FINAL REPORT

A SIMULATION ANALYSIS OF TRAFFIC FLOW ELEMENTS FOR RESTRICTED TRUCK LANES ON INTERSTATE HIGHWAYS IN VIRGINIA

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ABSTRACT

In recent years, increases in truck traffic on Virginia's highways have raised issues concerning safety and capacity on interstates such as I-81 and I-95. Lane restrictions represent a strategy that is intended to reduce conflicts between trucks and cars and facilitate traffic flow. Field experiments to determine the effects on existing traffic under lane restrictions for an interstate freeway segment are usually not feasible, and an alternative approach was selected. In this study, the simulation model FRESIM was used to estimate various traffic flow elements. The purpose of this study was to analyze changes in traffic flow elements (density, lane changes per vehicle, and speed differential) under conditions of restricted and unrestricted truck lane configurations.

Prior to application of the simulation model to actual sites in Virginia, a scenario analysis was completed. The scenario analysis tested the variability of each traffic flow element considering the following variables: traffic volume, percentage of trucks, percentage of total volume by lane, presence or absence of lane restrictions, and grade. A statistical paired-sample *t* test was used to determine significant differences in the values of the three traffic flow elements when lane restrictions were applied. An analysis was also completed for three case studies in Virginia, located on I-81 near Buchanan, Christiansburg, and Wytheville. Two types of restrictions were tested: restricting trucks from the left lane and restricting trucks from the right lane.

From the results obtained in this study several conclusions were drawn: (1) restricting trucks from the left lane with steep grades causes an increase in speed differential and may decrease density and the number of lane changes, (2) restricting trucks from the right lane causes an increase in the number of lane changes, and (3) site characteristics dictate the effects of truck lane restrictions. Based on the results of this study, it is recommended that (1) trucks be restricted from the left lane when grades are 4 percent or greater and (2) trucks not be restricted from the right lane. The study results did not support removal of truck lane restrictions in Virginia.

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INTRODUCTION

In recent years, increases in heavy truck traffic on Virginia's highways have raised issues concerning safety and capacity on interstates such as I-81 and I-95. Between 1982 and 1992, the amount of freight hauled in Virginia increased by 43 million tons and accounted for 80 percent of all manufactured freight in Virginia.[1] A variety of strategies have been proposed or tested with the intent of mitigating or reducing conflicts between heavy and light vehicles. Middleton and Fitzpatrick identified 11 strategies for reducing truck accidents.[2] The first, lane restrictions, is defined as "facilities that restrict trucks to a separate roadway for operational or safety reasons." Truck lane restrictions were identified in 25 states, but most restrictions have been used without detailed planning or the provision for before and after studies.[2]

Officials of the Virginia Department of Transportation (VDOT) expressed an interest in examining the lane restriction option, and, in response, the Virginia Transportation Research Council (VTRC) conducted a study to evaluate the potential benefits of exclusive truck lanes on Virginia's interstate highways.[3] The study applied the Federal Highway Administration's (FHWA) computer model Exclusive Vehicle Facilities (EVFS) to determine the economic benefits of various lane restriction scenarios and concluded that significant benefits could be achieved if exclusive lanes were implemented at the site studied. The study was the first to quantify the costs and benefits of implementing exclusive lane strategies for heavy and light vehicles. However, the study did not address operational and safety issues. But Sirisoponsilp and Schonfeld concluded in another study that "unless comprehensive studies are undertaken the effects of truck lane restrictions on traffic operations are still not well known and their cost effectiveness is still in doubt."[4]

PROBLEM STATEMENT

Previous work has established the potential economic benefits of exclusive truck lanes. However, little is known about the behavior of traffic flow elements for this option as few operational and safety studies have been conducted. Accordingly, before an exclusive lane strategy can be developed, knowledge of traffic flow element characteristics is required. Further, since the application of exclusive truck lanes are site specific, the use of a computer simulation model is an appropriate means to forecast likely traffic behavior.

PURPOSE AND SCOPE

The purpose of this study was to simulate traffic flow elements on freeway segments under conditions of restricted and non-restricted truck lane conditions and to compare the results. The FHWA freeway simulation model FRESIM was used. Traffic flow elements considered in the simulation model were density (vehicles per mile), lane changes per vehicle, and speed differential (difference in average speed of cars and trucks).

METHODS

The following tasks were completed:

(1) Review the prior studies of truck lane restrictions and related traffic flow elements.

(2) Review the significance of traffic flow elements for use in the computer simulation.

(3) Specify steps required to simulate traffic flow elements for freeway segments.

(4) Apply the FRESIM model to a set of hypothetical scenarios.

(5) Apply the FRESIM model to selected freeway segments in Virginia.

(6) Analyze the results.

PRIOR STUDIES OF OPERATIONAL EFFECTS OF TRUCK RESTRICTED LANES

Capital Beltway

In 1984, truck lane restrictions were implemented on the Capital Beltway (I-95 and I-495) in Virginia following a major truck accident. Political pressure also influenced this implementation of truck lane restrictions. Primarily, the Beltway has four lanes in each direction. All trucks are restricted from the left lane and trucks carrying hazardous materials are restricted to the right two lanes. A study was performed to determine the effects of the lane restrictions in which accident data collected for 2 years prior to the lane restrictions were compared with accident data collected for 2 years after this implementation. The results of the study showed that the total accident rate increased 13.8 percent following the implementation of the restrictions. However, since the severity of the accidents did not change, it was recommended that the restrictions remain in place.[5]

Results of a subsequent analysis of I-95 conducted in 1988 were consistent with earlier results in that the total accident rate increased when truck lane restrictions were in effect. This, along with the accident rate increase in the prior research, led to the recommendation that the truck lane restrictions be removed. Nonetheless, truck lane restrictions are still in place.[5]

Broward County, Florida

A study in Broward County, Florida, analyzed the effects of truck restrictions on accidents between trucks and cars. The study evaluated a 40-km section of highway with three lanes in each direction on I-95 on which trucks with three or more axles were banned from the left lane. This site was compared to a control site in Palm Beach County without lane restrictions. Accident data were taken at both sites before the implementation of lane restrictions and then again after the restrictions were in place. The statistical *z* test was used to determine differences in accidents before and after lane restrictions. Accident data from 9 years were used in this study.[6]

The study assumed that the site with truck restrictions should behave similarly to the control site. Results of the study, however, show that the Palm Beach site had a significant increase in truck accidents from the before to the after period, and the Broward County site did not. In fact, the Broward County site did not exhibit any significant change in accidents following the implementation of lane restrictions. In the comparison to the Palm Beach site, the truck lane restrictions at the Broward County site effectively reduced the number of truck accidents by 38.43 percent and the number of truck injury accidents by 56.81 percent. For this reason, lane restrictions were recommended as an effective countermeasure to reduce accidents.[6]

Virginia: I-64

Garber and Gadiraju conducted a simulation study to determine the effects of truck restrictions on traffic flow and safety. The objectives of the study were to determine speed-flow relationships for different traffic lanes at different locations, to investigate the relationship between congestion and accident rates, to determine the effect of strategies on speed and flow distributions, and to investigate the effects of lane-use restrictions on accident rates and time headways.[7]

Nine locations were used that had 5 to 40 percent truck traffic. Spot speeds and volume counts were collected for use in the study. The simulation software package SIMAN was used to simulate a 5-km section of highway. Two types of restrictions were evaluated: one that limited trucks to specific lanes on the highway and one that lowered the speed limit for trucks. Ten strategies were created by combining these restrictions, with only 2 strategies investigating the impact of truck lane restrictions without a differential speed limit.[7]

The study showed that restricting trucks to the right lane decreased headways in the right lane at some sites. The study concluded, however, that there were no safety benefits from any of the strategies. Also, there was the potential for increased total accident rates with the implementation of each strategy, particularly with high annual average daily traffic and a high percentage of trucks.[7]

Houston, San Antonio, and Dallas, Texas

Many operational problems are created from trucks interacting with other traffic. Stokes and McCasland looked at freeways in Houston, San Antonio, and Dallas/Fort Worth. The study focused on the impact of six truck regulations that could be used to improve safety and operations on freeways in Texas. One of these regulations was lane restrictions.[8]

The truck traffic followed several trends. Trucks accounted for about 3 to 6 percent of total weekday traffic volumes with truck peaks from 9 A.M. to 11 A.M. and noon to 3 P.M. Also, the middle lane carried the highest amount of truck traffic. Truck speeds did not differ from car speeds. Accident data showed that 33 percent of truck-related accidents occurred in the middle lane with an additional 56 percent occurring in the outside lane or on the ramp and shoulder. The freeways studied experienced many weaving movements because of frontage roads. Also, with frequent lane drops, trucks did not usually travel in the far left or far right lanes. If lane restrictions were applied to the inside or outside lanes, transition areas near interchanges and lane drops would have to be created for trucks to legally travel in the lane. Restricting trucks to the right lane could block signs on the right side of the freeway. In addition, the pavement might not be able to handle all truckloads in one lane.[8]

This study concluded that the restriction of trucks to one lane with mixed traffic does not improve safety and operations, although drivers may perceive this to be the case. However, prohibiting trucks from the left lane where three or more lanes exist would be beneficial, as would restricting trucks to the two rightmost lanes where four or more lanes exist. A short-term recommendation was made to prohibit trucks from the left lane(s) on a trial basis.[9]

Fort Worth-Weatherford, Texas

Zavoina, Urbanik, and Hinshaw examined the restriction of trucks to increase the operational performance of I-20. Some engineers and freeway users felt that large trucks impede the free flow abilities of smaller vehicles. Because of low truck volumes and high truck speeds in the left lane, a restriction from this lane was used to study highway operations on I-20. The study site was a 14-km section of a six-lane, two-way rural interstate on I-20 between Fort Worth and Weatherford. Speeds, time gaps, and vehicle classifications were recorded before and after implementation of the left lane truck restriction. Before and after data were compared in four categories: westbound peak, westbound non-peak, eastbound peak, and eastbound non-peak.[10]

The results of the study showed that truck volumes in the left lane decreased between 62 and 76 percent in all four groups. All of these decreases were statistically significant. After the restriction was in place, only 3 percent of trucks traveled in the left lane, whereas the distribution of cars remained the same. Significant changes were seen in the speeds of trucks before and after the truck lane restrictions, but they could not be attributed to the truck restrictions.[10]

The authors concluded that truck restrictions have the potential to improve capacity and safety, but since this study involved little truck traffic, these results should be applied only to low-volume roadways. It was recommended that the restriction be left in place for 2 years to study accident rates. In addition, it was stated that there was a need for further research on higher volume roadways or roads with larger truck percentages along with more research on differential design of pavement.[10]

Results of Prior Truck Restrictions Studies

Prior experiences with truck lane restrictions have produced inconsistent results. Accordingly, based on the literature, the effect of restricted lanes on freeway operations apparently differs based on factors unique to each site, such as the type of restrictions used, the traffic characteristics, and the terrain. For example, at some sites, accident rates were reported to be reduced whereas at other sites they increased. However, beneficial results were reported for most sites because of the restrictions of trucks from one lane, and some indicated a potential to improve safety and capacity.

TRAFFIC FLOW ELEMENTS

In this study, three elements that depict the characteristics of vehicles in the traffic stream were used to evaluate the performance of various exclusive truck lane scenarios: density, lane changes, and speed differential. Each of these is an output of the FRESIM model and provides insight into the likely performance of a freeway section under a set of traffic and geometric conditions.

Density

Density is defined as the number of vehicles occupying a given length of highway or lane.[12] For the purposes of this study, *density* was defined as equivalent passenger cars per kilometer per lane to account for the presence of trucks, recreational vehicles, and buses. Pickup trucks and vans were considered cars. Density is a critical variable in traffic flow relationships, as seen in the following equations:

flow = density * space mean speed[13]

space mean speed = flow * space headway[13]

density = 1/space headway[13]

Density is the primary characteristic used in determining the level of service (LOS) for a section of freeway as shown in Table 1. Level of service for sections of highway with various lane restriction scenarios are determined based on the density values obtained in the simulation. In addition, a statistical analysis was completed to determine the level of significance of changes in density when lane restrictions are implemented.

Table 1. LOS Criteria For Basic Freeway Sections[13]

Free-Flow Speed = 104.6 km/h				
LOS	**Maximum Density (pc/km/ln)**	**Minimum Speed (km/h)**	**Maximum Service Flow Rate (pcphpl)**	**Maximum v/c Ratio**
A	6.2	104.6	650	0.295/0.283
B	9.9	104.6	1040	0.473/0.452
C	14.9	103.8	1548	0.704/0.673
D	19.9	98.2	1952	0.887/0.894
E	24.4/27.0	90.1/85.3	2200/2300	1.000
F	Var.	Var.	Var.	Var.

Note: In table entries with split values, the first value is for four-lane freeways, and the second is for six- and eight-lane freeways.

Speed Differential

Speed differential is the difference between the average speeds of cars and the average speed of trucks. In this study, the speed differential over a simulated section was used to compare various alternatives. Speed differential is a significant operational variable and serves as a measure of the extent of interaction between cars and trucks on the highway. A large speed differential could result in an increase in the number of accidents. The implementation of truck lane restrictions could affect speed differential since cars may be able to travel faster when not impeded by trucks and truck speeds might decrease because of the lane restrictions. Statistical tests were used to determine the significance of changes in speed differential.

Lane Changes

Vehicles change lanes for several reasons. This movement is typically made either to avoid slower vehicles, to allow faster vehicles to pass, or to exit the highway. In an LOS analysis for highways, the number of lane changes is not used as a performance measure. With the addition of lane restrictions, however, lane changes become critical since trucks will be required to be in specific lanes, therefore affecting the number of lane changes made. When the number of lane changes increases, the potential for collisions increases since there are more interactions between vehicles. This performance measure was analyzed through significance statistics and was determined in terms of the average number of lane changes per vehicle.

EVALUATION PROCEDURES

To determine the traffic effects of truck lane restrictions on interstate highways, the following steps were completed.

Site Selection

When evaluating the operational effects of truck lane restrictions, the first step is to choose a site that may warrant restrictions. Several criteria can be used to select sections of roadway. Criteria used in this study included traffic volume, percentage of trucks, and exit and entry ramp locations.

1. *Traffic volume.* The volume of traffic on the section of interstate should be of such magnitude that changes made to the system will have an effect on the flow of traffic.

2. *Percentage of trucks.* The percentage of trucks traveling on the sections of roadway selected should also be a significant fraction of the total volume.

3. *Exit and entry ramp locations.* The presence or absence of exit and entry ramps could have an effect on lane restrictions; thus the location of ramps should be noted.

Data Collection

Traffic data were obtained from loop detectors and reported by volume by type by lane, volume by speed by lane, and volume by headway by lane. Each of these reports uses the FHWA Type F Vehicle Classification Scheme. A list of the various types of vehicles can be seen in Table 2. For this project, cars included vehicle classes 1 through 3 and trucks included vehicle classes 4 through 14.

Table 2. FHWA Type F Vehicle Classification Scheme

Vehicle Classification	Description
1	Motorcycles
2	Passenger cars
3	Pickups, vans, and other 2-axle 4-tire vehicles
4	Buses
5	2-axle, 6-tire single unit truck
6	3-axle single unit truck
7	4 or more axle single unit truck
8	4 or less axle single trailer truck (combo)
9	5-axle single trailer truck (combo)
10	6 or more axle single trailer truck (combo)
11	5 or less axle multi-trailer truck (combo)
12	6-axle multi-trailer truck (combo)
13	7 or more axle multi-trailer truck (combo)
14	Unclassified vehicles

In addition to traffic counts, site plans of the locations were obtained so that lengths, grades, and curvatures could be determined. Visits to the site were necessary to observe conditions not seen on the plans.

Simulation

A simulation model is used to determine the operational effects of truck lane restrictions on highways. Several simulation models were considered for this project. The first was the Georgia model. The Georgia model is a digital freeway simulation model that can be used to simulate freeway operations. However, it cannot simulate entering and exiting traffic at ramps.[14] Since this is a concern for the project, the Georgia model was not selected.

Another model is FREFLO, a macroscopic model that uses a dynamic speed equation to simulate traffic flow. This model could provide results of truck lane restrictions only through changes in capacity.[15] Since information concerning density, number of lane changes, and speed differential is required, FREFLO was not selected.

The FRESIM model was selected. This model is one of a package of models known as CORSIM. Microscopic models use car-following and lane-changing logic to simulate freeway operations by tracking each individual vehicle.[15] This is compared to macroscopic models that use deterministic relationships to model the freeway section by section.[15]

The FRESIM model can evaluate design elements of lane configurations, merge and diverge points, and complex weaves.[16] When entering the system, a vehicle is assigned various qualities. These qualities include destination, vehicle type, and driver type. FRESIM can simulate various highway conditions including truck lane restrictions.[15] FRESIM also has some user-defined parameters that can be adjusted if the model is not simulating the existing roadway accurately. One of these parameters is driver aggressiveness. Driver aggressiveness refers to how a driver reacts to other vehicles such as driving closer to another vehicle or leaving a large gap between vehicles. Driver aggressiveness can be adjusted in a case where the average headway at the existing site does not match the average headway produced by FRESIM.

To simulate various truck lane restriction scenarios, the site is modeled using the site plans and traffic counts. Then characteristics of the site such as headway and grade are applied using existing data.

After the model has been calibrated to simulate the existing roadway, various truck lane restriction scenarios can be applied. To determine whether or not significant changes have occurred because of lane restrictions, a base case must be run without lane restrictions. After this scenario is run, scenarios with restrictions can be simulated. The following scenarios are suggested for simulation of six-lane and eight-lane highways:

For six-lane highways:

- Trucks restricted from left lane (must use right two lanes)

- Trucks restricted from right lane (must use left two lanes).

For eight-lane highways:

- Trucks restricted from far left lane (must use right three lanes)
- Trucks restricted from left two lanes (must use right two lanes)
- Trucks restricted from far right lane (must use left three lanes)
- Trucks restricted from right two lanes (must use left two lanes).

Analysis

Once the simulations were run for various truck lane restriction scenarios, the output data were analyzed. The performance measures discussed earlier, i.e., density, speed differential, and lane changes, were used in the analysis.

For each performance measure, statistics must be used to determine whether or not the differences between various truck lane restriction scenarios are significant. For this project, the paired-sample *t* test was used.

The paired-sample *t* test was used since measurements were taken for the same combinations of volumes and percentages of trucks but for two different cases. The cases are x_i and y_i, which correspond to before and after truck lane restrictions for a volume-% trucks pair *i*. For this test, x_i and y_i are related since the values were taken for the same case *i*. To adjust for very high or low values, the difference $w_i = x_i - y_i$ is calculated. The differences $w_i, w_{i+1},\ldots, w_n$ form a sample size *n* for a distribution with the mean $\mu_1 - \mu_2$ and variance σ_w^2.[17] The test statistic seen in Equation 1 can be used to test the hypotheses.

The following hypotheses are tested:

H_0: $\mu_1 = \mu_2$ $\qquad$ H_1: $\mu_1 > \mu_2$

If Equation 3 is true, then H_0 must be rejected. This means that there is a significant difference between the two cases and H_1 is true. The tests use a 95th percentile significance level with $\alpha = 0.05$. Values of t (α; n - 1) can be found in Hogg and Ledolter.[17]

$$t = \frac{\overline{w}}{s_w / \sqrt{n}} \qquad (1)$$

$$s_w = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)^2} \qquad (2)$$

$$\frac{\overline{w}}{s_w / \sqrt{n}} \geq t(\alpha; n-1) \qquad (3)$$

where n = sample size

w = difference in before and after values, $x_i - y_i$

w = mean of w

s_w = sample variance of w.

To illustrate the statistical test used in this study, the effect of a lane restriction strategy is to be determined. Values were obtained for the vehicle density (vpm), *i,* for the condition before and after truck lane restrictions are in place for a given roadway section. The data consist of the densities before, *x(i),* and after, *y(i),* for 10 truck lane scenarios representing various vehicle volumes and percent trucks for a given lane distribution and grade. These values are:

Density, *i*	**Before, *x***	**After, *y***	***w = x – y***
1	12.0	11.0	1.0
2	18.0	17.5	0.5
3	16.5	16.0	0.5
4	16.2	16.4	-0.2
5	13.0	12.4	0.6
6	21.0	19.0	2.0
7	19.5	18.7	0.8
8	16.5	16.5	0.0
9	14.2	13.8	0.4
10	13.8	13.5	0.3

For this example case, the following values were calculated:

$\overline{w} = 0.59$

$S_w = 0.606$

$t = 3.08$

Since the test statistic for t (α;9), with n = 10, is 1.833, the calculated value 3.08 > 1.833, H_0 is rejected. This means that there is a significant difference between the cases. In other words, the truck lane restrictions did have an effect on the vehicle density.

In the same manner as the example, the t tests were applied to the various scenarios to determine if significant differences occurred when truck restrictions were implemented. For the scenario analysis, t tests were used to compare the situation without restrictions to those where trucks are restricted from the left lane.

For the case studies, the following pairs were compared using the three performance measures:

- No lane restrictions vs. trucks restricted from left lane

- No lane restrictions vs. trucks restricted from right lane.

Samples of the statistical tests for each performance measure are provided in the next section on scenario analysis. The results of the statistical analysis determined if truck lane restrictions significantly affected operations on the highway system.

SCENARIO ANALYSIS

Before applying the procedures to real data, a scenario analysis was conducted in which selected variables, such as grade and lane volume distribution for a given truck restriction scenario, were used to determine the effects on different traffic characteristics, such as density, lane changes, and speed differential.

Scenarios

For this project, five variables were used to create various scenarios. These variables can be seen in Table 3 along with the values used. Combinations of these variables form 24 scenarios, which are compared in this section.

Table 3. Sensitivity Analysis Variables

Variables	Values Used
Volume (vehicles/hour)	1000, 1500, 2000, 2500, 3000
Percentage of trucks	10, 20, 30, 40
Initial volume distribution by lane	33 – 33 –34
(by percentage) (Left – middle – right)	30 – 35 – 35
	25 – 50 – 25
	25 – 38 – 37
Lane restrictions	No, Yes
Grade	0%, 2%, 4%

The volumes used ranged from 1000 to 3000 vph. These values were selected because 1000 vph is lower than current volumes on the test sections used later and 3000 vph represents truck volumes that will occur in the future. The range in truck percentages of 10 to 40 percent is inclusive of typical situations where truck restrictions would be considered.

Four initial lane volume distributions were included in the scenario analysis. Volume distributions are continually changing, and there are many possible combinations. For this study, the first lane volume distribution used was 25, 38, and 37 percent, for all vehicles and for the left, middle, and right lanes, respectively. This is probably the best estimate of actual traffic travelling on a typical highway segment. The second lane volume distribution was 30, 35, and 35 percent. This shifts some vehicles to the left lanes. The next distribution, 25, 50, and 25 percent, reflects the tendency for most vehicles to travel in the middle lane and then to equally distribute the remaining traffic between the left and right lanes. The fourth lane distribution, 33, 33, and 34 percent, was selected because it equally distributes traffic among lanes. In the simulation, the initial volume distribution does not remain constant but changes as vehicles move throughout the system.

The lane restriction variable is based on whether or not there are restrictions. For the scenario analysis, trucks were restricted from the left lane. The final variable in the scenario analysis was road grade. Three grades were used: 0, 2, and 4 percent, all of which were uphill grades. Upgrades were chosen since trucks typically have difficulty climbing the grades. Downgrades were not used in the scenario analysis since they have a similar impact on operational performance as do automobiles.

To reference the various scenarios throughout the rest of this report, a labeling system was created. Each volume distribution was assigned a roman numeral; lane restrictions used U for unrestricted and R for restricted; and the grades used 0, 2, and 4 to represent the appropriate grade.

The volume distributions were as follows:

I = Volume Distribution: 33% – 33% – 34%
II = Volume Distribution: 30% – 35% – 35%
III = Volume Distribution: 25% – 50% – 25%
IV = Volume Distribution: 25% – 38% – 37%

Each of the 24 resulting scenarios is listed in Table 4. For each scenario, 20 (5 x 4) combinations (five different values for traffic volume and four different values for truck percentage) were simulated using the values shown in Table 3.

The scenarios were tested using FRESIM for a hypothetical section 4.83 km long with three through lanes in each direction. For the simulations, the free flow speed was 104.6 km/h. The simulations were run for 3600 seconds (1 hour). Statistical analysis as explained in the previous section was performed on comparable scenarios for before and after truck lane restrictions. The result of the scenario analysis is discussed in the following sections.

Density

The density was determined for each of the 24 scenarios by dividing the total traffic volume by the speed and the number of lanes. The densities were found in terms of vehicles per lane per mile. However, to analyze the LOS, the density must be in terms of passenger cars per lane per mile. To convert the density to the correct terms, the following equations were used where f_{HV} = heavy vehicle factor

P_T = truck percentage (in decimal form)

Table 4. List of Scenarios

Scenario	Initial Volume Distribution by Lane (%) (Left – Middle – Right)	Restrictions	Grade (%)
I-U0	33 – 33 – 34	No	0
I-U2	33 – 33 – 34	No	2
I-U4	33 – 33 – 34	No	4
I-R0	33 – 33 – 34	Yes	0
I-R2	33 – 33 – 34	Yes	2
I-R4	33 – 33 – 34	Yes	4
II-U0	30 – 35 – 35	No	0
II-U2	30 – 35 – 35	No	2
II-U4	30 – 35 – 35	No	4
II-R0	30 – 35 – 35	Yes	0
II-R2	30 – 35 – 35	Yes	2
II-R4	30 – 35 – 35	Yes	4
III-U0	25 – 50 – 25	No	0
III-U2	25 – 50 – 25	No	2
III-U4	25 – 50 – 25	No	4
III-R0	25 – 50 – 25	Yes	0
III-R2	25 – 50 – 25	Yes	2
III-R4	25 – 50 – 25	Yes	4
IV-U0	25 – 38 – 37	No	0
IV-U2	25 – 38 – 37	No	2
IV-U4	25 – 38 – 37	No	4
IV-R0	25 – 38 – 37	Yes	0
IV-R2	25 – 38 – 37	Yes	2
IV-R4	25 – 38 – 37	Yes	4

E_T = truck equivalence.

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right)}$$

Then:

$$PassengerCars/hour = \frac{vehicles/hour}{f_{HV}}$$

The truck equivalencies (E_T) used in the scenario analysis are for specific freeway upgrades since the simulated section is 4.83 km long and has a continuous upgrade. The following values were used:

0% grade; all truck percentages: $E_T = 1.5$
2% grade; 10% trucks: $E_T = 2.5$
2% grade; 20%, 30%, and 40% trucks: $E_T = 2.0$
4% grade; 10% trucks: $E_T = 6.0$
4% grade; 20% trucks: $E_T = 5.0$
4% grade; 30% and 40% trucks: $E_T = 4.5$

After the simulations were run, statistical analysis was conducted to determine if there were significant differences in the densities between highways without restrictions and highways with truck lane restrictions. For the scenario analysis portion of this project, simulations were considered only for restricting trucks from the left lane.

The paired-sample *t* test was used for pairs of scenarios with the same characteristics except the presence or absence of truck lane restrictions. An example of a statistical test can be seen when comparing Scenario I-U0 and Scenario I-R0. The two scenarios have an initial volume distribution by lane of 33 percent in the left lane, 33 percent in the middle lane, and 34 percent in the right lane. Both have a grade of 0 percent. Scenario I-U0 does not have lane restrictions, and Scenario I-R0 restricts trucks from the left lane. For all of the statistical tests, the significant differences are dependent on the grade and the initial distribution but are independent of both volume and percentage of trucks. The volume-% truck pairs are used to represent potential sites that have varied volumes and percentages of trucks.

The results of the test for significance between Scenario I-U0 and Scenario I-R0 follow. The sample size is $n = 20$.

For the significance test, the following hypotheses were made:

$H_0: \mu_1 = \mu_2$ $\qquad$ $H_1: \mu_1 > \mu_2$

where μ_1 = density before truck lane restrictions

μ_2 = density after truck lane restrictions.

When the data from Scenario I-U0 and Scenario I-R0 were used, the results were as follows:

$$\overline{w} = 0.015$$

$$S_w = 0.0405$$

$$t = 1.6581$$

Standard *t* test tables show that $t = 1.729$.

Since the calculated *t* is not greater than the *t* from the table, H_0 must be true. This means that there is no significant difference in density for these scenarios when truck lane restrictions are implemented. A graph of the data from Scenario I-U0 and Scenario I-R0 can be seen in Figure 1.

As seen in the graph, both scenarios, Scenario I-U0 without restrictions and Scenario I-R0 with restrictions, have virtually identical densities. Graphs of other compared scenarios showing densities and LOSs were also prepared but not reproduced in this report.

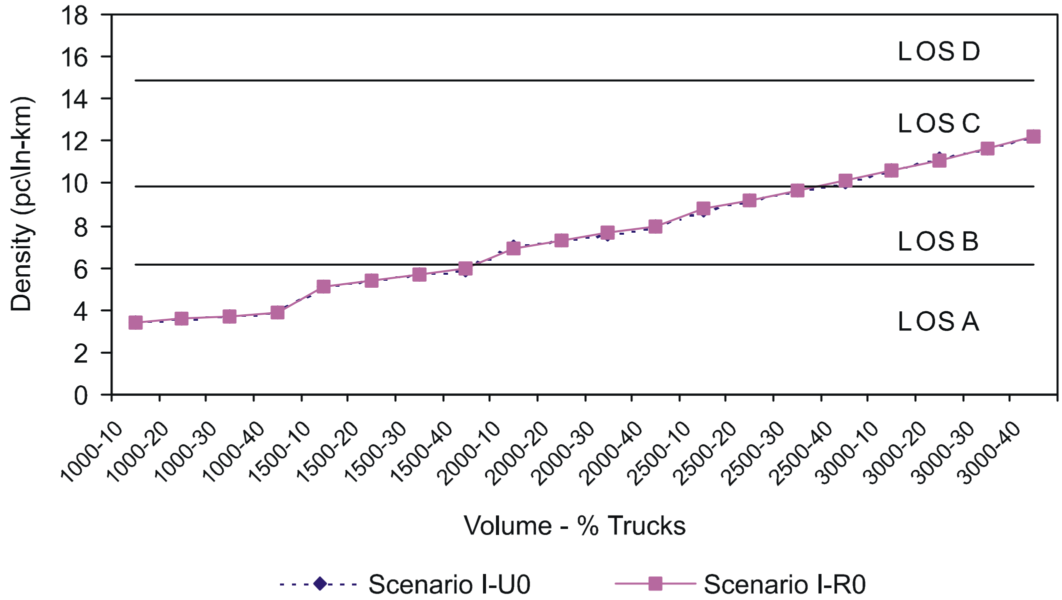

Figure 1. Scenario I-U0 vs. Scenario I-R0 for Density

Table 5 shows the combinations of data used in paired-sample *t* tests and whether or not they had significant differences. If there were significant differences, truck restrictions caused either an increase or a decrease in the density, which is also noted. A summary of the statistical tests with values of *t* can also be seen in this table.

Table 5. Summary of Statistical Tests on Density ($\alpha = 0.05$)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
I-U0 & I-R0	1.6581	1.729	No	No change
I-U2 & I-R2	-1.4802	1.729	No	No change
I-U4 & I-R4	-1.9613	1.729	Yes	Decrease in density
II-U0 & II-R0	1.9898	1.729	Yes	Increase in density
II-U2 & II-R2	-0.0971	1.729	No	No change
II-U4 & II-R4	-2.8107	1.729	Yes	Decrease in density
III-U0 & III-R0	1.1540	1.729	No	No change
III-U2 & III-R2	-1.4530	1.729	No	No change
III-U4 & III-R4	-3.4742	1.729	Yes	Decrease in density
IV-U0 & IV-R0	2.6237	1.729	Yes	Increase in density
IV-U2 & IV-R2	1.8155	1.729	Yes	Increase in density
IV-U4 & IV-R4	-3.4349	1.729	Yes	Decrease in density

The data show that density increases as the percentage of trucks increases. When comparing the scenarios with 0 percent grade and an initial volume distribution of 30, 35, and 35 percent, truck lane restrictions caused the density to increase significantly (Scenarios II-U0 and II-R0). This was also true when the initial volume distribution was 25, 38, and 37 percent by lane (Scenarios IV-U0 and IV-R0). However, when the grade reached 4 percent, truck restrictions caused densities to decrease for all initial volume distributions. The decrease in density could be due to trucks having difficulty climbing the grade, causing the traffic to spread out.

In addition to changes in density, it is also important to determine if any changes in LOS occurred with the implementation of truck lane restrictions. The LOSs for one scenario are shown in Figure 1. The LOS for other scenarios was not affected by the lane restrictions but changed only according to the volume, thus indicating that restricting trucks from the left lane had no significant effect on the LOS of the freeway section.

Lane Changes

Another performance measure used to determine how the implementation of truck lane restrictions would affect the operational performance of a highway is lane changes. The value used for the analysis was the average number of lane changes per vehicle.

The paired-sample *t* test was also used on lane change data to determine when significant changes occurred for a hypothetical section of highway.

For the significance tests, the same hypotheses were made as in the previous section:

H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$

where μ_1 = number of lane changes before truck lane restrictions

μ_2 = number of lane changes after truck lane restrictions.

When using data from Scenario I-U0 and Scenario I-R0, the results were as follows:

$$\overline{w} = 9$$
$$S_w = 11.26$$
$$t = 3.575$$

Standard *t* test tables show that $t = 1.729$.

Since the calculated $t = 3.575$ is greater than the tabulated *t* value, H_0 must be rejected. This means that there is a significant difference in the number of lane changes after the implementation of truck lane restrictions between Scenario I-U0 and Scenario I-R0. It can be seen from the data that the truck lane restrictions increase the number of lane changes that occur on the highway section in these two scenarios.

The lane change data have been displayed graphically for each of these pairs. The graph for Scenario I-U0 and Scenario I-R0 can be seen in Figure 2. Graphs for the other compared pairs were also prepared but are not shown in this report. A summary of the statistical tests can be found in Table 6.

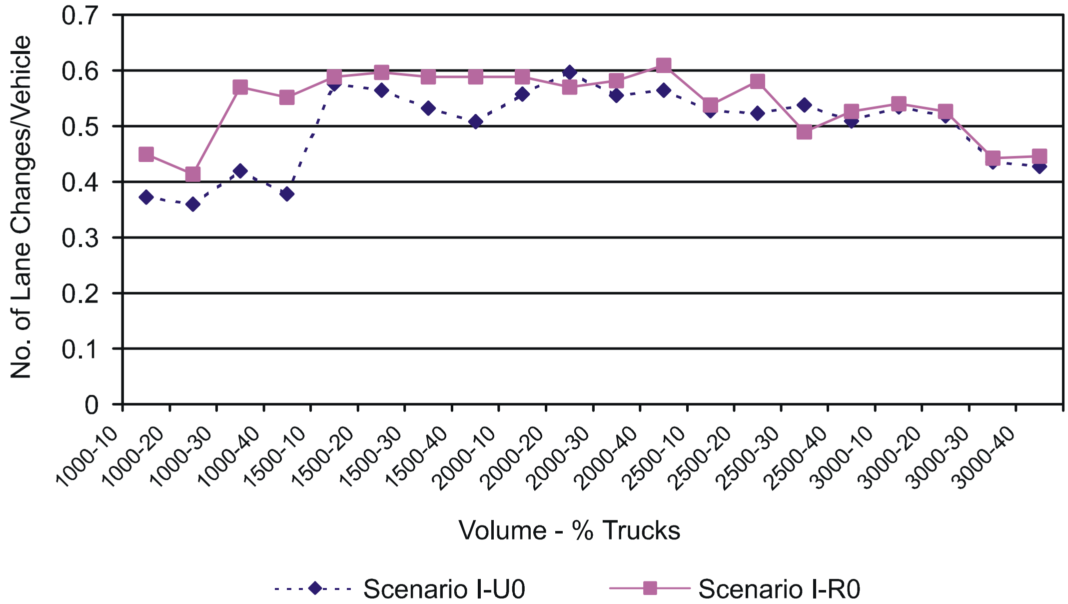

Figure 2. Scenario I-U0 vs. Scenario I-R0 for Lane Changes

Table 6. Summary of Statistical Tests on Lane Changes (α = 0.05)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
I-U0 & I-R0	3.3438	1.729	Yes	Increase in number of lane changes
I-U2 & I-R2	-1.6470	1.729	Yes	Decrease in number of lane changes
I-U4 & I-R4	-5.2331	1.729	Yes	Decrease in number of lane changes
II-U0 & II-R0	2.4469	1.729	Yes	Increase in number of lane changes
II-U2 & II-R2	-1.0633	1.729	No	No change
II-U4 & II-R4	-6.6227	1.729	Yes	Decrease in number of lane changes
III-U0 & III-R0	0.9053	1.729	No	No change
III-U2 & III-R2	-1.8206	1.729	Yes	Decrease in number of lane changes
III-U4 & III-R4	-5.5363	1.729	Yes	Decrease in number of lane changes
IV-U0 & IV-R0	1.0003	1.729	No	No change
IV-U2 & IV-R2	-1.1760	1.729	Yes	Decrease in number of lane changes
IV-U4 & IV-R4	-7.5298	1.729	Yes	Decrease in number of lane changes

The results from the significance tests show that restricting trucks from the left lane has an effect on the number of lane changes that occur for Scenarios I-U0 and I-R0. For the scenarios with a road grade of 0 percent, the number of lane changes increased for lane distributions I and II. For both a 2 and 4 percent grade, except lane distribution II at 2 percent grade, the restrictions caused the number of lane changes to decrease. The increase in lane changes at 0 percent grade could be from trucks having to change lanes to follow the restrictions. This was not seen for distributions III and IV since there are more vehicles traveling in the rightmost lanes already. The number of lane changes probably decreased at 2 and 4 percent grade because trucks were no longer traveling fast enough to pass other vehicles.

Speed Differential

The third performance measure used to determine how the implementation of truck lane restrictions would affect the operational performance of a highway is speed differential. The speed differential is the difference between the average speed of trucks and the average speed of cars on the highway. Speed differential is found in terms of kilometers per hour. The speed differential was found for the 24 scenarios that were simulated.

The paired-sample *t* test was also used with the speed differentials to determine if significant changes occur between various scenarios.

For the significance tests, the same hypotheses were made as in the previous sections:

H_0: $\mu_1 = \mu_2$ $\qquad$ H_1: $\mu_1 > \mu_2$

where μ_1 = speed differential before truck lane restrictions

μ_2 = speed differential after truck lane restrictions

When using data from Scenario I-U0 and Scenario I-R0, the results were as follows:

$$\overline{w} = -0.141$$
$$S_w = 1.0126$$
$$t = -0.6228$$

Standard *t* test tables show that $t = 1.729$.

Each of the scenarios compared has been displayed graphically. The graph for Scenario I-U0 and Scenario I-R0 can be seen in Figure 3. Graphs for the other compared pairs were also prepared but are not reproduced in this report. The results of the statistical tests for speed differential can be found in Table 7.

Table 7. Summary of Statistical Tests on Speed Differential (α = 0.05)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
I-U0 & I-R0	-0.6227	1.729	No	No change
I-U2 & I-R2	0.7064	1.729	No	No change
I-U4 & I-R4	2.7389	1.729	Yes	Increase in speed differential
II-U0 & II-R0	-1.3590	1.729	No	No change
II-U2 & II-R2	0.7282	1.729	No	No change
II-U4 & II-R4	3.8034	1.729	Yes	Increase in speed differential
III-U0 & III-R0	1.6654	1.729	No	No change
III-U2 & III-R2	1.8009	1.729	Yes	Increase in speed differential
III-U4 & III-R4	2.0908	1.729	Yes	Increase in speed differential
IV-U0 & IV-R0	1.1598	1.729	No	No change
IV-U2 & IV-R2	0.1122	1.729	No	No change
IV-U4 & IV-R4	2.6357	1.729	Yes	Increase in speed differential

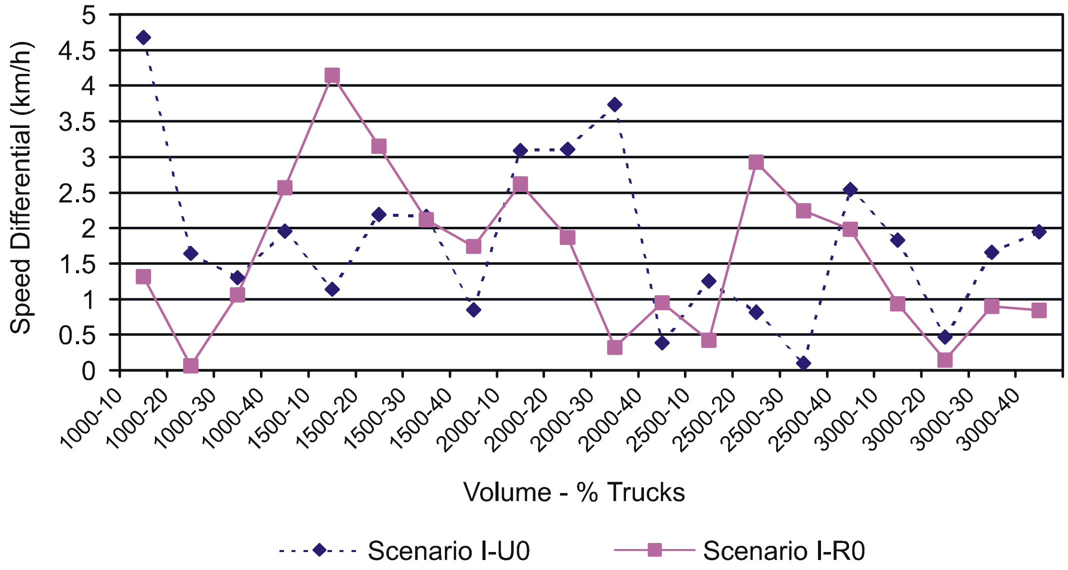

Figure 3. Scenario I-U0 vs. Scenario I-R0 for Speed Differential

A summary of significant differences for all of the performance measures can be seen in Table 8.

Table 8. Summary of Significant Differences in Performance Measures

Scenarios	Density	Lane Changes	Speed Differential
I-U0 & I-R0	No	Yes	No
I-U2 & I-R2	No	Yes	No
I-U4 & I-R4	Yes	Yes	Yes
II-U0 & II-R0	Yes	Yes	No
II-U2 & II-R2	No	No	No
II-U4 & II-R4	Yes	Yes	Yes
III-U0 & III-R0	No	No	No
III-U2 & III-R2	No	Yes	Yes
III-U4 & III-R4	Yes	Yes	Yes
IV-U0 & IV-R0	Yes	No	No
IV-U2 & IV-R2	Yes	Yes	No
IV-U4 & IV-R4	Yes	Yes	Yes

CASE STUDIES

After the scenario analysis was completed, the methodology was applied to several case studies. These case studies allowed implementation of truck lane restrictions on real sections of highway to determine whether or not actual sites behaved in the same manner predicted by the scenario analysis.

Site Selection

The site selection began by determining which sections of highway had adequate data for the project. In cooperation with VDOT district offices, it was determined that the existing stationary loop detectors in I-81 could be used to obtain traffic volumes by vehicle type, speed data, and headway data. This met the site selection criteria of available data.

Three sites were selected in conjunction with VDOT that were all within an acceptable driving distance from Charlottesville. One site includes exit and entry ramps, and two sites do not include ramps. This would allow for comparison between the two types of sites. After the traffic counts were obtained, it was determined that both the traffic volumes and percentage of trucks were high enough for this project.

Site Description

All three sites for the case studies were located on I-81 in Virginia. The first site is located near Buchanan and is 10.15 km long. The second site is an 11.12-km section located near Christiansburg. The third site is located near Wytheville and is 10.20 km long. The endpoints of each site are distinguished as distances from specific mileposts. For purposes of identifying the sites on the maps, the sites are shown as being between two exits. However, the actual sites extend past the exits. All three sites are rural and have speed limits of 104.6 km/h. The grades of the roadways varied for each site. The percentages of trucks on each site can be seen in Table 9.

Table 9. Truck Percentages on Case Study Sites

Site	Percentage of Trucks
Buchanan Northbound	35
Buchanan Southbound	30
Christiansburg Northbound	21
Christiansburg Southbound	21
Wytheville Eastbound	25
Wytheville Westbound	34

Data Collection

The data used in this project were acquired from VDOT district offices. They provided data from the stationary loop detectors for the sections of highway being studied. Included in these data was volume by vehicle type by lane. For the purposes of this project, cars were defined as vehicle classes 1 through 3 and trucks include vehicle classes 4 through 14 as seen in Table 2. These data were summarized to determine the percentage of trucks on each section of highway. In addition, VDOT supplied roadway plans to acquire grades and curvature data.

Studies of I-81 are currently underway by VDOT, and volume data were obtained from them. To create a more accurate picture of the effects of truck lane restrictions, it was determined that simulating the site with current volumes and then future volumes would be beneficial. For the Buchanan site, future volumes had already been predicted by VDOT. For the purpose of this study, the Christiansburg and Wytheville sites used the same growth rates as the Buchanan site since all three sites had behaved similarly in the past. These growth rates were 62 percent between 1998 and 2010, and 23 percent between 2010 and 2020. The volumes used in the simulations can be seen in Table 10.

The truck percentages at each site remained the same for all 3 years. After the necessary data were collected, the relevant date for each site was entered into the FRESIM model.

Table 10. Site Peak Hour Volumes (in vehicles/hour)

Site	Present Year	Year 2010	Year 2020
Buchanan Northbound	1120	1815	2240
Buchanan Southbound	1080	1740	2160
Christiansburg Northbound	1290	2090	2571
Christiansburg Southbound	1070	1733	2132
Wytheville Eastbound	1130	1831	2252
Wytheville Westbound	1110	1798	2212

Simulation

To run FRESIM, a link-node diagram is created such that each new node is located when there is a change in road geometry. For this study, nodes were located at grade changes, curvature changes, and entry and exit ramps. Links connect each node, and relevant information, such as the number of lanes and grade, is entered as a characteristic of the link. Volume data, along with truck percentages, are entered through node points. After all of the roadway data are entered into the model, the simulation can be run for a given time period. To ensure that the site is being simulated accurately, those parameters defined by the user are adjusted so that the simulation model replicates existing conditions.

Analysis

The analysis of each case study is similar to the scenario analysis described previously. The paired-sample *t* test is used to determine if lane restrictions cause significant differences in three performance measures: density, number of lane changes, and speed differential. However, instead of having sample pairs based on volume and percentage of trucks, each site has three sample pairs representing the present year, the year 2010, and the year 2020. The *t* test can then determine if truck lane restrictions will affect the specific site.

Each site was simulated with no restrictions, trucks restricted from the left lane, and trucks restricted from the right lane. Statistical tests were completed that compared results obtained before and after each type of restriction was in place. The results of the *t* tests for all three sites are shown in Table 11 for density, Table 12 for lane changes, and Table 13 for speed differential.

Table 11. Summary of Statistical Tests on Density ($\alpha = 0.05$)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
No Restrictions vs. Trucks Restricted from Left Lane				
Buchanan Northbound	0.06	2.92	No	No change
Buchanan Southbound	0.19	2.92	No	No change
Christiansburg Northbound	0.04	2.92	No	No change
Christiansburg Southbound	1.941	2.92	No	No change
Wytheville Eastbound	0.571	2.92	No	No change
Wytheville Westbound	3.737	2.92	Yes	Increased density
No Restrictions vs. Trucks Restricted from Right Lane				
Buchanan Northbound	-0.528	2.92	No	No change
Buchanan Southbound	-1.286	2.92	No	No change
Christiansburg Northbound	1.066	2.92	No	No change
Christiansburg Southbound	0.189	2.92	No	No change
Wytheville Eastbound	0.655	2.92	No	No change
Wytheville Westbound	-0.820	2.92	No	No change

Table 12. Summary of Statistical Tests on Lane Changes ($\alpha = 0.05$)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
No Restrictions vs. Trucks Restricted from Left Lane				
Buchanan Northbound	-0.585	2.92	No	No change
Buchanan Southbound	-1.941	2.92	No	No change
Christiansburg Northbound	0.855	2.92	No	No change
Christiansburg Southbound	0.714	2.92	No	No change
Wytheville Eastbound	0.608	2.92	No	No change
Wytheville Westbound	4.583	2.92	Yes	Increased lane changes
No Restrictions vs. Trucks Restricted from Right Lane				
Buchanan Northbound	4.441	2.92	Yes	Increased lane changes
Buchanan Southbound	3.381	2.92	Yes	Increased lane changes
Christiansburg Northbound	4.542	2.92	Yes	Increased lane changes
Christiansburg Southbound	4.871	2.92	Yes	Increased lane changes
Wytheville Eastbound	0.805	2.92	No	No change
Wytheville Westbound	-0.901	2.92	No	No change

Table 13. Summary of Statistical Tests on Speed Differential ($\alpha = 0.05$)

Scenarios Tested	Calculated *t*	Critical *t*	Significant Difference	Result
No Restrictions vs. Trucks Restricted from Left Lane				
Buchanan Northbound	0.779	2.92	No	No change
Buchanan Southbound	1.597	2.92	No	No change
Christiansburg Northbound	3.741	2.92	Yes	Increased speed differential
Christiansburg Southbound	0.550	2.92	No	No change
Wytheville Eastbound	7.504	2.92	Yes	Increased speed differential
Wytheville Westbound	1.531	2.92	No	No change
No Restrictions vs. Trucks Restricted from Right Lane				
Buchanan Northbound	6.137	2.92	Yes	Increased speed differential
Buchanan Southbound	1.915	2.92	No	No change
Christiansburg Northbound	1.253	2.92	No	No change
Christiansburg Southbound	-0.231	2.92	No	No change
Wytheville Eastbound	4.443	2.92	Yes	Increased speed differential
Wytheville Westbound	2.206	2.92	No	No change

Buchanan, Virginia

As previously described, this case study was conducted on a 10.15-km section of I-81. This section has no interchanges and currently has two lanes in each direction. The site was first modeled with two lanes in each direction and was then converted into having three lanes in each direction after adjustments were made so that FRESIM was replicating existing conditions. This was necessary since truck lane restrictions cannot easily be applied to highways with fewer than three lanes. No initial volume distribution was known since the current road has only two lanes. Therefore, in the three-lane model, a distribution of 33, 33, and 34 percent was used for the left, middle, and right lane, respectively, for both northbound and southbound cases. This distribution was chosen since it will produce results for a worse case scenario as opposed to forcing better results from another volume distribution. This site was considered to have mountainous terrain with road grades ranging from –4.00 to +4.00 percent, so E_T = 6.0 was used for the density analysis.

Christiansburg, Virginia

The 11.12-km Christiansburg site is also located on I-81 and currently has two lanes in each direction. Like the Buchanan site, the site was simulated with two lanes and then with three lanes so that the truck lane restrictions could be applied. The simulation model was also adjusted so that it was replicating existing conditions. The initial volume distribution by lane was again 33, 33, and 34 percent. The site had a rolling terrain with grades ranging from –4 to +2 percent northbound and –3.77 to +1.91 percent southbound, so E_T = 3.0 was used for passenger car equivalence in the density analysis. The site was simulated without restrictions and then for a situation where trucks are restricted from the left lane and another when trucks are restricted from the right lane. Statistical tests were completed for before and after the restrictions.

Wytheville, Virginia

The site at Wytheville is a 10.20-km section that currently has three lanes in each direction. The initial volume distribution at the site was 39, 45, and 16 percent eastbound and 38, 46, and 16 percent westbound. Like the other two sites, this section of roadway was simulated for no restrictions, trucks restricted from the left lane, and trucks restricted from the right lane. This site was also mountainous with grades ranging from –4 to +3.14 percent eastbound and –3.3 to +4 percent westbound, so the value E_T = 6.0 was used for density analysis.

DICUSSION

Scenario Analysis

The results from the scenario analysis allowed for several general trends to be determined. For density, the data showed that at a 4 percent grade, restricting trucks from the left lane decreased average density on the hypothetical highway section. This decrease in density is probably attributed to cars being able to pass slower moving trucks up the incline.

With the implementation of truck restrictions at 0 percent grade and volume distributions I and II, the number of lane changes increased. At 2 percent grade for all of the volume distributions except II, the number of lane changes decreased. At 4 percent grade for all volume distributions, restricting trucks from the left lane caused a decrease in the number of lane changes. The decreases at higher grades are most likely due to trucks not changing lanes as much while going uphill and cars passing slower moving trucks without having to change lanes as frequently.

The results of the scenario analysis on speed differential showed that at 0 percent grade and 2 percent grade, no effects were seen due to restricting trucks. However, at 4 percent grade, the speed differential increased for all volume distributions.

Case Studies

The results of the case studies varied among the sites. For the Buchanan and Christiansburg sites, restricting trucks from the right lane caused the number of lane changes to increase. For the Buchanan site, both northbound and southbound, restricting trucks from the left lane had no impact on the three performance measures. This was also true for the Christiansburg site southbound. At the Christiansburg site northbound and the Wytheville site eastbound, restricting trucks from the left lane caused the speed differential to increase. An increase in the speed differential was also seen at the Wytheville eastbound site when trucks were restricted from the right lane. These increases in speed differential could affect the number of accidents.

The Wytheville westbound site was the only site that had restrictions affecting density. When trucks were restricted from the left lane, density increased. The number of lane changes also increased for this site. The Wytheville site had exit and entry ramps along the section, and maneuvers involving these ramps could contribute to an increased density and number of lane changes.

CONCLUSIONS

1. *Restricting trucks from the left lane with steep grades causes an increase in the speed differential.* Results from the scenario analysis and the case studies show that restricting trucks from the left lane at steep grades causes an increase in speed differential. This restriction acts in a similar manner as truck climbing lanes.

2. *Restricting trucks from the left lane with steep grades may decrease density and the number of lane changes.* The scenario analysis showed that at a constant 4 percent upgrade, restricting trucks from the left lane would decrease density and the number of lane changes. For the case studies, however, these trends were not seen. Since the scenario analysis was completed for a variety of volumes, it is predicted that sites with volumes higher than the

ones used and a more consistent high grade will have decreases in density and lane changes when trucks are restricted from the left lane.

3. *Restricting trucks from the right lane causes an increase in the number of lane changes for sites without exit and entry ramps.* The effect of restricting trucks from the right lane was addressed only for each case study. At the sites without exit and entry ramps, restricting trucks from the right lane increased the number of lane changes. The increase in lane changes occurs since trucks are required to shift to the left lanes under the restrictions and then make additional lane changes to accommodate passing cars in the left lane.

4. *Site characteristics dictate the effects of truck lane restrictions.* The scenario analysis is useful in determining typical trends, but when one is trying to determine the effect of truck restrictions at a specific site, the site characteristics are the most important factors. Each site has a different volume, volume distribution, percentage of trucks, curvature, and grade. When determining if lane restrictions should be implemented at a specific site, modeling that site is necessary.

RECOMMENDATIONS

1. *Restrict trucks from the left lane on highways with grades of 4 percent or higher.* Restricting trucks from the left lane of roads with high grades will be helpful in allowing for faster vehicles to pass slower trucks. These restrictions could be implemented through the use of climbing lanes and restricting trucks to the climbing lanes. When grades vary over a section of roadway, excessive changes in truck restrictions should be avoided.

2. *Do not restrict trucks from the right lane.* Restricting trucks from the right lane caused increases in lane changes and could lead to safety problems. An increase in the number of lane changes results in more interactions between vehicles and the potential for more vehicle conflicts.

3. *Continue the use of left lane restrictions at existing sites.* The results of this research have not produced findings that would support removing restrictions on Virginia highways regarding truck lane use. The scenario analysis and the case studies did not produce apparent negative effects from these restrictions that suggest that restrictions are not warranted. This recommendation is based only on FRESIM output and not accident data

.

AREAS NEEDING FURTHER RESEARCH

1. *The impact of truck lane restrictions on the three performance measures—density, number of lane changes, and speed differential—using real data taken from actual traffic counts and measurements.* Although these performance measures were investigated in this study, it is necessary to determine what is actually occurring on the highways. Observing lane changes and speed differential along with calculating the actual densities at a specific time would

produce more accurate results than the simulation model. Efforts should be made to begin collecting data at sites with newly implemented lane restrictions. These data can be compared to past data to determine the effects of the lane restrictions.

2. *Effect of truck lane restrictions on emissions.* The simulation model in this study, FRESIM, also produces output regarding emissions. Determining the effect of truck lane restrictions on emissions is important to see if restricting trucks could improve the level of emissions on I-81 if the area is suffering air quality problems addressed by FRESIM.

3. *Restriction of trucks to the middle two lanes on a highway section with four lanes in each direction.* Restricting trucks to the middle lanes of a four-lane highway could allow for cars to pass in the left lane and exit from the rightmost lane. The operational effects of such a restriction would be important to investigate before implementation of these restrictions.

4. *Comparison of accident rates and FRESIM data.* Accident rates were not directly addressed in this research but are important to study related to truck lane restrictions. It would be beneficial to compare the accident rates at sites with truck lane restrictions to the FRESIM simulation data to see if FRESIM output parameters are an accurate predictor of safety.

5. *Truck lane restrictions in urban areas with higher total volumes.* This study did not simulate sites that were in urban areas. The effect of truck restrictions in urban areas could be different than those in rural areas as seen in this study and need to be investigated. Also, urban areas have higher volumes that could lead to other operational problems. The results of this research should not be applied to urban areas without further study. In addition, many urban areas do meet the criteria of having at least 20 percent trucks at the studied section. However, studying all urban areas with a variety of truck percentages would be beneficial.

6. *Merging and diverging problems at ramp areas.* This study examined one case study that had ramp areas but did not investigate actual merging and diverging movements around the ramp areas. Also, the delay at ramps must be studied since delays tend to increase as vehicles enter the highway when trucks are restricted from the left lane. Also, the probability of accidents at ramps must be studied. Detailed interchange studies must be conducted to determine how cars and trucks behave around ramps when restrictions are implemented.

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