumes; significant truck percentages; and long, sustained grades. Eventually, three control sites in southwestern Virginia were identified. The interstate sites were then reviewed to identify sites that had similar geometries and traffic volumes to the control sites. Eventually, four sites on I-64 and I-77 were identified. The characteristics of the test and control sites are summarized in Table 12. No sites on I-81 were selected because the traffic volumes were much higher than those seen at the control sites. Although all sites had at least 10 percent trucks, the sites with restrictions had percentages that sometimes approached 30 percent. Although more trucks were at the test sites, it should be possible to control for this effect in the analysis. Once again, the posted speed limits differed between the test and control sites, but actual operating speeds were very similar.

Table 12. Two-Lane Sites Examined for Operational Analysis

Type of Site	Site	Posted Speed Limit (mph)	Grade	Length (mi)	2005 AADT	Truck %
Test Sites	I-64 EB, MP 100	65	3.1%	3.5	14,847	15%
	I-64 WB, MP 0	65	4.1%	7.0	4,827	29%
	I-64 EB, MP 41	65	5.1%	3.5	4,089	28%
	I-77 SB, MP 58	65	3.9%	3.4	12,803	24%
Control Sites	US 460 WB, Giles Co.	55	3.0%	2.2	5,324	11%
	US 19 NB, Washington/Russell County Line	55	5.1%	3.4	8,271	10%
	US 23 NB, Norton	55	3.9%	3.7	7,161	11%

Operational Analysis of Sites with Three or More Lanes by Direction

The operational analysis for sites with three or more lanes by direction focused on three areas: compliance with the restrictions, the number of trucks in the restricted lane impeding flow, and the overall impact of the restrictions on travel speed. Each of these areas is discussed separately in the following sections.

Compliance with Restrictions

The first task was to examine the impact of the truck lane restrictions on the number of trucks in the left lane. Table 13 shows the number of trucks traveling in each of the lanes and the percentage of trucks traveling in the left lane for all of the test and control sites. Table 13 shows that there was generally a high rate of compliance with the current restrictions at the test sites, with between 2.4 and 5.1 percent of trucks not complying with restrictions.

Table 13. Compliance at Three-Lane Sites

Type of Site	Site	Total Number of Trucks				% of Trucks in Left Lane
		Right Lane	Center Lane	Left Lane	Total	
Test Sites	I-295 EB, MP 6	84	187	7	287	2.4%
	I-64 WB, MP 178.2	66	176	13	255	5.1%
	I-64 EB, MP 196	127	180	10	317	3.2%
Control Sites	I-264 WB, MP 4	42	101	19	162	11.7%
	I-464 NB, MP 3	79	51	1	131	0.8%
	I-464 SB, MP 3	210	57	3	270	1.1%

A Chi-square analysis was performed to examine whether the lane distribution of trucks was significantly different between the test and control sites. Figure 4 breaks down the percentage of trucks in the left lane by 15-minute interval. The number of intervals analyzed was identical for the sites with and without restrictions (47 15-minute intervals each). The Chi-square analysis shows that the distribution of trucks is significantly different between the sites with and without restrictions at $\alpha = 0.05$. Figure 4 indicates that the sites with restrictions did not have more than 14.9 percent of all trucks traveling in the left lane, whereas the sites with restrictions had over 30 percent of trucks in the left lane during some intervals. The right "tail" of the distribution appears to have been significantly shortened by adding the truck lane restrictions.

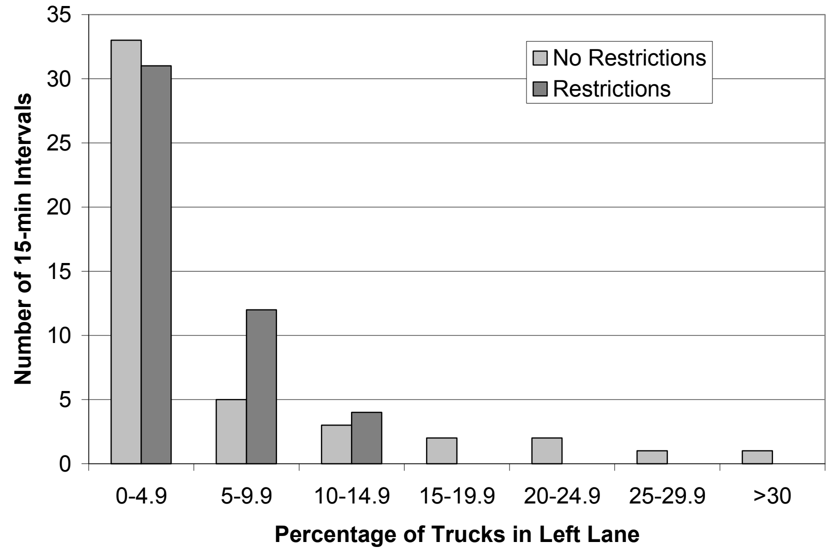

Figure 4. Comparison of Truck Lane Distribution.

A regression equation with strong explanatory power could not be constructed for the three-lane sites, so ANOVA was used to determine whether the mean percentage of trucks in the left lane was significantly different between the sites with restrictions and those without restrictions. For this case, the presence of restrictions was used as the explanatory variable and the violation rate per 15 minutes was used as the response variable. The advantages of using ANOVA are that it is a simpler method of comparison, although it does not have the ability of regression to allow you to control external factors such as traffic volume. By examining violations in terms of a rate, it is possible to control somewhat for truck volume, however. The results shown in Table 14 show that there was a statistically significant difference in violation rates, with the percentage of trucks in the left lane at the test sites being 1.73 percent lower than the sites without restrictions. Thus, it appears that the restrictions were helping to reduce the number of trucks in the left lane, further corroborating the results of the Chi-square analysis.

Table 14. ANOVA Results of Compliance Analysis

Restriction	Mean Violation Rate	F	Significance
No Restriction	4.46%	5.698	0.026
Restriction	2.73%		

Trucks Impeding Flow

The primary operational benefit of truck lane restrictions would be derived from removing slow-moving trucks from the left lane. To evaluate if the slow moving vehicles were impacting traffic flow, the number of trucks obstructing traffic flow in the left lane was examined. The results of this analysis are shown in Table 15. Vehicles following trucks with headways of 3 seconds or less were defined to be traveling in an impeded manner. Table 15 shows that at sites throughout Virginia there were low percentages of trucks impeding the flow of traffic in the left lane. This is due to the high rates of compliance and low truck volumes in the left lane. Furthermore, examination of the data collected at these sites seems to indicate that slow-moving trucks seem to self-regulate themselves. In other words, trucks traveling substantially above the speed limit tended to drive in the left lane, whereas slower moving trucks traveled in the other lanes. Based on the data collected, there did not appear to be a significant problem with trucks obstructing faster vehicles at either the test or the control sites.

Table 15. Trucks Impeding Flow at Three-Lane Sites

Type of Site	Site	No. of Trucks in Left Lane	No. of Trucks Impeding in Left Lane	Mean No. of Vehicles Following	% Trucks Impeding in Left Lane
Test Sites	I-64 WB	13	3	1	23.08
	I-64 EB	10	0	0	0
	I-295 EB	7	0	0	0
Control Sites	I-264 EB	19	0	0	0
	I-464 NB	1	0	0	0
	I-464 SB	3	1	1	33.33

Impact on Speeds

Once again, ANCOVA was used to examine the impact of lane restrictions on overall mobility. In this case, the presence/absence of the restriction was treated as a fixed factor and the 15-minute truck flow and 15-minute total flow were treated as covariates. The analysis showed no statistically significant difference in the overall speeds on the roads once volumes were controlled for. The sites with restrictions had a mean speed of about 0.5 mph higher than the sites without restrictions, but that was not significantly different. These results appear to be consistent with the various field studies that were performed in other states.

The restrictions at the three-lane sites would be expected to produce the largest mobility impact on the left travel lane, which was usually the lane with the least volume. As a result, it may be possible that speeds in the left lane increase as a result of the restriction, but the larger volumes in the center and right lane serve to hide those differences in the overall roadway mean speed. As a result, the speed differential between the left and center lane was also examined using ANCOVA. That analysis found that speeds in the left lane were approximately 7.9 mph higher relative to the center lane at the sites with restrictions than at those without restrictions when all other factors were controlled for. This difference was statistically significant.

The importance of the increased traffic speeds in the left lane over the middle lane is that many researchers have seen that high speed differentials have negative safety implications.[20] Although the truck restriction may have improved mobility in the left lane, the high speed differentials between the lanes could produce some safety problems relating to merging between the two lanes. This may partially explain some of the crash analysis results from the high-volume sites.

Operational Analysis of Sites with Two Lanes by Direction

The operational analysis of the two-lane sites differed slightly from the analysis of the three-lane sites. Since primary roads had to be used as comparison sites in this analysis, it was especially important to control for a variety of geometric factors that could influence the operational impacts of the truck lane restrictions. The results of the analysis of the two-lane sites are summarized in this section.

Compliance with Restrictions

For two-lane sites, a truck is prohibited from the left lane when it is traveling 15 mph or more below the posted speed limit. Since all of the interstate segments examined had a posted speed limit 65 mph, trucks were not complying with the law when they were traveling less than 50 mph. Table 16 shows the total distribution of trucks by lane for all four test sites combined. The table shows that a total of 117 trucks, corresponding to 6.4 percent of all truck traffic, were traveling in the left lane below 50 mph. These slow-moving trucks obviously have the potential to significantly impact overall operations on the road. In observing the videotape, it appeared that many of the slow moving trucks traveling in the left lane were passing other trucks in the right lane that were traveling even slower.

Table 16. Truck Lane Distribution by Speed for Test Sites

Speed Category	Number of Trucks			% of Trucks in Left Lane
	Right Lane	Left Lane	Total	
< 40 mph	144	36	180	20.0%
40 to 44.9 mph	122	29	151	19.2%
45 to 49.9 mph	127	52	179	29.1%
50 to 54.9 mph	171	98	269	36.4%
55 to 59.9 mph	188	166	354	46.9%
> 60 mph	244	454	698	65.0%
Total	**996**	**835**	**1831**	**45.6%**

The results in Table 16 showed that there was non-compliance with the speed-based restrictions. A regression model was developed to try to explain what factors influence non-compliance with the restrictions, as well as to determine whether the restrictions were making an impact in lane choice versus the control sites that did not have restriction. The regression model developed to explain the number of violations per hour was:

$$\text{Number of violations per hour} = -18.313 + 0.183V_T - 10.488R + 4.143G$$

where V_T = total volume of trucks
R = 0 if no restrictions were present, 1 if restrictions were present
G = average roadway grade (%)

The R^2 of this equation was 0.845, again indicating a good fit to the data since 84.5 percent of the variation in the response variable was explained by the regression model. Similarly, all factors were again significant to at least $\alpha = 0.01$. High truck volumes and steep grades tend to increase the number of violations as trucks seek to pass other vehicles that are traveling even slower in the right lane. The model indicates that installation of restrictions reduces the number of violations by an average of 10.5 per hour, when all other factors were held constant.

Vehicles Impeding Flow

To evaluate how slow moving vehicles were impacting traffic, the number of vehicles impeding the flow of traffic in the left lane was determined. This is shown in Table 17. Once again, a vehicle was considered to be traveling in an unimpeded manner when it had a headway of at least 3 seconds. The average reduction in the speed for these trailing vehicles was estimated by subtracting the average following speed in the platoon from the free-flow speed of all left lane vehicles.

An interesting finding is that although trucks were more likely to be traveling at extremely slow speeds (< 40 mph) in the left lane, more total passenger vehicles were traveling below 50 mph in the left lane than trucks. In fact, 148 passenger vehicles were found to be traveling below 50 mph in the left lane as compared to 117 trucks. Of these slow-moving vehicles, 34 percent of trucks and 13 percent of passenger vehicles were impeding at least 1 vehicle. The videotapes showed that the passenger vehicles traveling at slow speeds were generally either older models or vehicles pulling trailers. Although VDOT currently posts "Slower Traffic Keep Right" signs, the guidance is relatively vague and difficult to enforce. Given these operational findings, it may be prudent to re-examine relevant sections of the Code of Virginia and determine whether changes to the Code or the signs posted are needed to reduce the number of slow moving passenger vehicles in the left lane.

Table 17. Vehicles Impeding Flow in the Left Lane at Test Sites

Speed Category (mph)	Trucks				Non-Trucks			
	No.	Number Impeding	Mean No. of Vehicles Following	Mean Reduction in Following Speed (mph)	No.	Number Impeding	Mean No. of Vehicles Following	Mean Reduction in Following Speed (mph)
< 40	36	9	1.60	17.64	25	1	2.0	26.28
40 to 44.9	29	8	1.50	14.74	33	7	1.30	13.61
45 to 49.9	52	23	2.83	7.17	90	11	1.91	10.80

Impact on Speeds

Since traffic and geometric characteristics varied among the sites, it was necessary to control for the differences between the test and control sites to assess the impact of the truck lane restrictions on mobility. Interestingly enough, even though the speed limit at the test sites was 10 mph higher than the control sites, the average operating speed at the test sites was 4.7 mph lower (59.3 mph at control sites versus 54.6 mph at test sites). As a result, it should be possible to directly compare the two types of sites even though the posted speed limit was different.

ANCOVA was used to test for the influence of the presence/absence of the restriction (fixed factor) and four covariates (length of grade, percent grade, 15-minute truck flow, and 15-minute total flow). The analysis found that every factor with the exception of the overall flow rate was significant at $\alpha = 0.01$ or less. The overall flow rate was likely not found to be significant since the total volumes on these segments were far less than capacity. The statistical results show that, all other factors being equal, it was estimated that the presence of the restrictions at these particular sites improved travel speeds by 5.55 mph. This was statistically significant at α = 0.01. This improvement applies to the data collected during the study period, which generally extended from about mid-morning until the end of the afternoon peak hour.

CONCLUSIONS

- *Initial data from the two-lane segments with restrictions show positive operational and safety improvements.* The overall number of crashes was estimated to have declined by 23 percent, and overall average travel speeds were estimated to have increased by about 5.5 mph. These differences were both statistically significant.

- *The operational analysis of the three-lane restrictions did not reveal any statistically significant improvement in mobility.* Speeds were estimated to be approximately 0.5 mph higher at sites with restrictions, but this was not statistically significant.

- *The safety impact of the three-lane restrictions appears to differ substantially between the lower volume and higher volume sites.* The EB analysis showed a reduction in crashes at sites with truck restrictions that had an AADT less than 10,000 vehicles per lane per day. Crashes were estimated to have increased at sites with truck restrictions that exceeded this volume threshold. The higher number crashes observed at the high-volume sites may be due to increased problems with merging, or it may be driven by the crash characteristics of Northern Virginia interstate sites.

- *Compliance with the restrictions was generally reasonable, especially at the three-lane sites.* Less than 6 percent of trucks were not complying with the restrictions at the three-lane sites. At two-lane sites, there were a number of trucks traveling substantially below the posted speed limit, but over 75 percent of slow moving trucks were traveling to the right lane. There may also be an opportunity to further examine existing regulations of slow-moving passenger vehicles, as non-trucks accounted for more vehicles traveling below 50 mph in the left lane than trucks.

RECOMMENDATIONS

Recommendations for Immediate Implementation

1. *VDOT's Traffic Engineering Division should pursue expanding truck lane restrictions on interstate highways with three or more lanes by direction and on interstate highways with directional AADTs below 30,000 vehicles per day regardless of the speed limit.* The analysis found a difference in the safety impact of truck lane restrictions that occurred at a level of around 10,000 vehicles per day per lane. For the sake of simplicity, an AADT level of 30,000 vehicles per day would be a reasonable threshold for most interstates analyzed. The crash analysis showed a significant reduction in the overall number of crashes and the number of severe crashes involving trucks on lower volume interstates, even though no significant operational benefits were observed. VDOT should pursue a change in the Code of Virginia to extend these truck lane restrictions to all interstates, regardless of speed limit.

This would add restrictions to several routes in Hampton Roads and extend the restrictions in Richmond.

2. *The speed-dependent, two-lane restrictions should be retained, and VDOT's Traffic Engineering Division should re-examine crash experience when at least 3 years of "after" data are available.* The analysis in this report shows positive impacts on mobility and safety based on 1 year of data after installation of the restrictions. Although these initial results are very positive, more data are needed to determine whether safety improvements are sustainable over time.

3. *VDOT's Traffic Engineering Division should determine whether stronger measures are needed to deal with slow-moving passenger vehicles in the left lane of two-lane segments.* The operational analysis indicates that more passenger vehicles were traveling below 50 mph in the left lane on two-lane segments than trucks. Removing slow-moving passenger vehicles from the left lane could further improve mobility on steep grades. The current signage and language in the Code should be reviewed to determine if changes are needed.

Recommendations for Further Research

1. *VTRC should conduct a detailed analysis of crashes on high-volume interstates with three or more lanes to determine if the truck lane restrictions are having a negative impact on merging and weaving.* The safety analysis in this report showed that the high-volume sites were experiencing much higher numbers of crashes than were predicted based on control sites and past trends. The approximately 10,000 crashes identified in this study should be subjected to a detailed analysis to determine how many of the crashes appear to be attributable to potential side effects of the restriction. Freeway segments and interchange areas should be examined separately to determine whether there are specific situations that are creating safety problems. Depending on the results of that analysis, it may be desirable to pursue removing the restrictions on many high-volume facilities.

2. *VTRC should consider an investigation of arterial truck lane restrictions.* There are currently truck lane restrictions in place on several primary roads in Virginia. The potential impacts of truck lane restrictions on a signalized arterial road would be much different than on a limited access freeway, and several districts inquired about the potential benefits of arterial restrictions during the course of this project. Furthermore, the legal basis for those restrictions in the Code of Virginia is unclear. Research is needed to determine whether truck lane restrictions could be beneficial on arterials and assess whether a change in the Code is warranted to permit these restrictions explicitly.

COSTS AND BENEFITS ASSESSMENT

The existing truck lane restrictions seem to have created some tangible benefits in safety and mobility. Although the three-lane restrictions did not appear to produce any significant operational improvements, the two-lane restrictions were estimated to have improved travel speed by approximately 5.5 mph during the study period. This mobility improvement can be extrapolated for the 41.8 miles impacted by this restriction if a value of time is assumed. Using a value of $13.45 per hour (used by the Texas Transportation Institute *Urban Mobility Report*),[21] this would translate into a monetary benefit of $4,845,387 during the first year after the restrictions were installed on the two-lane segments. This benefit is probably high since it assumes that the 5.5 mph improvement occurs throughout the day even though it is likely that benefits of this magnitude would not be seen in the middle of the night.

The restrictions also appear to be creating some safety benefits. The number of crashes was estimated to have been reduced by 23 percent on the two-lane segments and by 10 percent on low-volume, three-lane segments. At two-lane sites, the reductions translate into 21 crashes (including 10 injury crashes) prevented in the first year by installing truck lane restrictions. At low-volume, three-lane sites, this translates into 141 crashes (including 93 injury crashes) prevented since the restrictions were first installed in 1997. The VDOT Highway Safety Improvement Program (HSIP) provides dollar costs for different types of crashes that can be used to translate these safety improvements into economic savings.[22] If a conservative assumption that all injuries prevented were relatively minor is made, the HSIP costs produce an estimated total economic benefit of $300,500 for the two-lane segments and of $2,441,700 for the low-volume, three-lane sections. These benefits translate into an average yearly benefit of $15,025 per site for two-lane segments and $43,601.79 per site for three-lane segments. The analysis notes that the high-volume, three-lane segments may be experiencing more crashes than expected after the restrictions were installed. More analysis is needed to confirm this finding, however. The safety benefits of the restrictions on the two-lane and low-volume, three-lane interstate sections certainly represent a substantial benefit, however.

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APPENDIX A
TRUCK RESTRICTIONS IN THE CODE OF VIRGINIA

§ 46.2-803.1. Commercial motor vehicles limited to use of certain lanes of certain interstate highways.

Except where the posted speed limit is less than 65 miles per hour, no person shall drive any commercial motor vehicle, as defined in § 46.2-341.4, on the left-most lane of any interstate highway having more than two lanes in each direction.

Furthermore, within the Eighth Planning District and on Interstate 81, no person shall drive any commercial motor vehicle, as defined in § 46.2-341.4, on the left-most lane of any interstate highway having more than two lanes in each direction, regardless of the posted speed limit. Every commercial motor vehicle shall keep to the right-most lane when operating at a speed of 15 miles per hour or more below the posted speed limit on an interstate highway with no more than two lanes in each direction.

The provisions of this section shall not apply to (i) buses or school buses or (ii) other commercial vehicles when (a) preparing to exit a highway via a left exit or (b) being used to perform maintenance or construction work on an interstate highway.

(1997, c. 733; 1998, c. 555; 2000, cc. 60, 306, 407; 2004, c. 809.)

APPENDIX B
SUMMARY DATA FROM SITES WITH THREE OR MORE LANES

Table B-1. Characteristics of Sites With Restrictions

Interstate	Direction	Start MP	End MP	Length	Install Year	2005 AADT	2005 Truck %
64	E	177.25	179.51	2.26	2002	31,002	7.0
64	E	194.9	198.29	3.39	2000	22,971	6.9
64	W	177.25	179.51	2.26	2002	30,468	7.9
64	W	194.9	198.29	3.39	2000	25,895	5.9
66	E	47.6	64	16.4	2000	75,079	9.5
66	W	47.6	64	16.4	2000	72,020	10.6
77	N	1.18	7.52	6.34	1997	18,261	29.7
81	N	0	3	3	2000	19,242	24.8
81	N	3	8.1	5.1	2002	24,131	24.8
81	S	0	8.1	8.1	2000	19,233	22.0
81	S	3	8.1	5.1	2002	22,904	22.0
95	N	89.24	101.33	12.09	2000	43,215	15.2
95	N	101.33	116.87	15.54	2000	37,946	15.2
95	N	116.87	132.44	15.57	2000	53,914	15.2
95	N	132.44	148	15.56	2000	65,490	9.6
95	S	89.24	101.33	12.09	2000	45,882	15.0
95	S	101.33	117.07	15.74	2000	38,707	17.3
95	S	117.07	132.68	15.61	2000	54,561	18.0
95	S	132.68	148	15.32	2000	68,376	11.7
295	E	0	8.51	8.51	2000	27,627	8.0
295	E	25.41	43.94	18.53	2000	17,049	25.0
295	W	0	8.51	8.51	2000	25,634	7.0
295	W	25.41	43.94	18.53	2000	18,127	24.0

Table B-2. Characteristics of Comparison Sites

Interstate	Direction	Start MP	End MP	Length	2005 AADT	2005 Truck %
64	E	180	186	6	53,479	2.0
64	E	191	194	3	38,964	6.9
64	E	277	292	15	64,782	8.0
64	W	180	186	6	49,585	4.0
64	W	191	194	3	44,450	6.9
64	W	277	292	15	66,591	5.0
95	N	52	74	22	46,933	11.1
95	S	52	74	22	46,854	11.0
264	E	3	7	4	39,685	5.0
264	E	9	25	16	65,583	5.0
264	W	3	7	4	34,998	5.0
264	W	9	25	16	67,609	5.0
464	N	0	5	5	24,307	4.5
464	S	0	5	5	21,853	5.3
664	E	2	7	5	24,535	7.0
664	W	0	7	7	28,195	7.0

APPENDIX C
SUMMARY DATA FROM TWO-LANE SITES

Table C-1: Characteristics of Two-Lane Sites with Posted Restrictions

Interstate	Direction	Start MP	End MP	Length	Mean Grade (%)	Install Date	2005 AADT
64	E	37.54	41.04	3.5	+4.89	12/17/04	4,089
64	E	96.5	100	3.5	+3.10	8/23/04	14,847
64	W	0	6.95	6.95	+4.10	1/6/05	4,827
64	W	44.1	48.04	3.94	+2.50	1/13/05	4,364
77	N	44.2	46.54	2.34	+2.66	8/13/04	13,666
77	S	20	22	2.0	+3.15	12/7/04	19,119
77	S	23	24	1.0	+2.84	12/7/04	19,119
77	S	55.17	58.6	3.4	+3.90	8/13/04	12,803
81	N	39.1	40.42	1.32	+3.07	8/13/04	17,575
81	N	105.7	107.4	1.7	+2.18	10/25/04	22,232
81	N	107.8	108.4	0.6	+3.78	10/22/04	22,232
81	N	129.6	130.6	1.0	+3.77	10/21/04	25,090
81	N	196.24	198.54	2.3	+2.92	12/6/04	23,305
81	N	200.76	201.96	1.2	+3.43	12/28/04	19,597
81	N	236.4	237	0.6	+4.05	8/25/04	21,765
81	N	299.2	299.98	0.78	Not collected	1/27/05	19,216
81	S	93.53	95.1	1.57	+2.90	10/8/04	21,206
81	S	121.08	123.3	2.22	+3.69	10/22/04	23,477
81	S	166.64	167.5	0.86	+3.72	10/7/04	20,087
81	S	235.18	236.16	0.98	+2.95	8/23/04	22,684

Table C-2. Crash History at Two-Lane Sites with Restrictions (P = Property Damage Only, I=Injury, F=Fatal)

Interstate	Direction	Milepost		Time Period														
		Start	End	4 Years Before			3 Years Before			2 Years Before			1 Year Before			1 Year After		
				P	I	F	P	I	F	P	I	F	P	I	F	P	I	F
64	E	37.54	41.04	2	0	0	0	0	0	1	1	0	1	0	0	3	0	0
64	E	96.5	100	10	3	0	10	1	0	15	4	0	12	3	1	3	6	0
64	W	0	6.95	5	3	0	0	2	0	1	2	0	2	0	0	3	1	0
64	W	44.1	48.04	2	1	0	2	0	0	3	2	0	3	1	0	1	0	0
77	N	44.2	46.54	1	0	0	1	0	0	2	0	0	0	0	0	1	0	0
77	S	20	22	4	2	0	0	1	0	1	0	0	4	2	0	3	3	0
77	S	23	24	0	0	0	2	1	0	0	1	0	2	2	0	4	0	1
77	S	55.17	58.6	3	2	1	3	3	0	4	1	0	2	1	0	0	1	0
81	N	39.1	40.42	1	0	0	1	0	0	1	3	1	2	2	0	1	0	0
81	N	105.7	107.4	4	1	0	0	2	0	1	2	1	2	0	0	5	3	0
81	N	107.8	108.4	1	2	0	0	2	0	0	0	0	0	0	0	1	1	0
81	N	129.6	130.6	2	0	0	2	0	0	4	1	0	4	2	0	2	1	0
81	N	196.24	198.54	3	4	0	4	4	0	7	7	0	7	2	0	2	1	0
81	N	200.76	201.96	4	2	0	1	1	0	7	3	0	5	5	0	3	2	0
81	N	236.4	237	4	0	0	1	0	0	1	2	0	3	0	0	2	1	0
81	N	299.2	299.98	5	2	0	3	1	0	2	0	0	2	0	0	1	1	0
81	S	93.53	95.1	4	2	0	4	5	0	5	2	0	2	4	0	4	0	0
81	S	121.08	123.3	5	4	1	6	9	0	7	6	1	8	3	0	3	1	0
81	S	166.64	167.5	0	1	0	1	0	0	3	1	0	0	0	0	1	0	0
81	S	235.18	236.16	0	0	1	2	2	0	3	0	0	2	3	0	3	1	0