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EVALUATING ALTERNATIVE TRUCK MANAGEMENT STRATEGIES ALONG I-81

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ABSTRACT

The study evaluates a number of lane management strategies along one of the most highly traveled roadway sections of I-81 in the State of Virginia using the INTEGRATION traffic simulation software. The lane management strategies that are considered include the separation of heavy-duty trucks from light-duty traffic, the restriction of trucks to specific lanes, and the construction of climbing lanes at strategic locations. Overall, the results demonstrate that a physical separation of heavy-duty trucks from the regular traffic offers the maximum benefits in terms of efficiency, energy, and environmental benefits. The study also demonstrates that restricting trucks from the use of the leftmost lane offers the second highest benefits in terms of efficiency, energy, and environmental impacts.

1. INTRODUCTION

I-81 is one of the top eight truck routes in the U.S. In the state of Virginia, I-81 traverses 325.51 miles from Tennessee in the south to the West Virginia border in the north and passes through 12 counties. The highway was designed for 15 percent truck traffic, however trucks now account for somewhere between 20 to 40 percent of the total traffic. In 2001, the Virginia Department of Transportation developed a list of key improvements for I-81. The improvements include: developing the corridor as a multi-modal facility, incorporating a high degree of efficiency and safety for all users, which may include the physical separation of commercial and passenger vehicles; considering transit or other higher occupancy travel in and around growing urban areas, and using Intelligent Transportation Systems as short-, mid-, and long-term solutions to improving transportation flow and management *(1)*. In 2003, a U.S. house transportation bill included $1.5 billion in federal funding for dedicated truck lanes. According to Representative Don Young (Alaska), author of the bill and a strong proponent of truck-only lanes, "Separate lanes for trucks will move freight more efficiently and make our highways significantly safer." Mr. Young expressed interest in making I-81 a national pilot project *(2)*.

This paper compares alternative truck management strategies along one of the most highly traveled sections of I-81 in the state of Virginia. The paper describes a study that attempts to quantify the efficiency, energy, environmental, and safety benefits of different alternatives to the existing conditions using simulation tools. Network-level impacts are determined from an analysis of microscopic simulation results using the INTEGRATION traffic simulation software *(3)*. Several scenarios are considered including extra lanes, managed-lanes, truck-lanes only, including physical separations of commercial and passenger vehicles, and the addition of climbing lanes.

The first section provides a brief background of the spatial and temporal scope of the Study Area, the concepts used to define the different management strategies, and the measures of effectiveness (MOEs) considered as part of this study. The next section describes the procedures that were utilized to project the traffic demands for the design year 2035. Subsequently, a description of the calibration procedures that were utilized to calibrate the traffic simulation software, including the data collection efforts that were conducted and the input parameters is presented. The next section presents a summary of how the network was constructed and the results of the simulation runs are presented and discussed. Finally, the conclusions of the study are presented together with recommendations for further research.

2. BACKGROUND

This section first describes the spatial extent of the Study Area. It also describes the various concepts that were considered in the study. In addition, the section describes the unique features of the INTEGRATION software for the modeling of trucks and their impacts on traffic stream behavior. Finally, the section describes the various measures of effectiveness (MOEs) that were considered in the study. These measures include efficiency, energy, and emissions.

2.1 Study Area

The section of I-81 that was considered for the study extends from the Blacksburg/Christiansburg area to Roanoke. This section serves the Roanoke/Salem area, a metropolitan area of 200,000 people, which connects to an Interstate spur connector to downtown Roanoke, I-581. The terrain along the I-81 Study Section varies from gently rolling to mountainous.

The Study Area connects the town of Blacksburg, City of Salem, and City of Roanoke. In addition to being used as a corridor for traffic to and from the Eastern and Western States, the corridor is heavily used by local traffic. This corridor covers a total of 25 mi from milepost 118 to milepost 143. It contains 8 interchanges at mileposts 118, 119, 128, 131, 137, 140, 141 and 143 and a rest area in the northbound direction. This section of I-81 is a two-lane freeway in most segments, with some locations with three lanes. The Study Area includes several service roads near urban areas.

2.2 Truck-Only Lanes and Managed-Lane Facilities

Truck-only lanes are defined as lanes that are separated from the remaining roadway lanes by a physical barrier and equipped with their own access and exit ramps. These truck lanes are custom designed for longer and heavier trucks because trucks have very different accelerating, turning, and braking characteristics in comparison to cars. According to *(4)* today's mixture of large trucks and small cars, traveling at high speeds poses serious collision risks. Regardless of which party may be at fault in initiating a car/truck crash, the results are very costly. For example, the National Safety Council has noted, "in truck/automobile collisions, the car driver is 49 times as likely to be killed as the truck driver because of the difference in mass" *(4)*.

For the proponents of these "freeways-within freeways" the benefits of this type of system include: increasing safety because they will put the heaviest and potentially most dangerous rigs behind sturdy concrete barriers and take them travel away from regular traffic lanes and potentially increase productivity because they will allow trucking companies to deploy highly efficient rigs, ultimately saving shippers billions of dollars a year. The full implementation of this type of system requires changes in truck, freeway, taxes and toll regulations. Alternatively, a managed-lane facility "is a lane that increases freeway efficiency by packaging various operational and design actions" *(5)*. Lane management operations may be adjusted at any time to better match regional goals. The restrictions that can be applied to this type of lane include: vehicle-type restrictions, allowing access to a specific type of vehicle; and time-of-day-restrictions, allowing access at certain periods or value pricing. The benefits of this type of lane are: maximizing existing capacity, improving safety, managing demand, reducing environmental impacts, and generating revenue *(5)*.

A 1999 report by the Virginia Department of Transportation (VDOT) *(6, 7)* used simulation to represent restricted truck lanes on specific sections of I-81 in Virginia. The conclusions of the report included: (1) restricting trucks from the use of the left lane along steep grade sections may decrease the traffic density and the number of lane changes, (2) restricting trucks from the right lane may increase the number of lane changes for sites without entry and exit ramps, (3) site characteristics have an impact on the effects of truck lane restrictions, and (4) trucks should be restricted from the left lanes on sections with grades of 4 percent or higher. Another traffic simulation study using VISSIM *(7)* concluded that the practice of prohibiting trucks from 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; furthermore, as the severity of the uphill grade is increased, the operational benefits to lighter vehicles become sizable.

2.3 Truck Climbing Lanes

A climbing lane is defined by AASHTO *(8)* as an extra lane for a vehicle moving slowly uphill so that other vehicles using the normal lanes are not restricted and are able to pass the slower moving vehicle. AASHTO recommends that a 16-km/h reduction criterion be used as the general guide for determining critical lengths of grades and locating truck-climbing lanes. Any one of the following criteria are used to justify climbing lanes: (1) upgrade traffic flow rate is in excess of 200 veh/h, (2) upgrade truck flow rate is in excess of 20 veh/h, or (3) either a 16 km/h or greater reduction in speed is expected for a typical truck, or Level-of-service E or F exists on the grade or a reduction of two or more levels of service is experienced when moving from the approach segment to the grade segment. The TruckSIM software *(9)*, developed by Virginia Tech, provides a flexible tool for locating truck-climbing lanes that mimics the AASHTO procedures. Specifically, the software identifies the start and end points of climbing lanes considering the AASHTO criteria previously specified. The application of the model to the Study Area is discussed in Section 4.3.

2.4 Operational Level

AASHTO *(8)* specifies that "although choice of the design level is left to the user of the Highway Capacity Manual (HCM), designers should strive to provide the highest level of service feasible and consistent with anticipated conditions….For acceptable degrees of congestion, freeways and their auxiliary facilities, i.e. ramps, main lane weaving sections and collector-distributor (C-D) roads in urban and developing areas should generally be designed for level of service C." Consequently, given the rural nature of I-81 it was assumed that the Study Area was designed for a level of service C.

The existing level of service along the Study Area and within each segment between interchanges was estimated based on traffic flow counts and speed measurements that were conducted by a number of consulting firms *(10)*. The existing conditions were compared against the design level of service C in order to establish the adequacy of the current operational conditions along the Study Area. An analysis of the level of service along the corridor indicates that this facility currently provides a level of service B or better during peak hours with the exception of two sections that operate at an LOS C.

2.5 INTEGRATION Model Overview

This section provides a brief overview of the INTEGRATION software given that it was the tool that was utilized to conduct the study. The INTEGRATION software is a microscopic traffic assignment and simulation model which was developed over the past decade. It was conceived as an integrated simulation and traffic assignment model and performs traffic simulations by tracking the movement of individual vehicles every 1/10th of a second. This allows detailed analyses of lane-changing movements and shock wave propagations. It also permits considerable flexibility in representing spatial and temporal variations in traffic conditions. In addition to estimating stops and delays *(11)*, the model can also estimate the fuel consumed by individual vehicles, as well as the emissions. The INTEGRATION model updates vehicle speeds every deci-second based on a user-specified steady-state distance headway and the speed differential between the subject vehicle and the vehicle immediately ahead of it. Unfortunately, using this type of car-following model does not necessarily result in realistic vehicle accelerations. Consequently, the model also uses a vehicle dynamics model that is used to estimate the maximum vehicle acceleration. Specifically, the model utilizes a variable power vehicle dynamics model to estimate the vehicle's tractive force that implicitly accounts for gear-shifting on vehicle acceleration. This model is described in more detail later in the section. In addition the model considers the aerodynamic, rolling, and grade resistance forces on the vehicle.

The INTEGRATION model computes a number of MOEs, including the network efficiency. Efficiency evaluation of highway alternatives involves computing the average speed and vehicle delay. The average vehicle speed is computed as the average of all vehicle speeds, where the vehicle speed is computed as the trip distance divided by the trip duration. Conversely, the instantaneous delay incurred by a vehicle over a given interval can be estimated as the difference between the time it would take the vehicle to complete its trip while traveling at the free-flow speed of the facility and the time the vehicle actually took. As expressed by Equation 1, the total delay would then be obtained by summing the delays incurred in all intervals comprised within the recorded trip. Subsequently, the delay is computed for all vehicles within the network.

$$D = \sum_{i=1}^{N} d_i = \sum_{i=1}^{N} \left(1 - \frac{u_i}{u_f}\right) \cdot t_i \qquad [1]$$

where:

D = Total delay incurred over entire trip
d_i = Delay incurred during interval i
t_i = Duration of interval i
u_i = Vehicle instantaneous speed in interval i
u_f = Free-flow speed of facility on which vehicle is traveling
N = Number of time intervals in speed profile

When second-by-second speed and acceleration data are available, microscopic fuel consumption and emission models are used to estimate the vehicle's instantaneous fuel consumption and emission rate. From a general point of view, the use of instantaneous speed and acceleration data for the estimation of energy and emission impacts of traffic improvement projects provide a major advantage over state-of-practice methods. State-of-practice methods currently estimate vehicle fuel consumption and emissions based exclusively on the average speed and number of vehicle miles traveled by vehicles on a given transportation link. These methods assume that differences in driver behavior can be neglected and implicitly assume that all vehicles traveling on a link pollute similarly for an identical average speed and vehicle-miles traveled. In reality, different speed and acceleration profiles with the same average speed and vehicle-miles traveled could result in different levels of fuel consumption and emissions. As with fuel consumption models, the emission models are sensitive to the instantaneous-vehicle speed and acceleration levels. Applications of these models have shown that the emission of compounds, hot-stabilized tail-pipe hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X), and particulate matter (PM) are related to vehicle travel time, distance, speed, and fuel consumption in an often highly nonlinear fashion. Consequently, traffic management strategies that may have a significant positive impact on one measure are not always guaranteed to have an impact of the same magnitude or even sign on any of the other measures.

The INTEGRATION model computes the speed of vehicles each deci-second. This permits the steady-state fuel consumption rate for each vehicle to be computed each second on the basis of its current instantaneous speed and acceleration level *(12*, *13)*. These models were developed using data that were collected on a chassis dynamometer at the Oak Ridge National Labs (ORNL), data gathered by the Environmental Protection Agency

(EPA), and data gathered using an on-board emission measurement device (OBD). The models use instantaneous speed and acceleration levels as independent variables *(14)*. Vehicle accelerations have significant impacts of vehicle fuel consumption rates especially at high speeds with the resulting high engine loads. The fuel consumption analysis features are built into the model and are executed every second for every vehicle in the network. They are applied in a fashion that is consistent across all facility types, operating regimes, and control strategies. This consistent internal use permits a very objective assessment of the fuel consumption implications across a wide range of potential traffic or demand management strategies.

As was mentioned earlier the INTEGRATION software incorporates a variable power vehicle dynamics model that computes the vehicle's tractive effort, aerodynamic, rolling, and grade-resistance forces, as described in detail in the literature *(15, 16)*. The INTEGRATION model has not only been validated against standard traffic flow theory *(14, 17)*, but also has been utilized for the evaluation of real-life applications *(12, 18)*. The types of analyses that can be performed with these built-in models extend far beyond the capabilities of EPA's MOBILE5 model *(19)*.

3. TRAFFIC ANALYSIS

The credibility of any modeling study hinges on the accuracy of the input data that is provided to the traffic simulation software. This section describes the simulation model input and any assumptions that were made in conducting the study. Taking into account that any of the alternatives proposed implies a major road construction, the design year selected was 2035.

Several data sources were taken into account to determine traffic projections. VDOT publishes the average daily traffic volumes (AADT) categorized by vehicle classification for every Interstate on an annual basis *(20)*. In addition, VDOT has permanent and mobile count stations around the Study Area. For the purpose of traffic simulation, the peak hours of traffic were analyzed. To convert the AADT to hourly peak traffic, data from the permanent count stations at milepost 114 were analyzed. Figure 1 shows traffic variations for trucks and non-trucks for different days of the week. The analysis of these data results in an average peak hour percentage of 7.6 and 5.2 percent for trucks and non-trucks, respectively. The peak hour traffic volume distribution of the Study Area for the northbound and southbound directions for the base year 2002 is shown in Figure 2. As is expected, higher traffic conditions are experienced around the urban area of the Roanoke/Salem cities. This statement is true for both cars and trucks. A slightly higher traffic volume is experienced in the southbound direction, with maximum AADT counts of 33,000 vehicles and truck percentages varying between 22 and 33 percent.

AADT data from 1998 to 2002 revealed an average annual growth of 3.8 percent for cars and 4.2 percent for trucks. However, after conversations with VDOT traffic engineers it was concluded that for the 2035 design year, a more conservative annual growth of 2.5 percent would result in a more realistic forecast. This percentage was applied to both trucks and passenger cars. Traffic projections for the year 2035 by vehicle type and direction are shown in Figure 2. As stated before, freeways and their auxiliary facilities should generally be designed for a Level of Service (LOS) C. The computation of traffic volume for use in estimating the LOS requires converting trucks, buses, and recreational vehicles into equivalent passenger cars. This factor was applied to compute the number of lanes needed to continue to operate at a level of Service C in 2035. FIGURE 3 demonstrates that the majority of the current 4-lane configuration provides a level-of-service within the LOS C threshold.

4. EVALUATION OF ALTERNATIVE MANAGEMENT STRATEGIES: SIMULATION RESULTS

The modeling effort that is described in this section attempts to evaluate the benefits of alternative truck management strategies through simulation. In order to model the different alternatives, the INTEGRATION microscopic traffic assignment and simulation model was selected for the study.

4.1 Traffic Data collection and Demand Calibration

The calibration of O-D demands to field observed link flows is a problem that has been the focus of extensive research. The most renowned of the approaches is the maximum likelihood approach that was first formulated by Willumsen *(21)* and Van Zuylen and Willumsen *(22)* and extended by Van Aerde *et al*. *(23)*. The 2035 traffic demand was estimated using a maximum likelihood synthetic O-D estimation software entitled QUEENSOD *(23)*.

The QUEENSOD software estimates the maximum likelihood O-D table that replicates the observed link flows solving Equation 2. The numerical solution begins by building a minimum path tree and performing an all-or-nothing traffic assignment of the seed matrix. A relative or absolute link flow error is computed depending on user input. Using the link-flow errors, O-D adjustment factors are computed and utilized to modify the seed O-D matrix. The adjustment of the O-D matrix continues until one of two criteria are met, namely the change in O-D error reaches a user-specified minimum or the number of iterations criterion is met.

$$\text{Max.}\quad T\ln\left(\frac{T}{t}\right)-\sum_{ij}T_{ij}\ln\left(\frac{T_{ij}}{t_{ij}}\right)-\sum_{ij}\left(\lambda_{ij}\cdot 2\left(\sum_{a}\left(V_a\cdot p_{ij}^{a}\right)-\left(\sum_{a}p_{ij}^{a}\left(\sum_{xy}T_{xy}p_{xy}^{a}\right)\right)\right)\right) \qquad [2]$$

Where:

T_{ij} = Estimated number of trips between zones *i* and *j* for the analysis period for all trip purposes
t_{ij} = Seed trips between zones *i* and *j*
T = Total number of trips ($\Sigma\Sigma T_{ij} = T$)
t = Total number of trips based on seed O-D matrix ($\Sigma\Sigma t_{ij} = t$)
$p^{a}{}_{ij}$ = Probability of O-D pair *ij* to utilize link *a*
λ_{ij} = Lagrange multiplier for O-D pair ij
V_a = Actual observed link volume on link “a”

The use of an initial seed O-D table refines the O-D estimation procedure by estimating an O-D table that resembles the seed O-D table to the extent possible while matching the observed flows. With the objective to generate a seed O-D for the Study Area, a field survey was conducted by tracking all trucks entering and exiting I-81 during four four-hour periods along the 25 mi study section. The data collection efforts were conducted on Sundays and Wednesdays. Mondays and Fridays were not considered as studies have shown that these days are not necessarily reflective of typical weekday conditions *(24)*. Previous research conducted at VDOT Troutville weight station showed that the peak demand for trucks is experienced on Wednesdays for weekdays and on Sundays for weekends. Figure 4 shows a similar distribution for car traffic for the northbound and southbound directions with a slight higher demand in the northbound direction on Sunday and in the southbound directions on Fridays and Saturdays. When trucks are considered, northbound traffic experience a higher demand for all days of the week with the exception of Fridays and Saturdays.

Data were gathered on Sunday from 10:00 to 2:00 p.m., to cover the highest demand for a 24 hour period as shown in Figure 1. Due to the relevance of truck traffic for I-81 the data collection effort focused only on trucks. Nine sites were monitored for the southbound direction and 10 sites for the northbound direction. The sites included the north and south ends of the study area, where video cameras were installed and traffic conditions were recorded for the four periods. The other sites included all possible entrances and exits for each interchange in the Study Area. The difference in the number of sites per direction is due to the presence of the rest area between exits 128 and 132 for the northbound direction. At each location, one or two people manually recorded the time and truck characteristics: color, manufacturer, and presence of trailers. The information and the video data were used to identify the truck movements in order to compute an O-D matrix. The generated O-D table was factored by 1.25 to simulate Wednesday traffic. The resulting table was utilized as a seed O-D table to generate a final synthetic O-D table. Figure 5 illustrates the match between the link flows that were generated by assigning the synthetic O-D table against the projected link flows that were input into the model. The figure clearly demonstrates a high level of consistency between the model output and projected link flows with R^2 of 0.99 and 0.98 for cars and trucks, respectively. A high level of consistency between the projected field survey O-D table and the estimated O-D table in matching the projected link flows is shown in Figure 5. Both figures demonstrate a traffic volume breakdown which is consistent with the traffic data analysis of the previous section (approximately 27 percent trucks and 73 percent cars). The total demand generated is 12,293 vehicles, the through trucks account for 56 percent of the total truck volume.

4.2 Simulation Model Construction

The simulation network construction involved building a network from AutoCAD designs. This design was used to define the horizontal profile with a high degree of accuracy. Alternatively, the roadway grades for each section were generated by driving a vehicle equipped with a Global Positioning System (GPS) along the study section. Lane characteristics in terms of capacity, free-speed, speed-at-capacity, and jam density were derived based on typical freeway sections.

Trucks were modelled as a 200 lb/hp truck as recommended by the Highway Capacity Manual (HCM) for highway design purposes. Based on a limited survey of 150 trucks at the Troutville weigh station, this represents the 95th percentile truck weight-to-power ratio. The cars were modelled as light-duty vehicle 3 (LDV3), which is a vehicle of model year 1995 or later, an engine size less than 3.2 L, and an average mileage of less than 83,653 km. The use of different vehicle types would affect the fuel consumption and emission estimates of the various scenarios.

The results obtained when the TruckSIM simulation model were utilized to identify locations of climbing lanes within the study section, as illustrated in Figure 6. When the truck speed is lower than the minimum design speed, a climbing lane is recommended. There is a clear need for a truck-climbing lane in the southbound direction from miles 127.9 to 125.6, from 123.4 to 122.4, and from 121 to 118.8.

4.3 Summary Results

Eight scenarios for improving traffic flow on the I-81 corridor were modelled, as follows:

- **Scenario 1 (S1). Do-nothing:** Represents the base case do-nothing scenario.
- **Scenario 2 (S2)**. **Separated Truck Lane**: Two truck lanes are included in each direction. These additional lanes are physically separated from the existing lanes and are dedicated to truck traffic only. Truck access is attained through the starting and ending points along the study section and through a flyover at milepost 132 from the truck express lanes to the general purpose lanes.
- **Scenario 3 (S3). Managed–Lane Facility**, **Left lane**: This scenario is identical to scenario 1 with one additional lane to the left dedicated to cars only and a truck climbing lane in the southbound direction from milepost 128 to milepost 122.
- **Scenario 4 (S4). Managed–Lane Facility**, **Right lane**: This scenario is identical to scenario 3 except that the managed lane is the rightmost lane instead of the leftmost lane as is the case in Scenario 3.
- **Scenario 5 (S5).-Extra Lane-No Managed Lane Facility**: This scenario is identical to scenario 3 except that there are no lane restrictions.
- **Scenario 6 (S6). Managed-Lane Facility, Left Lane, LOS C**: This scenario is identical to scenario 3 with additional lanes to guarantee a level of service C for the entire section.
- **Scenario 7 (S7). Managed-Lane Facility, Right Lane, LOS C**: This scenario is identical to scenario 6 except that the managed lane is the rightmost lane instead of the leftmost lane as is the case in scenario 6.
- **Scenario 8 (S8). Extra Lanes to guarantee LOS C**. **No Managed Lane Facility:** This scenario is identical to scenario 6 without any lane restrictions.
- **Scenario 9 (S9)**. **S3 without Truck Climbing Lanes**: This scenario is identical to scenario 3 without truck climbing lanes.

A complete economic analysis must include: 1) construction and maintenance costs, 2) road user costs (fuel and vehicle maintenance cost), 3) travel time savings and 4) environmental benefits. The simulation results presented in this paper quantifies points 2, 3 and 4. Consequently, decision makers may take into account all these factors when comparing different alternatives.

In the alternative selection process it is important to analyze the impact of the different scenarios on the entire network and on individual vehicle classes. For this reason the results were also categorized by four vehicle classes, namely: local cars (LC), local trucks (LT), through cars (TC), and through trucks (TT). Through cars and trucks were defined as the vehicles that complete the entire section from north to south and vice versa. Vehicles that originate or end their trip along the study section are categorized as local trucks or cars.

Table 1 shows the average speed, travel time, delay and vehicle emissions for the nine alternatives. All scenarios produce significant benefits when compared to the base case scenario. However, the strategy of separate truck lanes (S2) produces the highest benefits. There is a substantial increase in speed (71 percent) and decrease in travel time (42 percent) and delay (73 percent) when this scenario is applied. The second highest benefits are obtained from scenario 6 which increases speed (57 percent), reduces travel time (36 percent), and delay (60 percent). The application of truck lane restrictions to the right lane (S7) results in slight negative impacts with respect to scenarios S6 and S8. Alternative S3 with truck restrictions to the left lane produce the most benefits among the manage-lane facilities that do not comply with an LOS for the entire corridor. This alternative also produces higher benefits than S9 that does not include the truck climbing lane. The restriction of the right lane for trucks (S5) has negative impacts compare to the left lane control (S3) and no control operation at all. The benefits obtained through scenarios 3 and 6 confirm previous studies that conclude that restricting trucks from the left lane with steep grades may decrease density (6). Table 1 also shows positive environmental impacts for all the strategies compared to the base case. However CO emission increases for all scenarios. The highest benefits for reduction in fuel consumption is given by alternative S2 (8 percent) followed by S6 (4 percent). Alternative S2 also produces the highest reduction in HC and NOx emission (16 percent and 5 percent respectively) and the lowest percentage increase of CO emissions.

In terms of vehicle-specific benefits, Figure 7 and Table 2 compare the various MOE's for each vehicle class. The following conclusions can be drawn. Local cars (LC) benefit the most from S2 with an average speed of 58 mph, reduction of travel times, delay and fuel consumption of 8 min, 6 min and 13 percent, respectively. The second best alternative for this type of vehicle class is S6, with and average speed of 48 mph. All the alternatives result in an increase in NOx and HC. S2 results in the lowest increase in HC (11 percent) and in one of the highest increases in NOx (19 percent). For local trucks (LT) S2 translates into an average speed of 50 mph and reductions in travel time and delay of 8.5 and 6.5 min, respectively. The highest reduction of HC emissions is obtained also through S2 (26 percent). However, the highest reduction in fuel consumption is obtained by S6 (5 percent), and the highest reduction in NOx is obtained by S7 and S8 (6 percent). Through cars (TC) obtained the same benefits by the separation of truck lanes (S2) and the restriction of trucks from the left lane (S6), with an average speed of 60 mph for both scenarios. Similar results are obtained when travel time and delay are considered with reductions of 16 and 14 min in delay. The best reduction in fuel consumption is obtained by S2 (7 percent) and S6 (6 percent). As with local cars all alternatives result in an increase in NOx and HC emissions. S2 offers the lowest increase in HC (5 percent) and the second highest increase in NOx (10 percent), after S4 (8 percent). The best benefits for through trucks (TT) are obtained from alternatives S2 and S7. These alternatives translate into significant benefits in speed with an average speed of 52 and 46 mph, respectively. Travel time is reduced by 15 min (S2) and 9 min (S7). S2 produces the highest energy and emission benefits reducing fuel consumption (8 percent), NOx (7 percent) and HC (21 percent) emissions.

Overall, the results demonstrate that a physical separation of heavy-duty trucks from the regular traffic offers the maximum benefits in terms of efficiency, energy, and environmental impacts. The study also demonstrates that restricting trucks from the use of the leftmost lane offers the second highest benefits. To further evaluate the relative impacts of these two alternatives, additional runs were conducted using 10 different random number seeds. The results of the simulation, which are illustrated in Figure 7, indicate that separating heavy-duty trucks from the general traffic results in an increase in system efficiency. Statistical t-tests indicate that the two alternatives produce statistically different speed, travel time, delay and fuel consumption MOE's with a degree of confidence of 95 percent. Furthermore, the results indicate that alternative S2 offers higher benefits compared to alternative S6 when the entire traffic stream is considered. A more detailed statistical analysis for each of the traffic subclasses (LC, LT, TC, and TT) also indicates statistically significant differences in favor of alternative S2.

5. CONCLUSIONS

The study evaluated a number of lane management strategies along one of the most highly traveled roadway sections along I-81 in the State of Virginia using the INTEGRATION simulation software. The lane management strategies that were considered include the separation of heavy-duty trucks from light-duty traffic, the restriction of trucks to specific lanes, and the construction of climbing lanes at strategic locations. Overall, the results demonstrate that a physical separation of heavy-duty trucks from the regular traffic offers the maximum benefits in terms of efficiency, energy, and environmental benefits. The study also demonstrates that restricting trucks from the use of the leftmost lane offers the second highest benefits in terms of efficiency, energy, and environmental impacts.

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LIST OF TABLES

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TABLE 1 Average MOE's for the Various Scenarios

	Scenario								
	1	2	3	4	5	6	7	8	9
Speed (mph)	33.38	57.10	47.53	41.08	46.85	52.29	50.36	51.44	46.37
Travel Time (min.)	31.74	18.54	22.30	25.80	22.62	20.29	21.07	20.63	22.85
Delay (min.)	13.79	3.77	7.53	11.03	7.85	5.51	6.29	5.84	8.09
Fuel (l)	3.28	3.03	3.18	3.31	3.19	3.14	3.17	3.14	3.18
HC (g)	3.31	2.77	3.20	3.28	3.20	3.13	3.06	3.13	0.35
CO (g)	35.17	42.42	66.53	62.19	63.76	68.33	57.50	67.83	62.21
NOx (g)	43.44	41.34	43.12	43.79	43.28	42.81	42.11	42.67	42.98

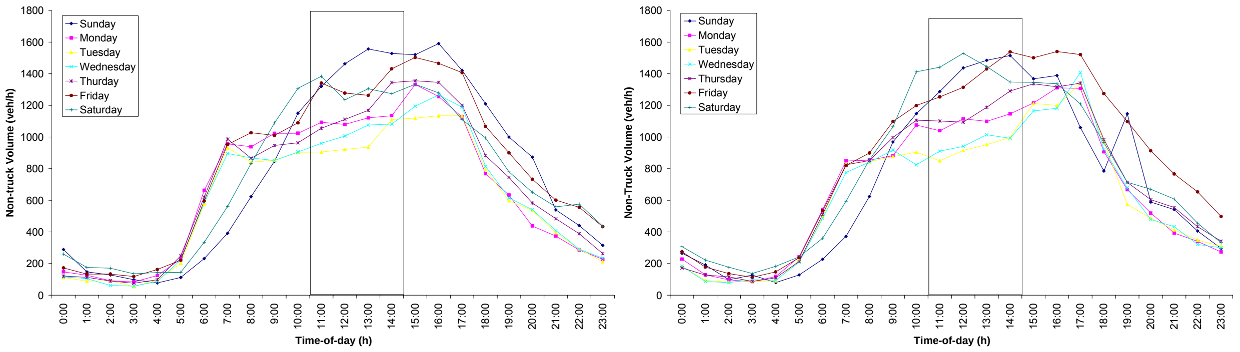
	Scenario								
	1	2	3	4	5	6	7	8	9
Speed (mph)	0%	71%	42%	23%	40%	57%	51%	54%	39%
Travel Time (min.)	0%	-42%	-30%	-19%	-29%	-36%	-34%	-35%	-28%
Delay (min.)	0%	-73%	-45%	-20%	-43%	-60%	-54%	-58%	-41%
Fuel (l)	0%	-8%	-3%	1%	-3%	-4%	-3%	-4%	-3%
HC (g)	0%	-16%	-3%	-1%	-3%	-6%	-8%	-6%	-89%
CO (g)	0%	21%	89%	77%	81%	94%	63%	93%	77%
NOx (g)	0%	-5%	-1%	1%	0%	-1%	-3%	-2%	-1%

TABLE 2 Summary Results by Vehicle Class

	Scenario 2				Scenario 3				Scenario 6			
	LC	LT	TC	TT	LC	LT	TC	TT	LC	LT	TC	TT
Speed (mph)	58	50	60	52	40	34	55	41	48	37	60	44
Travel Time (min.)	7	8	29	33	9	11	32	42	8	10	29	40
Delay (min.)	1	2	5	10	4	6	8	18	2	5	5	16
Fuel (l)	1	2	3	9	1	2	4	9	1	2	3	9
HC (g)	0	3	1	12	0	4	2	14	0	3	2	13
CO (g)	13	10	83	45	26	14	132	55	33	12	130	53
NOx (g)	2	56	8	216	2	54	8	229	2	53	8	227

a1. Car Traffic Volume Southbound

b1. Car Traffic Volume Northbound



a2. Truck Traffic Volume Southbound

b2. Truck Traffic Volume Northbound

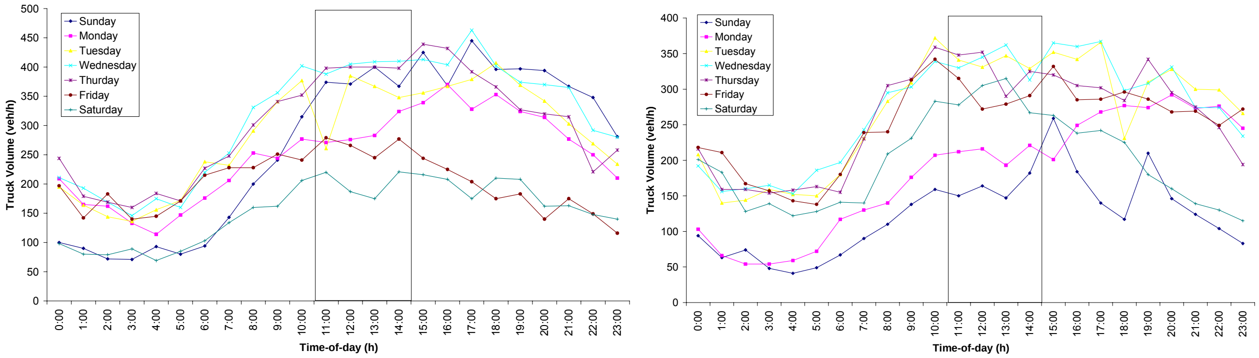
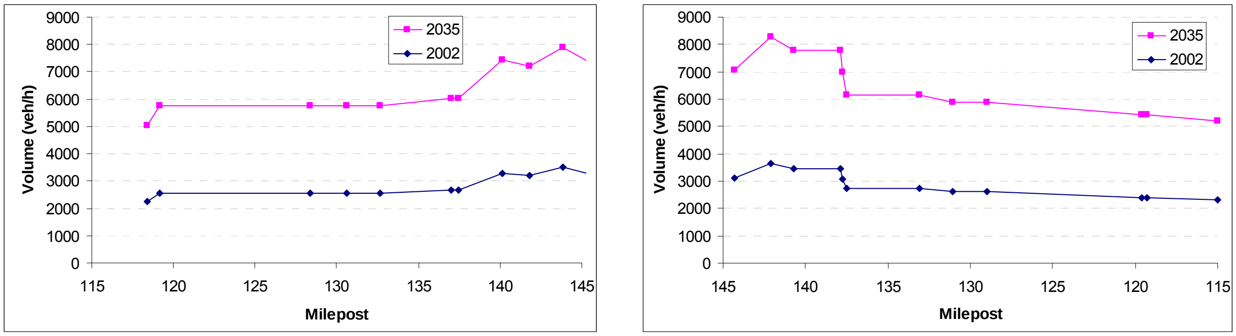
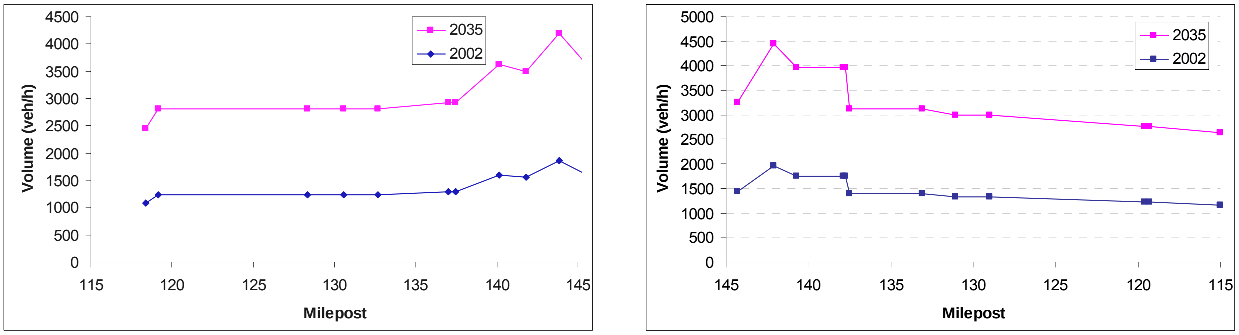


FIGURE 1 Traffic Volume Distributions by Type of Traffic and Direction.



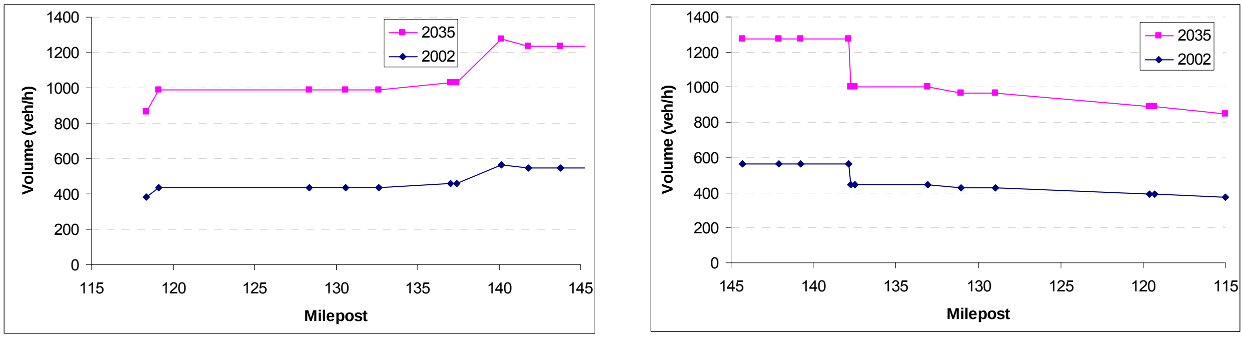
a1. Total Traffic Volume Northbound

b1. Total Traffic Volume Southbound



a2. Car Traffic Volume Northbound

b2. Car Traffic Volume Southbound

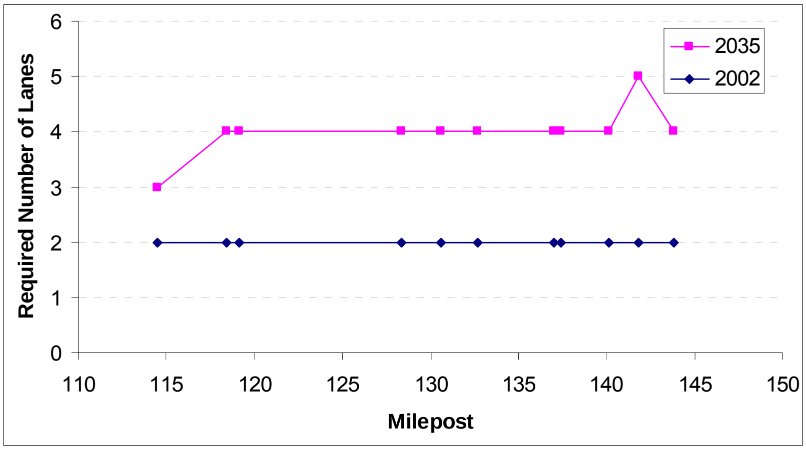


a3. Truck Traffic Volume Northbound

b3. Truck Traffic Volume Southbound

FIGURE 2 Study Area Peak Hour Traffic Volume Distributions.

a. Northbound



b. Southbound

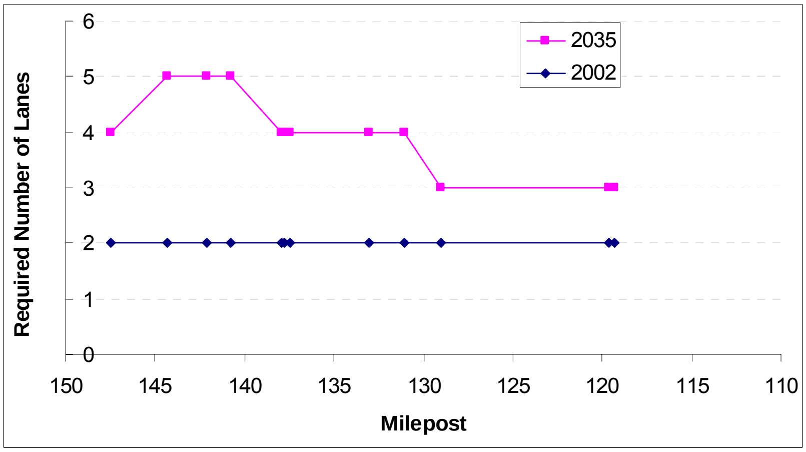


FIGURE 3 Required Numbers of Lanes for an LOS C.

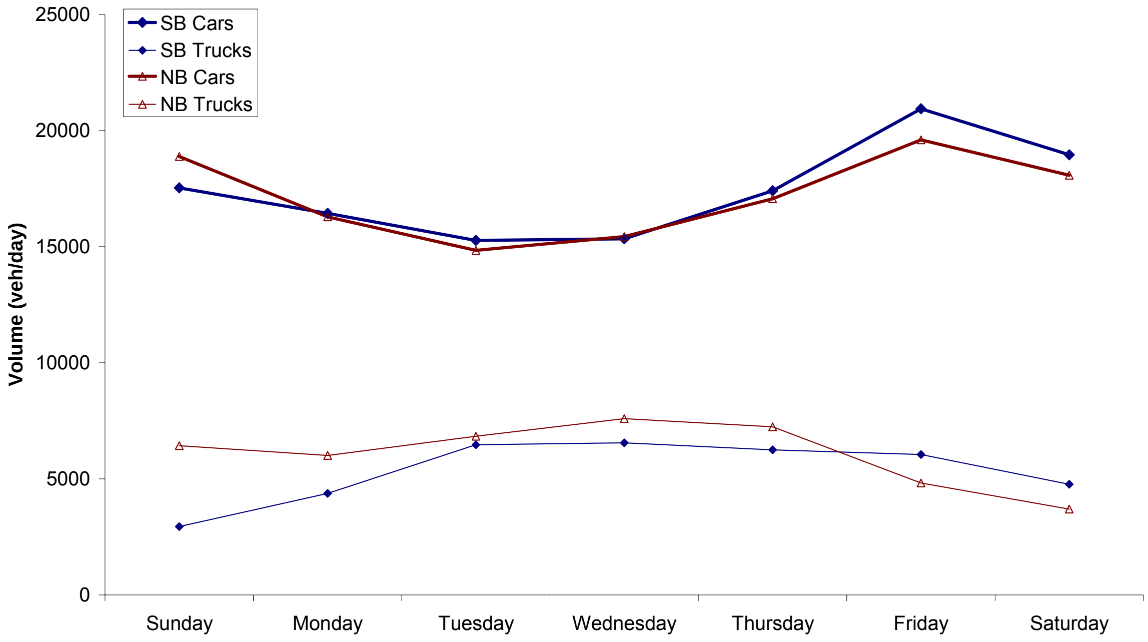


FIGURE 4 Traffic Volume Distributions by Day-of-the-week.

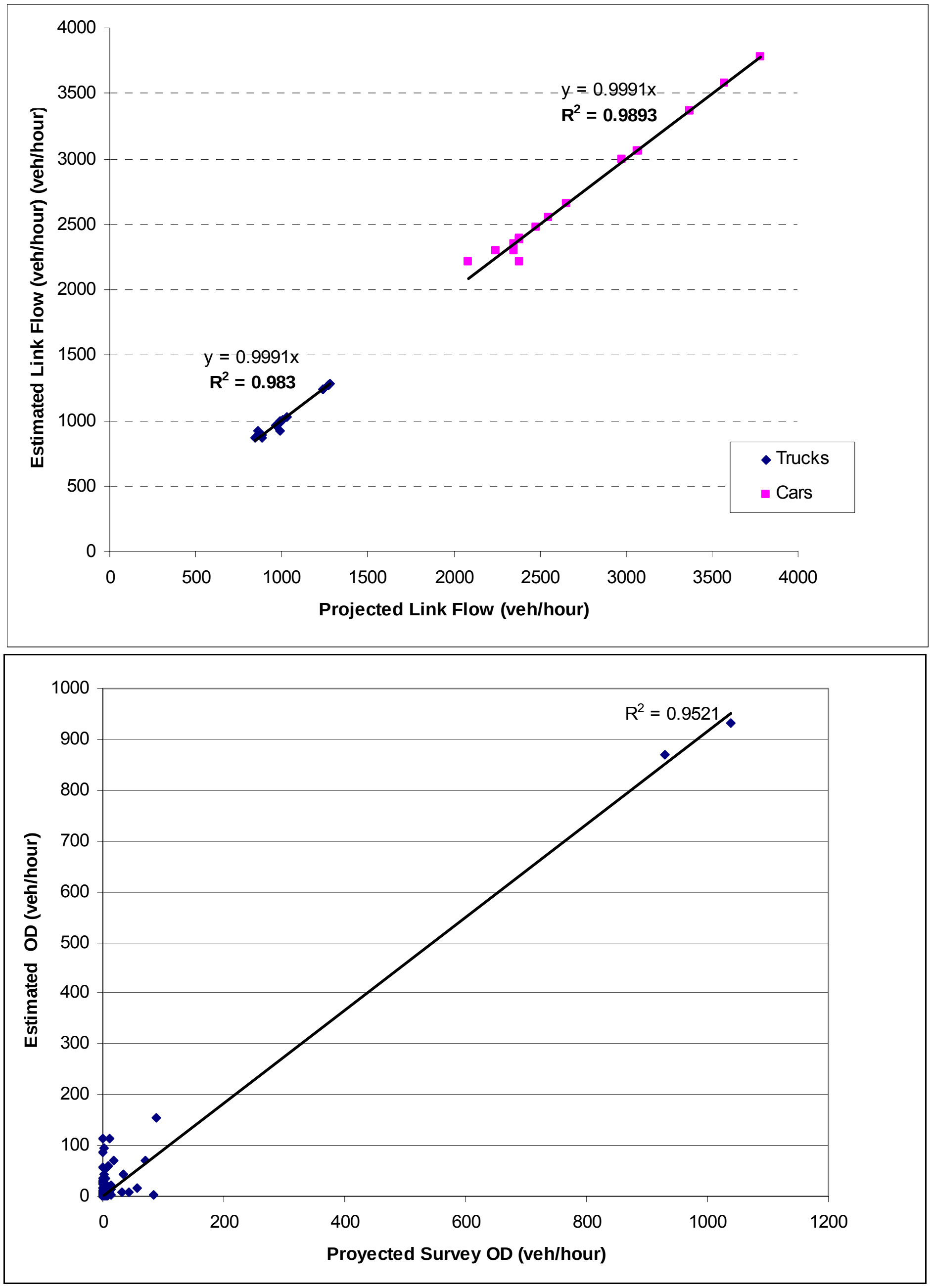
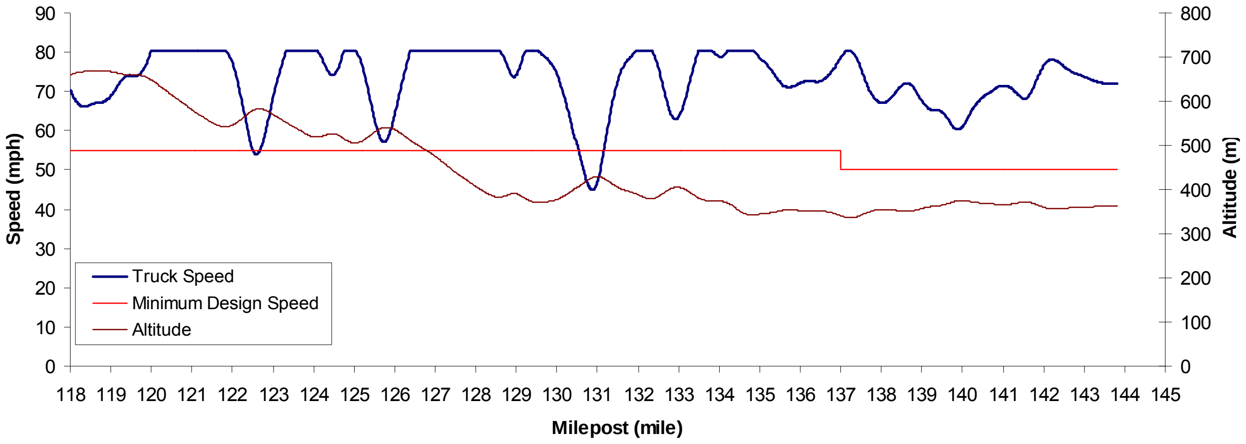


FIGURE 5 Demand Calibration.

a. Northbound



b. Southbound

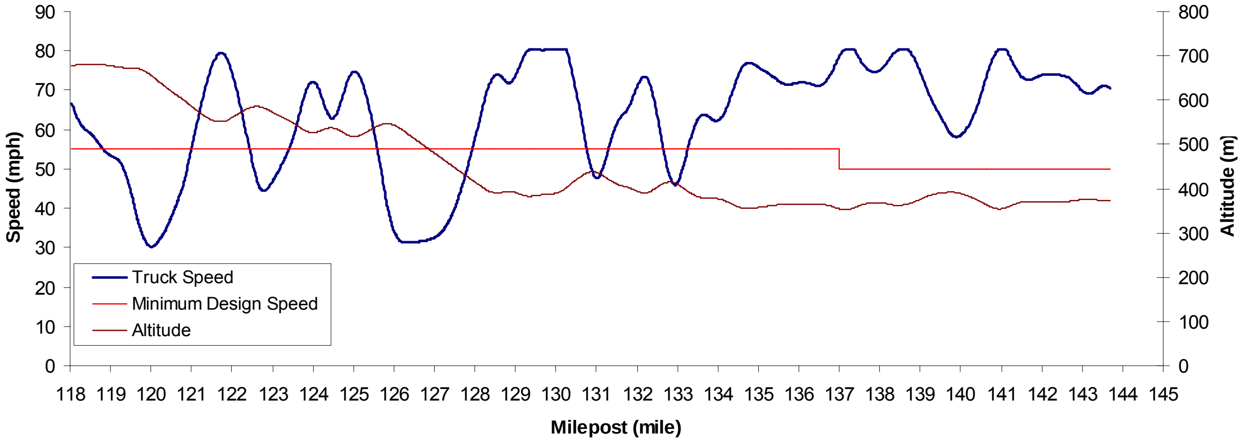
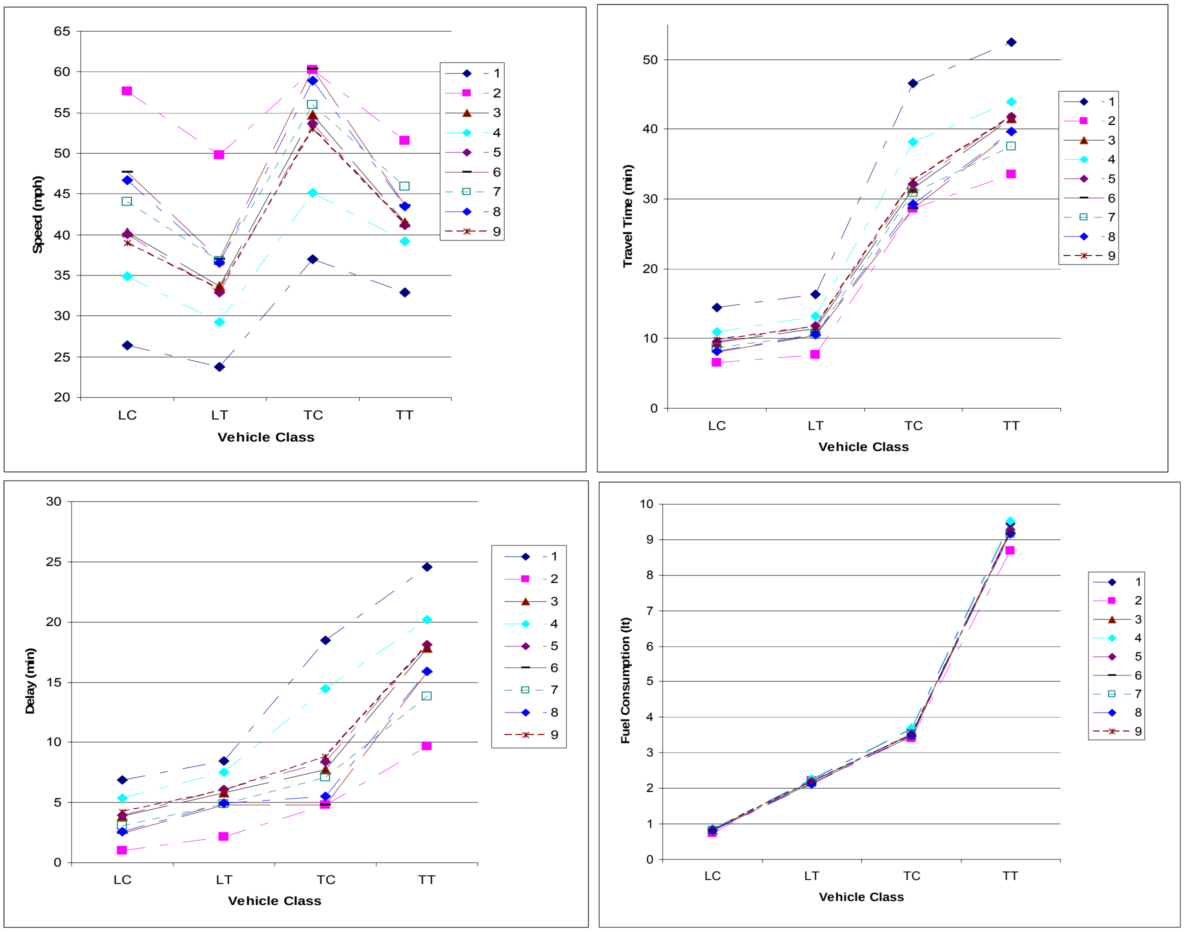


FIGURE 6 Study Area Truck-climbing Lanes Needs' using TruckSIM.

a) For all Alternatives Separated by Vehicle Classes



b) MOE's for additional runs for Alternatives S2 and S9

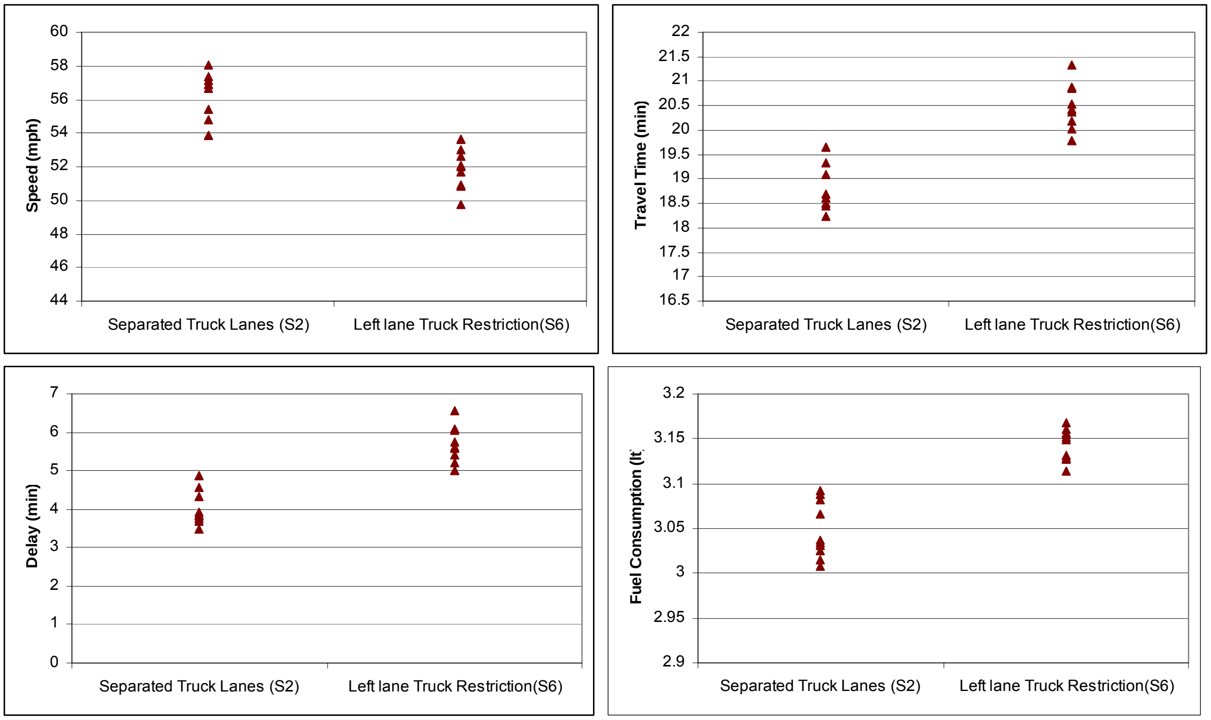


FIGURE 7 MOE's for Different Alternatives