

Another View of Truck Lane Restrictions

Submitted to the Transportation Research Board November 14, 2003

5,098 Words, 7 Tables

Matthew A. Cate
Senior Research Associate
The University of Tennessee
Center for Transportation Research
309 Conference Center Building
Knoxville, TN 37996-4133
Tel: (865) 974-4614
Fax: (865) 974-3889
Email: mcate@utk.edu

Thomas Urbanik II, P.E.
Professor and Goodrich Chair of Excellence in Transportation
The University of Tennessee
Department of Civil and Environmental Engineering
219-B Perkins Hall
Knoxville, Tennessee 37996-2010
Tel: (865) 974-7709
Fax: (865) 974-2669
E-mail: turbanik@utk.edu

Abstract. As truck volumes on US highways continue to increase, both elected officials and members of the general public often look to the use of lane restrictions for large trucks as a means to increase operating efficiency and highway safety. In the past, research has offered little evidence that either safety or efficiency is positively impacted by widespread use of this practice. This paper offers another view of truck lane use restrictions on high-speed, limited access facilities.

To determine the effects of lane use restrictions, scenarios which varied traffic characteristics such as volume, grade, percentage of trucks, and the presence of entrance and exit ramps, were developed using the VISSIM model. In each scenario traffic along the model freeway segment was monitored to determine the effect of the lane use restrictions by comparing values of various traffic measures from a model run first without and then again with truck lane restrictions.

As in past research efforts, the implementation of truck lane restrictions in a variety of scenarios is shown to have little effect on a number of traditional measures, including average speed, speed differential between cars and large trucks, and level of service. However, further examination of data resulting from the simulation process shows that significant gains in the area of safety and driver comfort may be realized through the reduction of lane-changing maneuvers by all vehicle types, lending support to past drivers surveys indicating strong support for this practice among drivers of passenger vehicles.

INTRODUCTION

As freeway volumes increase (especially those of large trucks), states across the country have sought new ways to increase driver comfort, operating efficiency, and traffic safety. More agencies are turning to the “managed lanes” concept rather than utilizing physical expansion of roadways. The managed lanes concept involves the assignment of special operating conditions to specific lanes of a roadway in order to improve the efficiency and/or safety of the roadway as a whole. This strategy typically involves restricting the use of one or more lanes on the basis of vehicle type or occupancy and may or may not vary by time of day (*1*). One such managed-lane concept utilized by many local and state agencies is truck lane-use restrictions.

While drivers of smaller vehicles are typically pleased with these lane restrictions, the previous research efforts in this area have revealed mixed results in the areas of safety and efficiency. This paper presents the results of an evaluation of truck lane restrictions using the VISSIM microscopic traffic simulation software package as an analysis tool. The objective of this application is to study truck lane restrictions at a very detailed level not previously available in general-purpose traffic simulation models. The suitability of VISSIM as a means of testing lane restrictions is confirmed and the necessary model adjustments are completed to determine the operational impacts of lane restrictions.

BACKGROUND

For various reasons, truck lane restrictions are often used by state departments of transportation across the county. In 1986, a survey of the 50 states plus the District of Columbia and Puerto Rico by the Federal Highway Administration revealed that 24 of the 52 agencies used some form of truck lane restriction to improve operations, reduce accidents, or provide for more predictable pavement wear (*2*). A subsequent survey of the 50 states, performed by the Texas Transportation Institute in 1997 (*3*), found that only 14 responding states indicated the use of lane restrictions on interstate highways. The survey also found that 2 states used restrictions in work areas, one state used lane restrictions only on non-interstate highways, and two states were considering lane restrictions on interstate highways in the future. It should also be noted that 13 of the 50 states provided no response to the survey (*3*). A comparison of these two surveys would seem to indicate that truck lane restrictions saw a decrease in use from 1986 to 1997.

While moderate to strong support for truck lane use restrictions exists among the general public (*4, 5, 6*), several studies of truck lane restrictions have produced mixed results in the areas of operations, safety, and pavement performance. In the earliest operational study reviewed, Hanscom studied three separate interstate sections in Wisconsin and Illinois (*7*). Using truck lane occupancy, delay to following vehicles, proportion of trucks impeding followers, and adjacent lane speed differential as the measures of effectiveness, the study performed tests before and after implementation of the truck lane restrictions. Two of the test sites were located in urban/suburban areas outside of Chicago with three lanes of travel in each direction. The third test site was located in rural

Wisconsin with 2 lanes of travel in each direction. Trucks were restricted to the 2 right lanes of both Illinois sites and to the left lane only at the Wisconsin site because of deteriorating pavement in the right lane. At each of the three sites, a high level of compliance with the truck lane restrictions was observed. For the two suburban Illinois sites, a decrease in the number of vehicles impeded by trucks was recorded relative to control sites despite an increase in traffic volume from the before studies. However, the two-lane Wisconsin site displayed some negative effects attributed to the crowding of trucks in the left lane and limited passing opportunities for cars following non-complying trucks in the right lane (7). In his conclusions, Hanscom indicates that the study results favor the continued use of truck lane restrictions on sections with 3 or more lanes of travel but many questions still exist regarding the safety of restrictions on 2 lane sections (7).

In its 1990 study, TTI evaluated 3 sites of 6-lane (total) rural interstate in Texas. One of the study sites included a 3 percent grade (2). Data collected for this study includes rate of compliance with the lane restriction, lane distribution by vehicle classification, time gap between vehicles, and vehicle speeds. Before and after comparisons indicate that compliance with the restrictions is high. After the restrictions, only 3 percent of the trucks remained in the left lanes of travel (2). Despite the fact that the lane distribution of trucks was significantly affected, the lane distribution of cars shows no corresponding change. While the time gaps in the before and after conditions offer little meaningful interpretation, the authors do note that the smallest average time gaps were observed for trucks following trucks. The study of speed by vehicle classification also offers few clear results. The major finding in this category is that speed of trucks is significantly lower than that of cars on a long upgrade (2). After a thorough comparison of before and after results for each data group, the researchers concluded that no negative effects were caused by the restriction and the practice of restricting trucks to the 2 right lanes should continue at the study sites (2).

In a 1997 report, TTI develops guidelines for the implementation of truck lane restrictions on Texas Highways (3). While much of the report offers a detailed discussion of previous research on lane restrictions, both in Texas and in other states around the country, the report does offer very specific situations where the use of truck lane restrictions is appropriate. Foremost among these conditions is that truck lane restrictions should only be used on access-controlled facilities with 3 or more lanes in each direction of travel (3). This requirement is consistent with the findings of Hanscom (7) and the 1990 TTI study (2). Also, the guidelines recommend that trucks are able to use all lanes, including those with restrictions, for the purpose of passing another vehicle or entering/exiting the roadway. Finally, the guidelines urge that a thorough review of each site is undertaken by TxDOT to insure that characteristics are appropriate for a truck lane restriction and that existing traffic control devices do not conflict with the new restriction (3).

Research by Hoel and Peek for the Virginia Department of Transportation focuses on the evaluation of truck lane restrictions using the FRESIM microscopic simulation software. Areas of consideration in the traffic simulation included vehicle density, lane changes per vehicle in the test area, and speed differential between cars and trucks in the restricted areas (8). The first phase of simulation involved the variation of a number of geometric characteristics on a hypothetical 3-mile-long, 3-lane freeway segment with a 65 mph free flow speed. Each simulation was run for 3600 seconds (1 hour). The variables under consideration included traffic volume, percentage of trucks, percentage of total volume by lane, presence or absence of lane restrictions, and grade (8). To account for a change due to lane restrictions, trucks were restricted from the left lane. A total of 24 different scenarios were constructed for simulation. Among the observations from the initial scenarios, a few important observations are made. First, in no scenario did the lane restriction affect the level of service. On upgrades, the number of lane changes was reduced with the lane restriction. For tests of speed differential, the speed differential between cars and trucks increased with lane restrictions for higher truck percentages (8). In the second phase of simulation, VDOT officials selected three sites on I-81 in the Charlottesville area. The FRESIM model for each site was calibrated using actual traffic data. Each site was then evaluated for two truck lane restrictions, one with trucks restricted from the left lane and one with trucks restricted from the right lane (8). From these scenarios and case studies, a number of conclusions and recommendations are reached. These include:

- Restricting trucks from the left lane with steep grades may decrease density and number of lane changes
- Restricting trucks from the right lanes increases the number of lane changes for sites without entry and exit ramps
- Site characteristics have an impact on the effects of truck lane restrictions
- Trucks should be restricted from the left lane on sections with grades of 4 percent or higher

- Trucks should not be restricted from the right lane (8)

Furthermore, the report concludes that the simulations revealed no reason to discontinue the use of truck lane restrictions at existing sites.

The most recent TTI study of large truck lane restrictions was performed as part of an effort to study truck safety alternatives on Houston Freeways. An 8-mile-long section of Interstate 10 East was selected for evaluation of the effects of a lane restriction in the Houston area in part because of its high crash rates, high truck volumes, and the availability of overhead sign structures that could be used to mount required signing (6). The initial analysis of crash records from the 36-week test period indicates a substantial decrease from previous crash records for the same interstate segment. In 1998, the most recent year for which Texas Department of Public Safety had complete data at the time of the study, the section showed an average of 7.5 crashes per week. In comparison, the same freeway segment showed an average of 2.9 crashes per week over the study period (6). The percentage of crashes involving large trucks was essentially unchanged from the before and after conditions. While this 68% reduction to the average number of crashes per week is impressive, the researchers note that a period of at least one year would typically be required to establish a shift in accident rates. Finally, the researchers used data from TxDOT's automated vehicle speed sensors to monitor changes in average speed at different locations along the test segment. Analysis shows that the average speed at some locations was slightly increased while other locations displayed a slight decrease. Overall, the report concludes that the truck lane restriction has no significant impact on freeway speeds.

The most recently completed study to quantify the operational effects of truck lane restrictions was performed for the Tennessee Department of Transportation by the University of Tennessee Center for Transportation Research (9). In this project, before and after conditions were compared for two sections of Interstate 40 in the Knoxville area. Data were collected at two sites along each freeway section. The primary measures of effectiveness for this study were truck lane distribution and 85th percentile truck speeds. A comparison of before and after data reveals that compliance with the lane restrictions was very high, even in the presence of minimal signing and limited enforcement. The western test area on Interstate 40/75 consisted of heavy traffic in a suburban setting with a mixture of 3 and 4 lanes in each direction. The eastern area on Interstate 40 was rural in nature with traffic volumes much lower in comparison to the western section. Despite the difference in the nature of these two test areas, each displayed very similar results. In the before condition, the percentage of trucks using the left lane was approximately 10 percent. In the after condition, the percentage of trucks using the left lanes decreased significantly, with approximately 3 percent of trucks in the left lane on the western area and less than 2 percent of trucks in the left lanes of the eastern area. However, results were not conclusive for the comparison of truck speeds. In some instances, the speed of trucks decreased after the restrictions were implemented. In others, the speed of trucks was increased. No consistent pattern was identified for the sites and the changes could not be attributed to the lane restrictions (9).

Overall, the past research seems to indicate very little concrete evidence that operations or safety are improved by the use of truck lane restrictions. One key area of agreement is that the use of truck lane restrictions on extended upgrades does improve operations by reducing density and the number of lane changes (8), though safety may be compromised by the resulting increase in speed differential between cars and trucks (2, 8). However, surveys of motorists in Texas and Washington State do show that motorist comfort is significantly increased in the presence of truck lane restrictions (2, 3).

STUDY DESIGN

Before the impact of truck lane restrictions can be studied, an evaluation must first be made to determine whether VISSIM can accurately model freeway operations in general and with truck lane restrictions specifically. VISSIM is a microscopic traffic simulation model with a number of user-adjustable parameters such as lane usage, free-flow speeds, lane-changing behavior (including several parameters that control driver "aggressiveness"), vehicle power, weight, and braking characteristics, and traffic composition (10).

A series of simulations was performed to test the effect of truck lane restrictions on performance measures such as density, travel time, and the number of lane changes. In keeping with the recommendations of the numerous

studies detailed in the background section, the modeling will focus exclusively on lane restrictions where large trucks are prohibited from using the far left travel lane on freeway sections with three or more lanes of travel in a single direction. This type of restriction is consistent with the practice in Tennessee, Texas, and other states that have chosen to test or implement truck lane restrictions.

In order to make the results of the testing as realistic as possible, field traffic data was utilized to create volumes and truck percentages representative of actual freeway operations. Traffic data was collected along westbound Interstate 40/75 in Knoxville, TN, using RTMS radar units. The main lane, entrance ramp, and exit ramp volumes and truck percentages used in the simulation process are derived from the traffic data collected on Interstate 40/75 at the Pellissippi Parkway interchange.

Once the average, maximum, and minimum volumes and truck percentages are identified for the main lanes and the ramps (Table 1), a number of scenarios must be identified under which the effect of the lane restrictions will be quantified. As in the Hoel and Peek study, a number of factors (including grade, volume, truck percentage, and presence of ramps) must be considered in various combinations in order to assess the impact of lane restrictions. While the time constraints of this study do not provide for simulation under all possible combinations of factors, a number of important scenarios were identified. These scenarios may be seen as Table 2. For each scenario, two simulations are performed. In the first scenario, all vehicles are free to travel in any lane. In the second simulation, large trucks are restricted to the two right lanes of travel (all other inputs and settings are unchanged from the first simulation). So that the vehicle behavior in the VISSIM simulations is representative of the traffic on Interstate 40/75 at Pellissippi Parkway, the desired speed ranges are set from 55 to 85 mph for passenger vehicles, and from 60 to 80 mph for large trucks.

TABLE 1 Traffic Inputs Used in VISSIM Simulation Models

| | Main Volume (vph) | Main % Trucks | Entering Volume (vph) | Entering % Trucks | Exiting Volume (vph) | Exiting % Trucks |
|----------------|-------------------|---------------|-----------------------|-------------------|----------------------|------------------|
| High | 3,100 | 25% | 530 | 42% | 650 | 3% |
| Average | 2,300 | 20% | 260 | 16% | 400 | 1% |
| Low | 1,250 | 13% | 130 | 2% | 250 | 0% |

In scenarios without ramps, the model consists of a single 5-mile-long segment with three lanes. In scenarios with ramps, the initial segment is 2 miles long with three travel lanes. At the 2-mile mark, the entrance ramp joins the freeway's main lanes with a 1320-foot-long (0.25 miles) acceleration lane. At the 3-mile mark, the exit ramp diverges from the freeway. From this point the final freeway segment continues for another 2 miles, for a total length of 5 miles. A weaving section was not used for the purposes of the lane restriction evaluation because the location where traffic data was gathered does not have a weaving section.

After the simulations for each scenario are completed, the output files generated by VISSIM are used to calculate the following performance statistics: vehicle density and level of service for each distinct freeway segment (*II*), average travel time for individual vehicle types and routes, the number and description of each lane change in the model over the simulation period. Comparisons between the "before" and "after" conditions are used to quantify the impact of the lane restriction.

TABLE 2 Summary of Simulation Scenarios

| Scenario | Volume | % Trucks | Grade | Ramps? |
|----------|---------|----------|-------|--------|
| 1 | High | Average | 0% | No |
| 2 | Low | Average | 0% | No |
| 3 | Average | Average | 0% | No |
| 4 | Average | Low | 0% | No |
| 5 | Average | High | 0% | No |
| 6 | Average | Average | 2% | No |
| 7 | Average | Average | 4% | No |
| 8* | Average | Average | 0% | Yes |
| 9 | Average | High | 4% | No |
| 10 | Average | Low | 4% | No |
| 11 | Average | Average | 0% | Yes |
| 12 | Average | High | 0% | Yes |
| 13 | High | High | 0% | Yes |

* Scenario 8 is prepared using the default VISSIM lane changing behavior and is included only to demonstrate the effect of these unadjusted values on the simulation results.

RESULTS

This section will discuss the results of the various analyses performed as a part of this project. Using the lane closure, it is easy to implement the lane restrictions. By selecting the appropriate lane and highlighting the vehicle types that are to be prohibited in the lane, VISSIM can effectively model a lane restriction.

An investigation of default vehicle characteristics reveals that the values for heavy trucks (HGV) in VISSIM tend to be more indicative of European vehicles than of the large trucks typically found on North American freeways. The default weight range for heavy trucks, 6200 to 88,000 lb (2800 to 40,000 kg) was deemed to be too light to accurately reflect the majority of trucks on American freeways. To adjust these values, a new value of 45,000 to 80,000 lb (20,430 to 36,320 kg) was selected. This change moves the overall distribution to a much higher load level, assuming that only those trucks carrying a substantial load will significantly affect the quality of traffic flow. The power range of the large trucks was also adjusted, from 135 – 670 hp (100 – 500 kW) to 335 – 670 hp (250 – 500 kW).

Additionally, a preliminary run of the simulation model using the default lane changing behaviors, shown in Table 2 as Scenario 8, revealed that the model did not function as well as the real-world situation which it was intended to simulate. A queue formed on the on-ramp as trucks were unable to merge into the main lanes of the freeway. The “aggressiveness” of lane changes by large trucks was increased by reducing the minimum distance and increasing the maximum speed differential between vehicles. Also, the lane-changing behavior of all vehicles was altered to increase the acceptable rate of acceleration and deceleration for necessary lane changes (i.e. entering or exiting the freeway). With these minor adjustments, vehicles were able to merge effectively without queuing.

Effects of Large Truck Lane Restrictions on 3-Lane Freeway Segments

Once the model parameters are adjusted to better reflect the characteristics of the traffic flow being modeled, the process of simulating the scenarios described in Table 2 can begin. Each scenario is run twice for a duration of one hour. In the first run, all vehicles are free to travel in any lane. In the second iteration, large trucks are restricted to the right two lanes of the freeway. Following the completion of each simulation period, the output files were exported to Microsoft Excel for analysis. The output data is used to evaluate each scenario for vehicle density, travel time, speed differential between cars and trucks, and lane changing frequency.

The first performance measure to be evaluated for each scenario is vehicle density. Density, in units of passenger cars per mile per lane (pcpmpl), can be used to describe the level of service of a given freeway section. The level of service remained unchanged in each of the scenarios evaluated by Hoel and Peek using the FRESIM software. The results of this project yield similar results: the introduction of truck lane restrictions typically had a minimal impact on the observed vehicle density.

On level sections, the truck lane restriction either resulted in no change or a slight increase in vehicle density and level of service. However, on uphill grades, the truck lane restrictions offer some improvement in the form of reduced density. In Scenario 6, featuring average volumes and truck percentages on a 2% uphill grade, the restriction yields a decrease of 0.2 pcpmpl. The overall level of service remains unchanged at level B in both the before and after conditions.

However, as the uphill grade is increased to 4%, the overall impact of the lane restrictions is much greater. In scenario 7, the traffic volumes and truck percentages are identical to those in scenario 6. However, because of the increased uphill grade, the large trucks are more greatly affected than in Scenario 7. As a result, the density in the after condition is 3.4 pcpmpl less than that of the before condition. This effect is even greater in Scenario 9, where traffic volume is at the average level but trucks are at a high percentage of overall vehicles. In this scenario, density is decreased by 4.2 pcpmpl. Additionally, the overall level of service for the segment is improved from level of service E to level of service D. Additional information regarding the effects of truck lane restrictions on level of service measures in the simulation scenarios is available from the authors by request.

While vehicle density is a helpful statistic in assessing the performance of a freeway section, it means little to the average motorist. For that matter, most drivers wouldn't understand the difference between level of service B and level of service C without explanation. However, drivers do understand the concept of travel time. If we are able to travel from point A to Point B in a relatively short amount of time, we are happy. As the time to travel between two points increases, we become increasingly displeased with the traffic flow. A comparison of travel times generated before and after the implementation of truck lane restrictions offers a tangible measure of the resulting impact to all observers. The average speed over a segment or route can also be derived from the travel time information, allowing for the evaluation of the speed differential between cars and trucks.

As seen in Tables 3, 4, and 5, the impact on average travel times is minimal on level terrain. However, as the uphill grade is increased, the results show noticeable improvement following the introduction of truck lane restrictions. In Scenario 6, the average travel time of cars is reduced by 4.9 seconds, while the travel time for trucks is only increased by 0.7 seconds. The change is much more drastic in scenarios with a 4% uphill grade. In Scenario 9, the overall travel time for passenger cars is reduced by 60.7 seconds over the five-mile-long segment. This translates in a reduction of 12 seconds to the time required to cover each mile in the section. On the other hand, the travel time results also show that there is little penalty to be paid by large truck operators to achieve this improvement. Truck travel times are not affected by more than 1.0 seconds in Scenarios 7, 9, and 10. The trends of the travel time analysis confirm the results of the comparison of vehicle density by indicating a minimal degradation of flow on level terrain and a significant improvement on steep (4%) uphill segments.

TABLE 3 Comparison of Before and After Travel Times without Ramps

| | Cars | | | Trucks | | | All Vehicles | | |
|-----------|--------|-------|--------|--------|-------|--------|--------------|-------|--------|
| | Before | After | Change | Before | After | Change | Before | After | Change |
| 1 | 267.9 | 269 | 1.1 | 271.6 | 275.3 | 3.7 | 268.7 | 270.3 | 1.6 |
| 2 | 261.5 | 261.5 | 0.0 | 263.3 | 265.1 | 1.8 | 262 | 262.3 | 0.3 |
| 3 | 264.7 | 265.1 | 0.4 | 267.4 | 269.8 | 2.4 | 265.3 | 266.1 | 0.8 |
| 4 | 264.5 | 264.5 | 0.0 | 267 | 269.6 | 2.6 | 264.9 | 265.2 | 0.3 |
| 5 | 264.7 | 265 | 0.3 | 267.9 | 270.1 | 2.2 | 265.5 | 266.3 | 0.8 |
| 6 | 276.3 | 271.4 | -4.9 | 323.9 | 324.6 | 0.7 | 286.2 | 282.4 | -3.8 |
| 7 | 355.2 | 301.4 | -53.8 | 492.8 | 493 | 0.2 | 382.9 | 339.6 | -43.3 |
| 9 | 365.1 | 304.4 | -60.7 | 492.7 | 493.5 | 0.8 | 396.1 | 349.9 | -46.2 |
| 10 | 324.6 | 291.8 | -32.8 | 490.7 | 490.6 | -0.1 | 346.7 | 317.8 | -28.9 |

TABLE 4 Comparison of Before and After Car Travel Times on Level Terrain with Ramps

| | Car 1 | | | Car 2 | | | Car 3 | | |
|-----------|--------|-------|--------|--------|-------|--------|--------|-------|--------|
| | Before | After | Change | Before | After | Change | Before | After | Change |
| 8 | 264.9 | 265.9 | 1.0 | 199.3 | 200.2 | 0.9 | 203.0 | 204.2 | 1.2 |
| 11 | 264.7 | 265.1 | 0.4 | 199.2 | 199.3 | 0.1 | 203.0 | 203.4 | 0.4 |
| 12 | 265.1 | 265.4 | 0.3 | 199.2 | 199.4 | 0.2 | 203.7 | 204.0 | 0.3 |
| 13 | 269.3 | 269.6 | 0.3 | 201.9 | 202.6 | 0.7 | 208.4 | 209.8 | 1.4 |

TABLE 5 Comparison of Before and After Truck Travel Times on Level Terrain with Ramps

| | Truck 1 | | | Truck 2 | | | Truck 3 | | |
|-----------|---------|-------|--------|---------|-------|--------|---------|-------|--------|
| | Before | After | Change | Before | After | Change | Before | After | Change |
| 8 | 268.1 | 273.0 | 4.9 | 196.5 | 194.4 | -2.1 | 216.2 | 217.3 | 1.1 |
| 11 | 267.7 | 270.9 | 3.2 | 194.9 | 196.2 | 1.3 | 215.6 | 216.1 | 0.5 |
| 12 | 267.9 | 271.2 | 3.3 | 199.8 | 201.2 | 1.4 | 216.9 | 218.6 | 1.7 |
| 13 | 273.1 | 277.8 | 4.7 | 201.5 | 203.4 | 1.9 | 219.3 | 222.0 | 2.7 |

Once travel times are established for each scenario, it is possible to convert these times to an average speed for each vehicle type. By observing the before and after values for speed differential between cars and trucks in each scenario, an assessment of the safety impact of truck lane restrictions may be undertaken. A decreased speed differential will theoretically lead to a reduced crash rate for a given section. On the other hand, increased speed differentials will result in an increased likelihood of rear-end collisions.

The simulation results indicate that the speed differential between cars and trucks is generally increased by less than 1 mph on level terrain. For vehicles joining the traffic stream from the entrance ramp in Scenarios 8 and 11, the speed differential between cars and trucks is actually reduced. On uphill grades, the speed differential is increased by a greater amount. In scenario 6 (2% grade), the speed differential is increased by 1.3 mph. This effect is much greater in the scenarios representing a 4% grade. Scenarios 7 and 9 display the greatest increases in speed differential, with changes of 9.1 and 9.9 mph, respectively. The impact is lessened in Scenario 10, where the total volume is equal to that in Scenarios 7 and 9 but the truck percentage is low (13%).

Another measure that allows for an evaluation of the safety impact of truck lane restrictions is the frequency of lane changes. As the number of lane changes is decreased, the opportunity for collision is reduced by limiting the interaction between vehicles. Table 8 details the change in each measure of lane-changing behavior due to the lane restriction, and Table 9 details the percent change caused by the lane restrictions.

In each valid scenario (excluding Scenario 8) the effect of the lane restriction is to reduce the overall occurrence of lane changing. As with the previous performance measures, the greatest reduction in lane changing is observed in scenarios with an uphill grade. A closer look at the numbers reveals that on level ground, the number of lane changes by trucks is reduced by a far greater percentage than those by cars. On uphill grades, the percent reduction of lane changes by cars and trucks is nearly equal.

Previously the analysis of travel times by vehicle type indicated a sharp increase in the speed differential between cars and trucks on steep (4%) uphill grades. However, the analysis of lane change results indicates that the average speed differential between the passing vehicle and the vehicle being passed is only slightly increased on these uphill grades. This fact indicates that the theoretical safety benefits of truck lane restrictions form of reduced lane changing may far outweigh the negative result of increased speed differential between cars and trucks.

TABLE 6 Changes in Lane Change Data from Before to After Conditions

| Scenario | # Lane Changes | Speed (mph) | Speed Differential | Spacing | # Car | # Truck | Car Passing Car | Car Passing Truck | Truck Passing Truck | Truck passing Car |
|----------|----------------|-------------|--------------------|---------|-------|---------|-----------------|-------------------|---------------------|-------------------|
| 1 | -550 | -0.4 | -0.1 | -3.7 | -290 | -260 | -224 | -66 | 95 | -355 |
| 2 | -80 | 0.0 | 0.1 | -1.1 | -34 | -46 | -783 | -18 | 22 | -68 |
| 3 | -182 | -0.1 | 0.0 | -2.0 | -39 | -143 | 8 | -47 | 72 | -215 |
| 4 | -186 | -0.1 | 0.0 | -2.0 | -78 | -108 | -79 | 1 | 12 | -120 |
| 5 | -292 | 0.0 | 0.2 | -2.3 | -121 | -171 | -21 | -100 | 56 | -227 |
| 6 | -1900 | 0.8 | 0.6 | -2.1 | -1432 | -468 | -726 | -706 | 137 | -605 |
| 7 | -8911 | 2.2 | 0.3 | -2.8 | -7037 | -1874 | -3865 | -3172 | -404 | -1470 |
| 8 | 58 | -1.2 | 0.2 | 0.7 | 172 | -114 | 95 | 59 | 63 | -175 |
| 9 | -10595 | 2.2 | -0.2 | -4.4 | -8645 | -1950 | -4362 | -4283 | -440 | -1510 |
| 10 | -6251 | 1.9 | 0.4 | 7.8 | -5778 | -473 | -3917 | -1861 | 329 | -802 |
| 11 | -112 | -0.3 | 0.1 | -1.3 | -1 | -111 | 49 | -57 | 48 | -159 |
| 12 | -234 | -0.1 | 0.1 | -2.3 | -101 | -133 | -68 | -59 | 80 | -214 |
| 13 | -692 | -0.4 | 0.0 | -0.9 | -282 | -410 | -194 | -95 | 54 | -469 |

TABLE 7 Changes (Percentages) in Lane Change Data from Before to After Conditions

| Scenario | # Lane Changes | Speed (mph) | Speed Differential | Spacing | # Car | # Truck | Car Passing Car | Car Passing Truck | Truck Passing Truck | Truck passing Car |
|----------|----------------|-------------|--------------------|---------|-------|---------|-----------------|-------------------|---------------------|-------------------|
| 1 | -7% | -1% | -5% | -3% | -5% | -24% | -5% | -5% | 45% | -41% |
| 2 | -6% | 0% | 6% | -1% | -3% | -17% | -100% | -7% | 31% | -33% |
| 3 | -4% | 0% | 3% | -2% | -1% | -20% | 0% | -6% | 52% | -38% |
| 4 | -4% | 0% | -2% | -2% | -2% | -22% | -2% | 0% | 15% | -29% |
| 5 | -7% | 0% | 10% | -2% | -4% | -19% | -1% | -10% | 22% | -36% |
| 6 | -18% | 1% | 21% | -1% | -17% | -21% | -15% | -20% | 15% | -46% |
| 7 | -32% | 4% | 5% | -1% | -31% | -36% | -30% | -33% | -16% | -54% |
| 8 | 1% | -2% | 13% | 1% | 4% | -14% | 3% | 6% | 41% | -29% |
| 9 | -38% | 4% | -3% | -2% | -39% | -36% | -36% | -43% | -15% | -59% |
| 10 | -25% | 4% | 7% | 4% | -26% | -16% | -28% | -23% | 33% | -40% |
| 11 | -2% | 0% | 6% | -1% | 0% | -14% | 2% | -6% | 32% | -27% |
| 12 | -5% | 0% | 6% | -2% | -3% | -12% | -2% | -5% | 23% | -31% |
| 13 | -8% | -1% | 0% | -1% | -4% | -22% | -4% | -5% | 9% | -42% |

CONCLUSIONS AND RECOMMENDATIONS

As in previous research, the truck lanes are shown to have little effect on vehicle density, level of service, average speed, and average travel times on level terrain. However, the effect of truck lane restrictions on these measures on steep uphill grades (4%) is substantial. The average travel times for cars traveling a 5-mile-long freeway segment with a 4% uphill grade is reduced by approximately 60 seconds. At the same time, the travel time of trucks on the same segment shows only a slight increase. To consider the safety impact of truck lane restrictions, the speed differential between cars and trucks and the total numbers of lane changes during the simulation period are examined. On level terrain, the speed differential between cars and trucks is affected by less than 1.0 mph in all scenarios. On 4% upgrades, the speed differential is increased by as much as 10 mph. This result would indicate a

possible safety penalty to be paid for lane restrictions on upgrades. However, the reduced overall occurrence of lane changes is decreased with the introduction of truck lane restrictions would seem to dispute the initial observation. In addition, the average speed difference between the passing vehicle and the vehicle being passed is increased by a maximum of 0.6 mph. The apparent reduction in the total number of lane changes easily offsets any concerns raised by the slight increase in speed differential.

The results of this research effort, when combined with the findings of past studies, indicate that the practice of prohibiting trucks in the leftmost lane where there are three or more lanes of travel in a single direction has no negative effect on traffic safety or efficiency. However, as the severity of the uphill grade is increased, the operational benefits to lighter vehicles become sizable. While these results are promising, future research should seek to further explore the use of truck lane restrictions to determine the effect of steeper grades, traffic volumes approaching capacity, higher truck percentages, and the effects of non-compliant trucks. Additionally, other scenarios such as left-hand exit ramps, weaving sections, and multiple restricted lanes merit further examination to identify any potential negative effects to the traffic flow.

In conclusion, the simulation of truck lane restrictions using a microscopic traffic simulation model such as VISSIM offers the observation of traffic characteristics, such as lane changing behavior, that are difficult to record in the real-world conditions. Without the analysis of numerous simulation scenarios, the use of traditional evaluation methods would indicate that truck lane restrictions would offer little or no benefit, and perhaps even serve to reduce the level of safety in certain conditions such as extended uphill grades. Instead, the use of a powerful simulation model reveals the possibility of substantial safety benefits from these restrictions in the form of reduced lane-changing activity with little or no operational penalty. This fact, when considered with the strong public support for truck lane restrictions, makes a very strong case for increasingly widespread use of this practice.

REFERENCES

1. Managed Lanes Website, <http://managed-lanes.tamu.edu/about/definition.stm>, Texas Transportation Institute, College Station, Texas, viewed November 13, 2003.
2. Zavoina, Michael, Thomas Urbanik II, and Wanda Hinshaw. *An Operational Evaluation of Truck Restrictions on Six-Lane Rural Interstates in Texas*. Research Report 1152-1F. Texas Transportation Institute, College Station, Texas, August 1990.
3. Jasek, Debbie, Mark A. Shafer, Dale L. Picha, and Thomas Urbanik II. *Guidelines for Truck Lane Restrictions in Texas*. Research Report 1726-S. Texas Transportation Institute, College Station, Texas, August 1997.
4. Zavoina, Michael, Thomas Urbanik II, and Wanda Hinshaw, "Operational Evaluation of Truck Restrictions on I-20 in Texas," *Transportation Research Record 1320*, Transportation Research Board, Washington, DC, 1991.
5. Koehne, Jodi, Fred Mannering, and Mark Hallenbeck. Analysis of Trucker and Motorist Opinions Toward Truck-Lane Restrictions. In *Transportation Research Record 1560*, TRB, National Research Council, Washington, DC, 1996, pp ###-##.
6. "Evaluation of the I-10 East Freeway Truck Lane Restriction Demonstration Project," Texas Transportation Institute, College Station, Texas, September 2001.
7. Hanscom, Fred R.. Operational Effectiveness of Truck Lane Restrictions. In *Transportation Research Record 1281*, TRB, National Research Council, Washington, DC, 1990.
8. Hoel, Lester A., and Jennifer L. Peek. *A Simulation Analysis of Traffic Flow Elements for Restricted Truck Lanes on Interstate Highways in Virginia*. Virginia Transportation Research Council, Charlottesville, Virginia, January 1999.

9. Kiattikomol, Vasin. *An Evaluation of the Impact of Lane Use Restrictions for Large Trucks Along I-40 near Knoxville*. Master's Thesis. The University of Tennessee, Knoxville, Tennessee, August 2002.

10. User Manual: Vissim 3.60. Planung Transport Verkehr AG, Karlsruhe, Germany, December 2001.

11. *Highway Capacity Manual*. Special Report 209, TRB, National Research Council, Washington, DC, 1994.

LIST OF TABLES

1. Traffic Inputs Used in VISSIM Simulation Models
2. Summary of Simulation Scenarios
3. Comparison of Before and After Travel Times without Ramps
4. Comparison of Before and After Car Travel Times on Level Terrain with Ramps
5. Comparison of Before and After Truck Travel Times on Level Terrain with Ramps
6. Changes in Lane Change Data from Before to After Conditions
7. Changes (Percentages) in Lane Change Data from Before to After Conditions