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Slip ramp spacing design for truck only lanes using microscopic simulation

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SLIP RAMP SPACING DESIGN FOR TRUCK ONLY LANES USING MICROSCOPIC SIMULATION

by

MANOJ VALLATI

A THESIS

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ABSTRACT

This research work proposes recommendations for slip ramp spacing between the TOLs and the general GPLs along Missouri rural interstate highways using a microscopic simulation model, VISSIM. Simulation of peak period rural traffic conditions indicated that heavy vehicle speeds were directly proportional to the lengths of the merge, diverge, and link sections. The proposed design recommendations for slip ramp spacing are based on the results of these section lengths. Design of experiments was carried out using a central composite design. As the slip ramp spacing depended heavily on the lane change behavior of drivers, a sensitivity analysis was performed of the main lane change parameter in VISSIM that analyzed its effect on the speed flow characteristics of heavy vehicles. This work provides practitioners and state Departments of Transportation (DOTs) with design recommendations for slip ramp spacing and lengths of merge, link, and diverge for the corridors of the future project.

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SECTION

1. INTRODUCTION

Traffic simulation tools are being increasingly used for different traffic design studies due to their ability to simulate different traffic designs in a more efficient way compared to other analytical tools that provide limited insights. Many studies (2) suggest that the results obtained from simulation tools are accurate and practitioners should look beyond traditional tools like HCM. Based on the level of detail of the traffic stream represented, traffic simulation models can be broadly classified into three categories

1.1. CLASSIFICATION OF TRAFFIC SIMULATION MODELS

1.1.1. Macroscopic Models. These models simulate traffic flows in network based on the relationships among the aggregated traffic flow variables - speed, flow and density. These models can be used to assess both the temporal and spatial extent of traffic phenomena such as congestion and delay but their inability to model individual vehicle interaction behavior, which can strongly influence network performance measures such as capacity, queue length.

1.1.2. Mesoscopic Models. These models have the ability to simulate individual vehicles but the individual reactions are based on aggregated traffic flow characteristics: average speed, flow and density. These models can be used to evaluate individual travel time of the vehicles based on average speed conditions prevailing in the system.

1.1.3. Microscopic Models. These models are more advanced from the above two models mainly due to their ability to simulate individual vehicles and their interactions. These models generate exact paths of individual vehicles based on certain car-following (Weidman 74 and 99) and lane changing algorithms. These models provide users the flexibility to change many parameters such as minimum headways, desired following distance, lane changing parameters to replicate field conditions

1.2. VISSIM

VISSIM is a microscopic, stochastic, discrete time-step based simulation where individual vehicles represent the most basic elements of the simulation. It is based on the wiedemann "psycho-physical" car-following model and lane changing model (*16)*. The characteristics and behavior of individual vehicles (and drivers) affect performance measures such as speed, throughput, and queue length. VISSIM has two car following models: Wiedemann 74 and Wiedemann 99 and a lane changing model. The car-following model that represents freeway conditions, Wiedemann 99 car following model (W-99), has 10 user defined driving behavior parameters: *CC0, CC1, CC2…, CC8, CC9* which classify drivers into one of the four driving modes (*5*):

1) Free driving: The driver always wants to maintain the desired speed and there is no influence of the preceding vehicle. In other words this driving scenario is similar to free flow driving condition.

2) Approaching: This driving condition is applied whenever a vehicle approaches another vehicle where the driver continues to decelerate to adapt its own speed with the lower speed of the preceding vehicle.

3) Following: Under this driving condition the driver would follow the preceding vehicle almost without accelerating or decelerating and maintaining approximately constant safety distance to the preceding vehicle.

In W-99 a driver either accelerates or decelerates to change from one driving mode to other as soon as some threshold value expressed in terms of relative speed and distance is reached (*5*). Thus the whole car following process is based on repetitive acceleration or deceleration of individual vehicles with drivers having different perceptions of speed difference, desired speed, and the safety distance between two successive vehicles. Here is a brief description of the 10 driving behavior parameters used in W-99 car following model.

CC0 is the standstill distance which defines the desired distance between two consecutive vehicles at stopped condition. The default value is 4.94 ft.

CC1 is the desired time headway for the following vehicle. Based on these values the safety distance can be computed as $dxsafe = CC0+CC1* v$, where v is the speed of the vehicle (*5*). The default value is 0.90 seconds (secs). Higher *CC1* values characterize less aggressive drivers.

CC2 defines the threshold that restricts longitudinal oscillation beyond safety distance in a following process. The default value is approximately 13 ft.

CC3 characterizes the entry to the “following” mode of driving. It initiates the driver to decelerate when he recognizes a slower leading vehicle. It defines the time at which the driver starts to decelerate before reaching the safety distance.

CC4 and *CC5* control the speed oscillations after the vehicle enters the “following” mode of driving. Smaller values represent a more sensitive reaction of the driver to the acceleration or deceleration of the leading vehicle. *CC4* is used for negative speed difference and *CC5* is used for positive speed difference. The default value of *CC4*/*CC5* is -0.35/0.35.

CC6 represents dependency of speed oscillation on distance in the “following” state. Increased value of *CC6* results in an increase of speed oscillation as the distance to the preceding vehicle increases. But when the distance to the preceding vehicle exceeds the “following” threshold value, the driver tends to behave independently of the preceding vehicle. *CC7, CC8, and CC9* parameters control the acceleration process.

The lane changing model in VISSIM is based on the driver response to the perception of the surrounding traffic. The decision to change lanes depends on the following hierarchical set of conditions: the desire to change lanes, favorable driving conditions in the neighboring lanes, and the possibility to change lanes (gap availability).It uses gap acceptance criteria where a driver changes lanes provided the available gap is greater than the critical gap Based on these conditions the lane changing phenomena is broadly classified into two types: 1) discretionary lane change which includes drivers who want to change from slow moving lanes to fast moving lanes and, 2) necessary lane change in case of any lane closure due to work zones, incidents and route selection. A detailed description of the lane changing algorithm is presented in Wiedemann and Reiter (*5*). Necessary lane changes depend on the aggressiveness of drivers in accepting/rejecting gaps in the adjacent lanes that is represented by parameters such as acceptable and maximum deceleration values of lane changing and trailing vehicles, and safety distance reduction factor (*SRF*). The safety reduction factor (*SRF*) refers to the reduction in safety distance (*dxsafe*) to the trailing and leading vehicle on the desired lane and the safety distance to the leading vehicle in the current lane. The default value of *SRF* is 0.6 which means the safety distance during lane changing is reduced by 40%. A lower *SRF* value (say 0.4) would mean that the safety distance for lane changing is reduced by 60% which suggests that drivers are more aggressive in accepting shorter gaps.

1.3. TRUCK ONLY LANES

Truck-only lanes (TOLs) are lanes designated exclusively for the use of heavy vehicles to separate them from other vehicles to enhance safety and improve traffic flow. TOLs have proved to enhance safety by reducing conflicting movements and are cost effective when truck volumes are higher than 30 percent (1). California did a research study and constructed two truck-only lanes, one Northbound and southbound I-5 in Los Angeles County and Southbound I-5 in Kern County. The Missouri Department of Transportation (MoDOT) has proposed TOLs along I-70 and I-44 to accommodate the high percentage of truck traffic and to minimize congestion along this freight-intensive corridor. Access at locations of intense truck activity will be grade-separated truck interchanges, however, most of the 250 mile corridor will be rural.

1.4. THESIS OVERVIEW

This thesis calculated the optimized slip ramp spacing for truck only lanes. It is organized as follows:

Paper 1 determines the optimized slip ramp spacing for truck only lanes, corridors of future project of MODoT

The conclusion summarizes the findings of the optimized slip ramp spacing distance for truck only lanes

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PAPER

1. SLIP RAMP SPACING DESIGN FOR TRUCK ONLY LANES USING MICROSCOPIC SIMULATION

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ABSTRACT

For the Corridors of the Future project, slip ramps will provide access to trucks between the proposed truck-only lanes (TOLs) and general purpose lanes (GPLs) for trucks to exit using at-grade interchanges. This paper proposes recommendations for slip ramp spacing between the TOLs and the GPLs planned along Missouri rural interstate highways using a microscopic simulation model, VISSIM. The slip ramp design procedure included: a) determining the acceleration/deceleration characteristics for heavy vehicles and buses, b) specifying VISSIM parameters based on vehicle characteristics and driver behavior, c) coding the TOL and GPL based on existing AASHTO Design Guide specifications, d) simulating the traffic on the TOLs and GPLs, e) studying the speed-flow relationship of passenger and heavy vehicles by analyzing the various lengths of link, merge and, diverge segments, and f) determining the slip ramp spacing for level, up- and down-grades. Simulation of peak period rural traffic conditions on level grades indicated that heavy vehicle speeds were directly proportional to the lengths of the merge, diverge, and link segments. The proposed design recommendations for slip ramp spacing are based on the results of these segment lengths. Central composite design was used to design the experiment and generate the cases required for simulation. As the slip ramp spacing depended heavily on the lane change behavior of drives, a sensitivity analysis was performed of the main lane change parameter in VISSIM that analyzed its effect on the speed-flow characteristics of heavy vehicles. Additionally, to ascertain the findings of the simulation study, Level-of-Service (LOS) for the segments on GPLs were determined. The LOS for the proposed slip ramp spacing for level, and up- and down-grades were found to be B. This paper provides practitioners and state Departments of Transportation with design recommendations for slip ramp spacing and lengths of merge, link, and diverge for the Corridors of the Future project.

Key words: Truck-only lanes (TOLs), microscopic simulation, capacity, acceleration behavior, deceleration behavior, Department of Transportation, Corridors of the Future project

1. INTRODUCTION

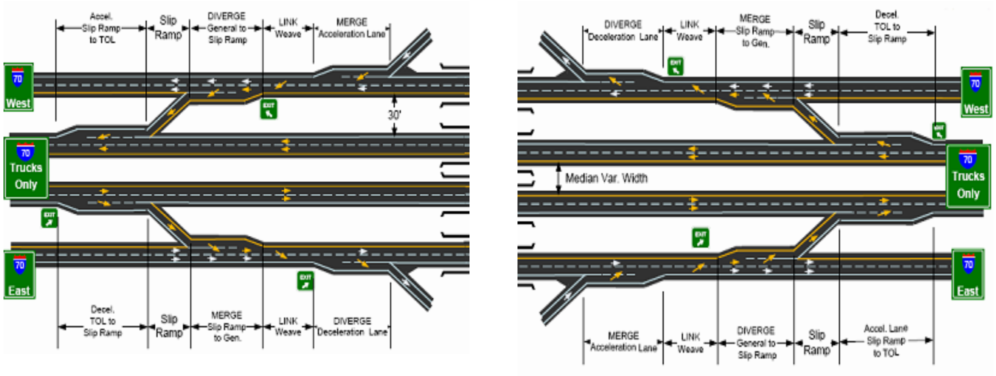
Truck-only lanes (TOLs), shown in Figure 1, are lanes designated exclusively for heavy vehicles (tractor-trailer trucks, recreational vehicles and buses) to separate them from other vehicles to enhance safety and improve traffic flow. TOLs have proved to improve safety by reducing conflicting movements and are cost effective when truck volumes are higher than 30 percent (1). The Missouri Department of Transportation (MoDOT) has proposed TOLs along I-70 and I-44 to accommodate the high percentage of truck traffic and to minimize congestion along these freight-intensive corridors. In

California, TOLs have been constructed on certain segments of I-5 in Los Angeles and Kern Counties.

In urban areas of Missouri with intense truck activity, grade-separated truck interchanges will be constructed. For most of the 250 mile rural corridor, however, slip ramps will connect TOLs with GPLs for heavy vehicles to exit and enter the highway using general traffic interchange. Figure 1(a) shows a rural location served by slip ramps.

In Missouri, in urban areas with intense truck activity grade-separated truck interchanges will be constructed, however, for most of the 250 mile rural corridor slip ramps will connect TOLs with GPLs for heavy vehicles to exit and enter the highway using general traffic interchange. Figure 1 shows a rural location served by slip ramps.

a) Proposed truck-only lane slip ramp configuration



a) Part 1 b) Part 2

Figure 1. Schematic: truck-only lanes and general purpose lanes.

For efficient movement of heavy vehicles during peak hours, this paper proposes specific design lengths for the segments from the slip ramp to the general traffic interchange to exit the highway presented as Part 1 in Figure 1(b). Similarly, the paper proposes design lengths for segments where heavy vehicles enter the TOLs through the GPLs from the general traffic interchange presented as Part 2 in Figure 1(c). A microscopic traffic simulation model, VISSIM, was used to study the effect of different segment lengths on the relationship between vehicle speeds and traffic flow.

2. LITERATURE REVIEW

Current publications do not address the spacing of slip ramps for TOLs. The AASHTO Design Guide (ADG) (15) does not provide specifications for the design of slip ramps for exclusive use of heavy vehicles. Previous studies have focused on the design of High Occupancy Vehicle (HOV) lanes and on truck lane restrictions. The studies reviewed below provide the details of ramp design and explains the selection of simulation parameters for use with VISSIM.

A Texas Transportation Institute (TTI) study (2) analyzed ramp design and truck performance for managed lanes in congested corridors. VISSIM was used to determine the effects of ramp spacing and weaving behavior on freeway operations. Speed was used as the primary measure of performance to evaluate the effects of various ramp spacings, traffic volume, and weaving percentages. In particular, the TTI report indicated that average freeway speed dropped faster with shorter ramp spacing, and ramp spacing was directly related to entering volume level. A flow rate of 275 vehicles/hour (vph) on a ramp that connected the managed lanes directly with the freeway resulted in acceptable speeds. Another study of ramp design (3) compared the Highway Capacity Manual (20) and simulation results to determine the effects of additional merge lengths. This study found that additional merge lengths increased the capacity and improved operations but the effect was relatively small.

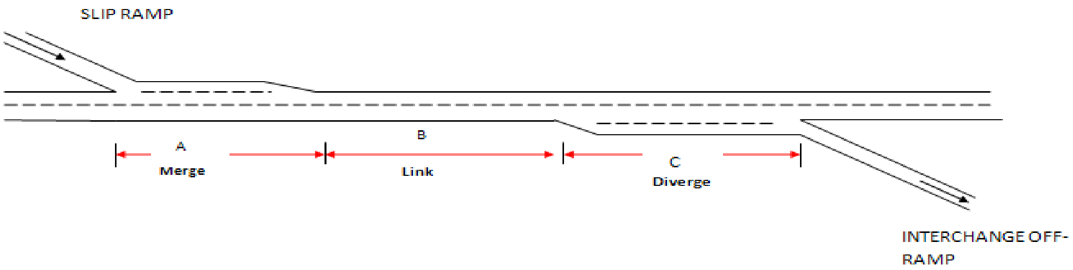
In California, VISSIM was calibrated using field data for a 15-mile stretch of I-210 WB. A freeway site consisting of three interacting bottlenecks and 20 metered on-ramps with and without HOV bypass lanes was simulated. VISSIM was used to model the congested freeway. The parameters in VISSIM were calibrated based on iterative runs and qualitative aspects of freeway operations such as queue clearance times, and on-ramp performance.

Acceleration performance of vehicles has a significant influence on roadway capacity and achievable travel speeds. If not hindered by other vehicles, a driver will travel at her desired rate of acceleration. Literature was reviewed to determine the acceleration characteristics of heavy vehicles. Gattis et al. (3) examined the attributes associated with acceleration of tractor trailers on freeway entry ramps and merging of such vehicles with the main lanes of the highway. The lengths of acceleration lanes for heavy vehicles to accelerate to the main line speed without hindering freeway traffic were specified. The data were collected from weigh stations in Missouri and Arkansas. A basis for determination of the acceleration lengths for rural freeway segments with a high percentage of tractor-trailers was provided. An acceleration lane length of about 2700 feet was proposed to allow a truck on a level grade to accelerate to within 10 mph of the posted speed of 65 mph. NCHRP Report 505 (2003) classified vehicular behavior into low and high-speed acceleration. The report also provided the acceleration rates for heavy vehicles with varying weight to power ratios. The study indicated that for trucks on grade, a marginal 1% grade requires a force equal to about 8% of the vehicle weight to overcome, slowing the speeds of vehicles considerably. The grade factor, therefore, will play an important role in designing TOLs for upgrades.

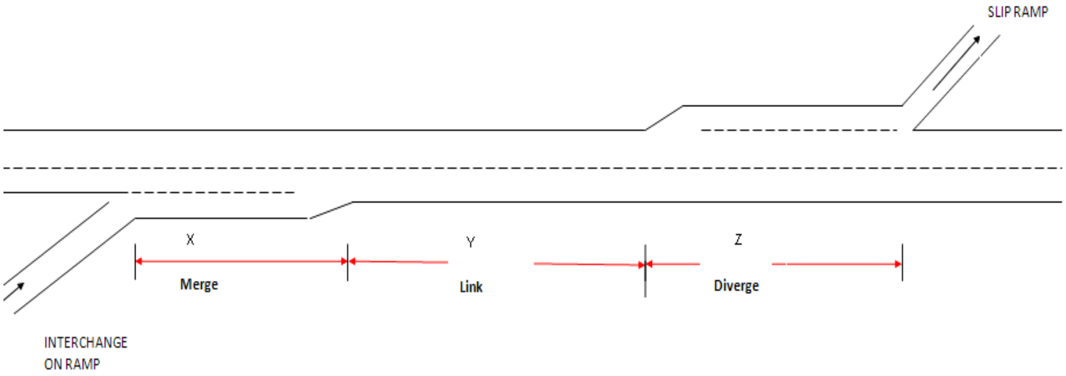
The acceleration characteristics of buses were also reviewed as they will use the TOLs. Gattis et al. (10) studied the acceleration behavior of buses by analyzing speed, time, and distance data collected for full size buses accelerating from a stopped position.

3. METHODOLOGY

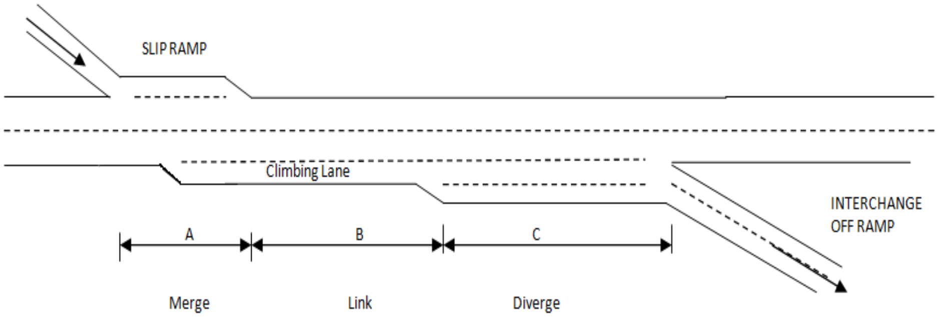
From this study, three key segments merge, link and diverge, presented in Figures 1 and 2, were analyzed to determine the slip ramp spacing. These segments were used by heavy vehicles to merge with passenger vehicles on the GPLs and then exit the GPLs. The TOL and GPL model was constructed in VISSIM as per the ADG specifications (15). The three key segments were evaluated for adequate lengths using multiple simulation runs of VISSIM. Central Composite design, a response surface design procedure was used to generate the design cases which were then simulated in VISSIM. Speed-flow plots on the merge, link, and diverge segments were studied. Based on the analysis of simulation results, design length recommendations for these segments were developed. LOS (Level-of-service) for the merge and diverge segments for the recommended design lengths case were calculated using the HCS software for comparison of results with VISSIM.



a) Schematics for the Different Segments of *Part 1* of General Purpose Lanes

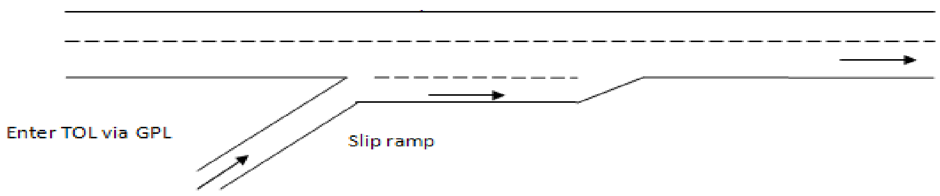


b) Schematics for the Different Segments of *Part 2* of General Purpose Lanes

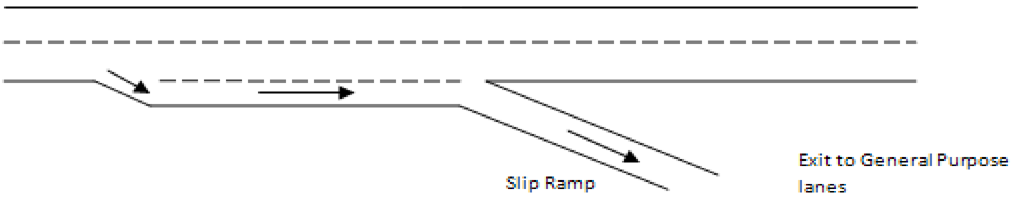


c) Schematics Showing the Climbing Lanes for Upgrade Sections on GPL, *Part 1*

Figure 2. General purpose lanes.



a) Schematics for the merge section of Truck Only Lanes, *Part 2*



b) Schematics for the diverge section of Truck Only Lanes, *Part 1*

Figure 3. Truck only lanes.

4. VISSIM

4.1. The VISSIM Simulation Model

Traffic simulation tools are heavily used for traffic analysis and design studies due to their ability to address complex traffic problems effectively compared to other analytical tools. Past research has shown that results from simulation tools are reliable (22). Given the importance of individual driver behavior and vehicle interactions in the TOLs and GPLs, a microscopic simulation model is appropriate for analyzing the traffic flow characteristics. For this study, VISSIM 5.1.0 was used for determining the slip ramp spacing. VISSIM provides significant control over individual driver behavior parameters in terms of both car-following and lane changing phenomenon compared to other simulation models.

The default behavioral parameters in VISSIM were modified for conditions appropriate for TOL and GPL and to simulate realistic traffic conditions. As the facility simulated in this study is proposed, important parameters that have a significant impact on driving behavior were identified from closely related studies. Heavy vehicles were assigned specific routes to enter and exit the highway. Speed limits were established for vehicles to follow on the freeway, slip- and the on- and off-ramps. The following segments provide details on the set up and the use of VISSIM to simulate the TOLs and GPLs.

4.2. The TOL and GPL Models

The TOLs and GPLs were modeled in VISSIM using the highway geometry (25) initially based on the ADG (15). The lengths of the merge, link, and diverge segments were specified as 800 ft, 900 ft, and 650 ft, respectively as shown in Figure 2. The lane widths specified were 12 feet. The taper lengths for single-lane entrance per Exhibit 10-69 (15) were set at 300 feet and for exit ramps per Exhibit 10-72 (15) at 250 feet. The appropriate length for slip ramps used was 800 feet for 30 feet median, 975 feet for 40 feet median and 1275 feet for 60 feet median (25). Figure 2 presents the schematics of TOLs and GPLs as coded in VISSIM.

For GPLs, the distance between Parts 1 and 2 as presented in Figure 1, was greater than 4000 feet, therefore, it was assumed that the vehicles in Part 2 did not influence the vehicles in Part 1.

4.3. Traffic Composition and Traffic Inputs in VISSIM

To simulate forecasted traffic conditions, traffic composition from a Missouri rural highway segment was used as input. The data were provided by MoDOT. The vehicles on the proposed TOL will include heavy vehicles as stated earlier whereas GPLs will include passenger cars, motorcycles, and pickups. Table 1 shows the traffic composition determined from the Annual Average Daily Traffic data for Missouri.

Table 1. Vehicle Composition

Description	**Percentage**
Truck Only Lanes	
Buses	1.50
2 axle 6 tire single units	2.70
3 axle single units	2.20
4 > axle single units	0.03
4 < axle single units	6.70
5 axle single trailers	79.00
6 > axle single trailers	0.48
5 < axle multi trailers	4.60
6 axle multi trailers	2.60
7 > axle multi trailers	0.19
General Purpose Lanes	
Motor Cycles	0.64
Passenger cars	75.00
2 Axle 4 tire single units	24.36

4.3.1. *Traffic Inputs.* From the Missouri traffic data, peak flow rates for heavy vehicle were determined to be around 1,220 trucks/hour (tph) for TOLs and the peak flow rate for passenger vehicles was around 2,500 vph for GPLs. During the peak hours, a maximum of 320 tph were expected to exit the TOLs using the slip ramps and the GPLs. Similarly, it was anticipated that 320 tph will enter the highway from the on-ramps during the peak hour. This figure was used as the highest truck volume on rural segments for TOLs with slip ramps. Truck volumes higher than 320 tph would require grade-separated interchanges. The traffic on the GPLs and TOLs was gradually increased till the peak flow was reached on both TOLs and GPLs and then gradually decreased. It was assumed that the traffic reaches the peak flow at the same time that 320 tph exit/enter using the slip ramp to test the GPLs. The TOLs and GPLs were not simulated to reach capacity conditions during the peak hour of simulation. The design of grade-separated interchange was not in the scope of the study.

4.3.2. Driving Behavioral Parameters.

4.3.2.1.Acceleration/Deceleration Behavior

VISSIM defines a range of values in the form of a distribution (rather than a fixed value) to reflect the stochastic nature of traffic. In VISSIM, to realistic simulate the acceleration/deceleration behavior of vehicles, the maximum and desired rates of acceleration and deceleration were specified as plots for heavy vehicles, buses, cars, and motorcycles.

Maximum acceleration rates for heavy vehicles on a level terrain were obtained from UMTRI (23). Equation 1 below was used to plot the maximum acceleration versus speed for heavy vehicles with a gross vehicle weight (GVW) of 70,000 lbs and engine power (P) of 240 hp (291 lbs/hp).

For differential speed changes between 30 and 70 mph, the following equation approximates the distance required to change speed.

$$D = \frac{V_f^2 - V_i^2}{2A} \cong \left(\frac{GVW}{2*P}\right)*\left(\frac{V_f^2 - V_i^2}{2g}\right) \quad \text{...(1)}$$

where:

D = distance traveled,

A = average acceleration which is related to the ratio of power to weight,

V_f = final velocity,

V_i = initial velocity,

GVW = weight,

P = HP, and G = acceleration due to gravity.

Equation 1 provided the values for acceleration versus speed plots for heavy vehicles (trucks, tractor-trailers) in VISSIM. The acceleration rates from the study by Gattis et al. were used to plot the acceleration versus speed relationship for buses. The acceleration rates for passenger cars and motorcycles were also obtained from the literature (4, 11). Table 2 shows the maximum and desired acceleration/deceleration values used in VISSIM.

TABLE 2. Acceleration/Deceleration Rates for Different Vehicles

Class of Vehicles	Max Acceleration (ft/sec^2)	Max Deceleration (ft/sec^2)	Desired Acceleration (ft/sec^2)	Desired Deceleration (ft/sec^2)
HEAVY VEHICLES	4.1	-18.0	4.0	-4.1
CAR	8.5	-20.0	6.8	-5.0
BUS	4.1	-15.0	4.0	-2.8
BIKE	10.5	-24.6	8.0	-5.0

4.3.2.2.Car following and lane changing parameters

VISSIM's Wiedmann-99 car-following model was used to simulate freeway traffic conditions. The VISSIM model has 11 main user defined driving behavior parameters: CC0…CC10 (17) that can be adjusted to simulate realistic driving behavior. The values of these parameters were selected from the literature, in particular from Gomes et al. (4) and Lownes and Machemehl (18), and were used for various segments of TOLs and GPLs. The parameters most significant for realistic simulation were found to be CC0, CC1, and the CC4/CC5 values. These variables are defined briefly below.

The variable CC0, stopped condition distance, defines the safety distance maintained by drivers. CC1 is headway time and along with CC0 it contributes to the determination of the safe distance to be maintained by the drivers. The CC4 and CC5 values determine the upper and lower thresholds in the driver car-following behavioral model. Low values of CC4 and CC5 increase sensitivity of driver reaction to the accelerations and decelerations of the preceding vehicle.

Many of the previous design studies have focused on the driver behavior parameters, none of the researchers have looked at the lane change behavior parameters that can impact driver behavior on a freeway in the best knowledge of the authors. The parameters that are important for realistic simulation of lane change behavior are lane changing distance and the safety distance reduction factor (SDRF). Lane changing distance is not a driving behavior parameter in the latest version of VISSIM 5.10. Rather, it is used to initiate the lane changing process by determining the position at which vehicles evaluate gaps in the adjacent lanes. It does not affect other aspects of the lane changing algorithm. The most important parameter was found to be SRDF. SDRF is defined as the distance to the trailing vehicle in the target lane necessary to change lanes safely (17). Detailed explanations of SDRF parameter is provided in the section below.

4.3.2.2.1. SDRF Sensitivity Analysis

As described in the previous section, SDRF is a critical parameter that reflects the aggressiveness of the drivers when changing lanes. This study used appropriate lane changing aggressiveness values in the VISSIM model to match the desired driver behavior in typical merge and diverge segments. Other driver behavior parameters such as CC0, CC1, CC2, and CC4/CC5 were mainly found to influence capacity (18) and were, therefore, not used in studying sensitivity analysis of slip ramp spacing. Necessary lane changes depend on the aggressiveness of drivers in accepting/rejecting gaps in adjacent lanes, which is represented by parameters such as acceptable and threshold deceleration values of lane changing and trailing vehicles, and SDRF. SDRF refers to the reduction in safety distance for trailing and leading vehicles on the desired lane and the safety distance to the leading vehicle in the current lane. The default value of SDRF specified is 0.6 which means the safety distance during lane changing is reduced by 40% compared to car-following. A lower SDRF value (say 0.3) would mean that the safety distance for lane changing is reduced by 70%, meaning the drivers are more aggressive in accepting shorter gaps.

To analyze the effect of change in SDRF, the SDRF value was incremented in 0.1 units varying from 0.2 to 0.8 to obtain different speed-flow characteristics of heavy vehicles on GPLs. The SDRF was varied for merge, link and diverge segments individually. For example, the SDRF values for link and diverge were set to default and SDRF values for merge were varied from 0.2 to 0.8. This process was repeated for the link and diverge segments. The speed-flow plots for different SDRF values and segments were then analyzed to observe the effect of SDRF values on speed-flow plots. The driver behavior parameters set were used for specific highway segments in VISSIM. In the following, the driver behavior developed for heavy vehicles and passenger cars for merge, link, and diverge segments are presented. Table 3 shows the various VISSIM parameters modified for this study.

4.3.2.2.2. Merge Behavior

Figures 2a and 2b indicate the merge segments for both Parts 1 and 2. Heavy vehicles exit the TOLs using the slip ramp and merge with vehicles on the GPLs. Similarly, heavy vehicles use the on-ramp to merge with vehicles on the GPLs. These behaviors affect passenger vehicle speeds on the GPLs.

To model the realistic merging behavior of drivers in VISSIM, the CC0 and CC1 parameters, waiting time for diffusion and SDRF values were specified. The CC1 value used was 1.4 seconds to simulate realistic headway times, higher than the default value of 0.9 seconds. The CC0 value for merge behavior used was 5.58 ft, higher than the default value of 4.92 ft, to increase the safety distance between the vehicles traveling on the merge segment. The waiting time for diffusion was set at 60 seconds, which provided ample time for vehicles to change lanes and join the mainstream traffic during peak traffic flow conditions. The SDRF value used was 0.2 to generate realistic but aggressive merge behavior on the freeways. This value was also used in a study by the Virginia Department of Transportation (8).

4.3.2.2.3. Freeway Link Section

Figure 2 defines this segment as 'B' and 'Y' between the merge and the diverge segments. The parameters specified were CC0, CC4, CC5, SDRF and the waiting time for diffusion. The CC0 parameter used was 5.58 ft, and values of CC4 and CC5 which specify vehicle following thresholds were modified to -2.0 and 2.0, respectively from the default values of -3.5 and 3.5. These values are similar to calibrated values for a freeway in California (4). The SDRF value on this segment was 0.6, appropriate for a freeway segment as no aggressive lane changing was required. The waiting time for diffusion was set at 1 second, so that vehicles coming to an emergency stop would automatically diffuse from the simulation and would not affect the main stream traffic.

4.3.2.2.4. Diverge Behavior

As shown in Figure 2, segment 'C' and 'Z' connect with deceleration lanes for vehicles to exit the GPLs and enter the TOLs. Driver behavioral parameters similar to those used for merging were used for this diverging segment as well. A SDRF value of 0.4 was used for off-ramps, selected in-between 0.2 (aggressive) and 0.6 (timid), to calibrate the SDRF factor for vehicles using the diverge segment. The waiting time for diffusion was kept at 60 seconds so that vehicles would have sufficient time to change lanes and join as well as leave the traffic on the GPLs during the peak flow conditions.

TABLE 3. VISSIM Parameters

Section	CCO Stand	CC1	CC4/CC5	Waiting time	SDRF
Default	4.92	0.9	-0.35/0.35	60	0.40
Merge	5.57	1.4	-2.0/2.0	60	0.20
Diverge	5.57	1.4	-2.0/2.0	60	0.47
Link	5.57	0.9	-2.0/2.0	1	0.60

4.3.3. *Routing Decision Parameters.* Routes were defined for the TOLs and GPLs so that vehicles exit and enter the TOLs/GPLs using the specified segments. Additionally, the routing decision parameters determined the percentage of truck traffic exiting from the slip ramp and the off-ramp. The percentages of trucks exiting the TOL via slip ramps were provided in such a way that passenger vehicles on GPLs and heavy vehicles from the slip ramp reached peak flows at the same time, thereby critically testing the design lengths of the key segments.

4.3.4. *Speed Decisions.* The speed limit for the TOLs, GPLs and slip ramps was set at 70 mph per interstate highway speed limit. A 70 mph speed limit was set for the slip ramps to maintain homogeneity in truck speeds between the TOLs and GPLs when trucks exit or enter using the slip ramps. This limit ensured consistent speeds among heavy vehicles merging with the GPL traffic and with the TOL traffic. The speed limit for vehicles on the off- and on-ramps was set at 50 mph, per the TOL report (25).

4.3.5. *Design of Experiment.* As part of design of experiment, central composite design (CCD) was used to generate design cases with different combinations of merge, link, and diverge lengths. CCD provides a reasonable basis for the selection of response surface design because the purpose is to select the design length combinations of merge, ling and diverge between the thresholds. It is far more efficient than incrementing the lengths by specific units as it allows judgment on the significance of the output based on input variables acting alone, as well as input variables acting in combination with one another. A study conducted by incrementing unit lengths always carries the risk that the designer may find either merge, link or diverge variable to have a significant effect on the response (output) while failing to discover that changing another variable may alter the effect of the first.

There are three different types of CCDs: face-centered CCD (FCCD), rotatable or circumscribed CCD (RCCD), and inscribed CCD (ICCD). RCCD was chosen to generate the cases as the design lengths exist at extremes of the design region and RCCDs provide equal precision of estimation in all directions. In addition, compared to FCCDs and ICCDs, RCCDs offer reduced prediction error for, and improved estimation of, quadratic (curvature) effects (21).

In a RCCD, the design points describe a sphere circumscribed about the factorial cube. For three factors (merge, link and diverge lengths), the RCCD points describe a sphere around the factorial cube. Figure 4 illustrates a RCCD, in which the stars are located at a distance α from the center based on the experimental error and the number of factors in the design. To maintain rotatability, the value of α depends on the number of experimental runs in the factorial portion of the RCCD (21).

Star point distance, α, is determined as:

$$\alpha = [2^{k}]^{1/4} \qquad (2)$$

where: k is the number of factors and equals 3 for the current study indicating the three segments ($2^{3/4} = 1.682$). The stars establish extremes for the low and high lengths for all factors.

The design cases to be simulated were determined by the JMP software (24). Pilot runs were conducted to determine the maximum and minimum lengths of each of the segments in which the speeds were acceptable, and the results were used as an input to the software in generating the different cases. From the RCCD design, the vertices of the cube (8 points), the center points (2 points), and radial axial points on the sphere passing through each face (6 points) form a total of 16 cases using three factor (merge, link, diverge) design combinations. These were generated by the JMP software. A combination at the center point was repetitive and was not considered in the simulation. The slip ramp spacing was determined by the sum of the lengths of the merge, link, and diverge segments.

Fifteen scenarios were each simulated 15 times using VISSIM with different random seeds to add variability to the results from the micro-simulation model. To ensure accurate results, the resolution of the simulation was set to two simulation steps for each time step of one second. Evaluation was performed based on the average results on the merge, diverge, and link segments. The traffic flow variables were averaged every five minutes for analysis.

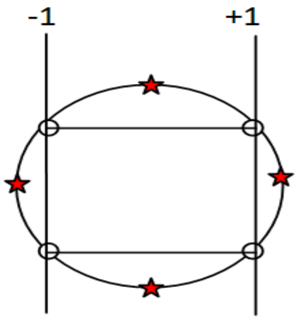


Figure 4. Rotatable central composite design.

4.3.6. *Level of Service (LOS).* For this study, the Highway Capacity Software (HCS) (20) was used to calculate the LOS and vehicle speeds obtained for the proposed optimized slip ramp spacing distance from TOL slip ramp to off-ramp. HCS was used to compare and verify the speeds of vehicles on the merge and diverge sections with the speeds of vehicles obtained in VISSIM for the same sections during peak flows for level, up- and down-grades. For the merge and diverge sections, merging and diverging procedures of the Highway Capacity Manual (20) were used.

4.3.7. *Evaluation Criteria.* For the level, up- and down-grade scenarios simulated, speed-flow relationships were plotted. Based on the discussions with MoDOT, the speed of 50 mph was set as the lower limit for vehicles on GPLs near the ramps. As such during simulation, when vehicle speeds remained above 50 mph and there were no signs of congestion during peak flow on the three key segments, those cases were deemed acceptable. Design cases in which vehicles slowed down to below 50 mph, those cases were unacceptable and indicated as failed in Table 4. The average speeds of vehicles, therefore, should be above 50 mph in the GPL lanes of merge, link, and diverge segments for a case to be acceptable.

TABLE 4. Simulated Lengths for Part 1 and Part 2 of the General Purpose Lanes

Cases	Merge	Link	Diverge	Total	Results	Comments
Level						
Case 1*	800	900	650	2350	Failed	Failed in link, diverge
Case 2	900	700	825	2425	Failed	Failed in diverge
Case 3	1000	900	650	2550	Failed	Failed in link, diverge
Case 4	900	1200	550	2650	Failed	Failed in diverge
Case 5	800	900	1000	2700	Failed	Failed in diverge
Case 6	750	1200	825	2775	Failed	Failed in merge, link, diverge
Case 7	1000	900	1000	2900	**Pass**	All sections passed
Case 8	900	1200	825	2925	Pass	All sections passed
Case 9	800	1500	650	2950	Failed	Failed in link, diverge
Case 10	1050	1200	825	3075	Pass	All sections passed
Case 11	1000	1500	650	3150	Failed	Failed in diverge
Case 12	900	1200	1100	3200	Pass	All sections passed
Case 13	800	1500	1000	3300	Pass	All sections passed
Case 14	900	1700	825	3425	Pass	All sections passed
Case 15	1000	1500	1000	3500	Pass	All sections passed
4% Down-Grade						
*Case 16**	550	900	750	2200	Failed	Failed in link, diverge
Case 17	750	900	1100	2750	Failed	Failed in link, diverge
Case 18	650	1200	925	2775	Failed	Failed in merge
Case 19	850	1200	925	2975	**Pass**	All sections passed
Case 20	550	1500	1100	3150	Failed	Failed in merge
Case 21	750	1500	1100	3350	Pass	All sections passed
Case 22	950	2000	1200	4150	Pass	All sections passed

Bold values indicate recommended slip ramp spacing distance

* Values indicate AASHTO recommended values

5. ANALYSIS OF RESULTS

The slip ramp spacing was evaluated by analyzing the speed-flow relationship on the key segments of the GPLs. Figure 2 shows the key segments that were evaluated before and after the interchange. These segments were chosen because heavy vehicles and passenger vehicles interact on these segments. The speeds of heavy vehicles and passenger vehicles were analyzed for more careful consideration for level, up- and down-grades.

Fifteen design cases for level grade determined by using the RCCD and as discussed in the ‘Central Composite Design’ were simulated to evaluate the lengths for the merge, diverge, and link segments. Six cases out of fifteen RCCD generated cases were selectively chosen for up, and down-grade and were simulated to analyze the appropriate lengths for the merge, diverge, and link segments. Slip ramp spacing distance was calculated by summing the lengths of the three segments. The recommended case was chosen based on the most consistent slip ramp spacing distances from cases with speeds above 50 mph. The results in Table 4 are sorted based on the total slip ramp spacing distance.

Most trucks can negotiate a 3% grade, however, grades of more than 4% can cause a decrease in vehicular speeds to the extent that traffic operations are affected (16). Therefore, this study used upgrades and downgrades of 4% to evaluate link, merge and the diverge segments. It needs to be kept in mind that on interstate highways with a 4% upgrade, a climbing lane is requried for heavy vehicles to use. The climbing lanes implementation would be per the ADG (15) criteria of critical grade, traffic flow exceeding 1700 vph including trucks, the length of grade and the percentage of trucks. For TOLs, heavy vehicles are separated out and two lanes are available for use. For upgrade, this study evaluated the GPLs with a climbing lane for heavy vehicles to exit and enter the TOLs using the GPLs.

5.1. Level Grade

Case 1 with a merge length of 800 feet, a link length of 900 feet, and a diverge length of 650 feet as recommended by the ADG (15), consistently performed poorly with very low speeds during peak flows. Figure 5a presents the speed-flow relationship for this case in Part 1, which indicates that heavy vehicles slowed down to 30 mph. The speeds of passenger vehicles were also affected as they were reduced to below 50 mph which is shown in 5b. This case failed because the vehicle speeds were unacceptable.

For Case 3, the length of diverge segment was set per the ADG (15) and the link length was 1000 feet. Case 3 failed with the speeds of heavy vehicles below 50 mph both in the link and diverge segments. Case 5 was simulated with a diverge length of 1000 feet much higher than Case 1. Slight increase in speeds were observed, however, the speeds of heavy vehicles were less than 50 mph, and the passenger vehicles recorded low speeds as well.

For Case 7, the design lengths were found to meet the criteria to maintain vehicle speeds while entering and exiting the GPLs. The plots, demonstrate that vehicle speeds for this particular case were consistently between 50 and 70 mph. This case was acceptable for heavy vehicles using the slip ramp with a peak flow rate of 320 tph. Greater design lengths and different combinations determined from the RCCD were also simulated and it was found that speeds of heavy vehicles and passenger vehicles for cases 8, 10, 12, 13, 14, and 15 were also acceptable. From Table 4, it can be concluded that the minimum length for diverge segment must be 825 feet for the speeds of heavy vehicles to be above 50 mph. Case 7 has the least slip ramp spacing of 2900 compared to other pass cases. Cases 8, 10, 12, 13, 14, and 15 had small improvement of 3 to 5 mph in speeds of vehicles compared to Case 7.

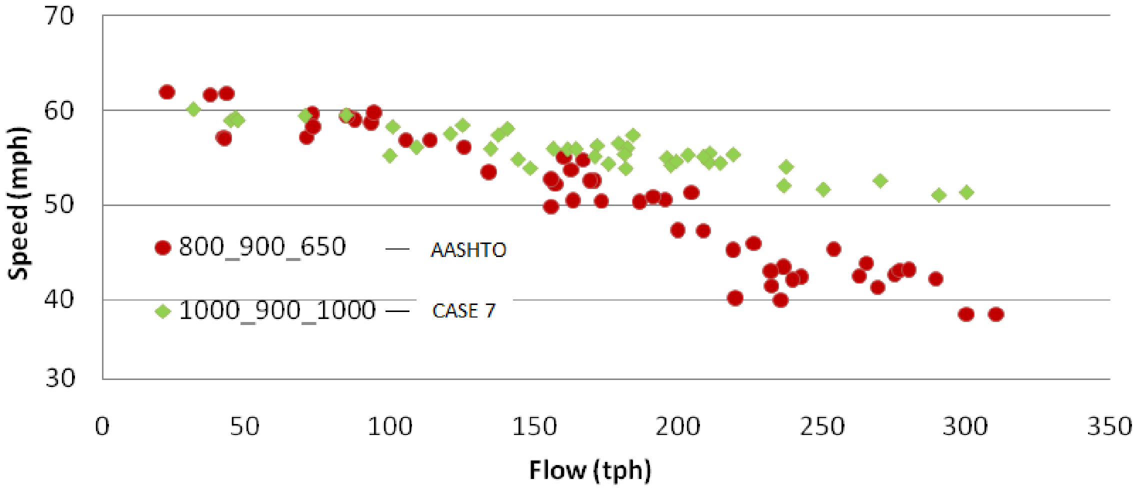


Figure 5. Before interchange (level grade), heavy vehicles on diverge section of GPL.

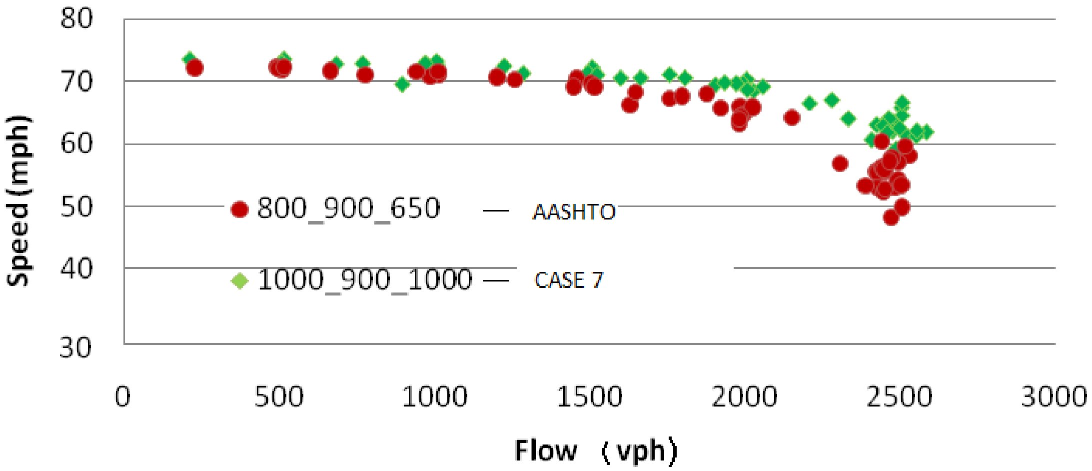


Figure 6. Before interchange (level grade), passenger vehicles on diverge section of GPL.

The speeds of passenger vehicles were consistent in the merge and link segments of Parts 1 and 2, varying from 60 to 70 mph for all cases except for Case 1. This study also analyzed the speed-flow characteristics for vehicles traveling on merge, link, and diverge segments of Part 2, as shown in Figure 2(b). The trends observed were similar to those in Part 1 for the speed-flow curves, with the additional lengths permitting higher vehicular speeds. The cases that successfully passed for Part 1 also passed for Part 2. This analysis showed that the governing lengths of merge, link, and diverge segments were the distance needed for heavy vehicles to complete the lane change from the slip ramp to the off-ramp for Part 1 and from the on-ramp to the slip ramp for Part 2.

5.1.1. *Analysis of Truck Only Lanes.* Figures 3(a) and 3(b) show the schematics of the segments on the TOLs before and after the interchange. Simulation was also carried out for the slip ramps and the merge segment before the slip ramp of the TOLs. Speed-flow characteristics were studied for various lengths of the merge segment, and heavy vehicles were able to exit the TOLs using the slip ramp at speeds between 60 mph and 70 mph. Similar analysis was carried out for Part 2 slip ramp of the TOL. The results indicated that the heavy vehicles were able to reach the TOLs using the slip ramps and maintain speeds between 60 and 70 mph. Figure 6 shows the speeds of heavy vehicles on the slip ramps for the lengths of 800 feet. From the figure it can be seen that there is a speed difference of 10 mph for heavy vehicles on slip ramp in Part 2 compared to speeds of heavy vehicles on slip ramp in Part 1. This can be attributed to the fact that the heavy vehicles on Part 2 interact with traffic on the GPLs which results in speed reduction on the slip ramp. The heavy vehicles on Part 1 exit the TOLs and enter the slip ramp with a speed limit of 70 mph. The speed-flow plots of heavy vehicles on diverge segment of TOLs Part 1 and merge segment of TOL Part 2 were also studied. The speeds of heavy vehicles were acceptable for ADG (15) specified merge and diverge lengths.

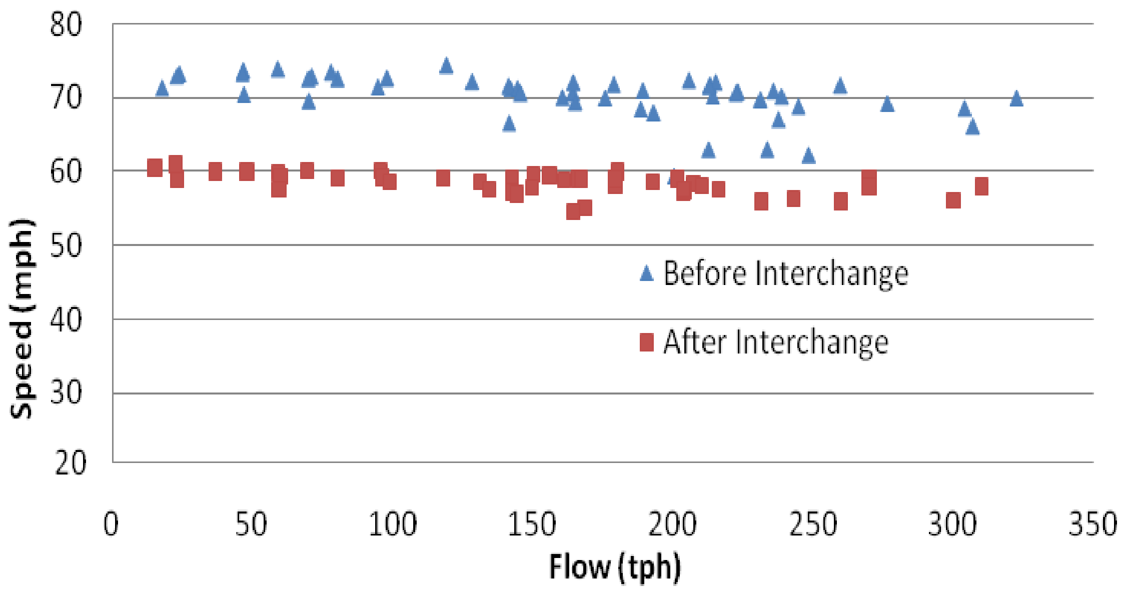


Figure 7. Before and after interchange, heavy vehicles on the slip ramp.

5.2. Upgrade

Speed-flow characteristics of segments in Figures 2(a) and 2(b) were analyzed for 2, 3, and 4% upgrade. All design cases including the ADG recommended case failed with heavy vehicles slowing below 30 mph on the freeway, resulting in congestion on the GPLs. A grade of 4% was taxing for heavy vehicles. The speeds of passenger vehicles during the peak hour also slowed down to below 50 mph.

5.2.1. *Climbing lanes.* To improve the speeds of heavy vehicles and prevent congestion as a result of slow moving heavy vehicles, climbing lanes as shown in Figure 2c were used with the GPLs for 2, 3, and 4 % grades. The traffic conditions on the segments of GPLs met the criteria specified by ADG (15) for climbing lanes. The heavy vehicles slowed down on the climbing lane. Based on the RCCD, six cases with climbing lanes were simulated for 2%, 3%, and 4% grade. Table 5 shows the cases simulated in VISSIM. Implementing the climbing lane increased the speeds of heavy vehicles on 4%

grade with minimum speeds of heavy vehicles at 40 mph compared to 30 mph without the climbing lanes. The heavy vehicles were unable to reach speeds above 50 mph.

For 3% grade, the minimum speeds of heavy vehicles during peak flows were found to be 45 mph, still below the acceptable speeds of 50 mph. The design cases with a gradient of 2% showed that speeds of heavy vehicles were acceptable in all three segments. Grade of 1% was not simulated as it was assumed that the design cases passing in 2% upgrade would also pass for a gradient of 1%. Case 25 and Case 27 were acceptable with speeds of heavy vehicles greater than 50 mph in all segments. Case 25 with climbing lane is recommended for a gradient of 2%.

TABLE 5. Simulated Lengths for Different Up-Grades for Part 1 and Part 2 with Climbing Lanes of the General Purpose Lanes

Cases	MERGE	LINK	DIVERGE	TOTAL	2%	3%	4%
Case 23	1000	900	1100	3000	Failed	Failed	Failed**
Case 24	850	1200	1050	3100	Failed	Failed	Failed
***Case** 25*	1250	1200	1000	3450	**Pass**	Failed*	Failed**
Case 26	1450	900	1100	3450	Failed	Failed	Failed
Case 27	1000	1500	1000	3500	Pass	Failed*	Failed**
Case 28	1450	1500	1000	3950	Failed	Failed	Failed

* indicates the minimum speed of 45 mph

** indicates the minimum speed of 40 mph

5.3. Downgrade

Speed-flow characteristics segments of the GPLs were analyzed for a gradient of 4% downgrade. Table 4 shows the cases simulated for a negative gradient. Case 16 was based on the design recommendations provided by ADG (15). The speed-flow plot from Figure 5c shows that this case failed, with heavy vehicles recording low speeds on the GPLs. Additional analyses with other cases with longer lengths were conducted to determine the appropriate slip ramp spacing. Cases 19, 21, and 22 performed better than the remaining cases; and are recommended with peak truck volumes. Except for Case 16, the speeds of passenger vehicles for all the remaining cases were found to be consistently between 60 and 70 mph. Case 19 with the least slip ramp spacing distance is recommended for a 4% downgrade on the GPL.

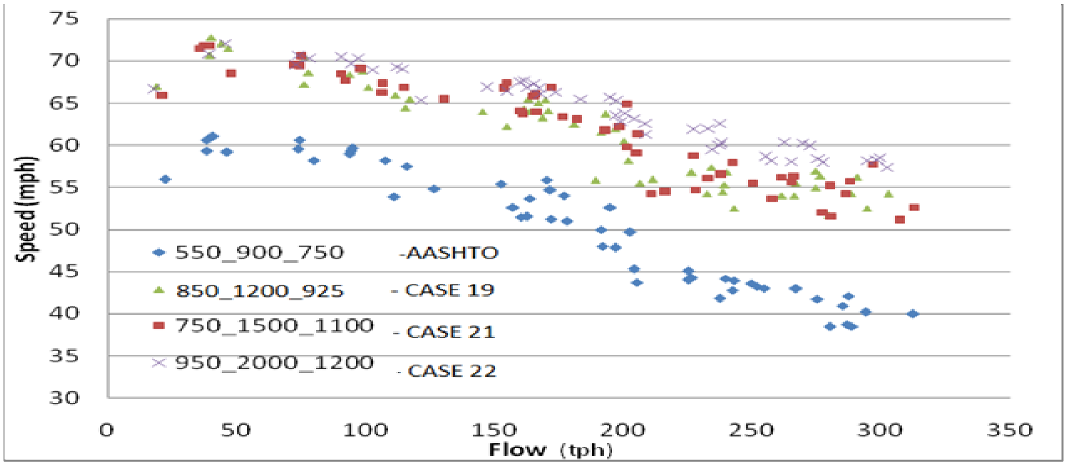


Figure 8. Before interchange (downgrade), heavy vehicles on the diverge section of GPL.

5.4. Level-of-Service

The LOS for merge and diverge segments for the recommended slip ramp spacings were calculated. The peak flow on the slip ramp was 320 tph and the peak flow of passenger vehicles on the GPL was 1000 vph and 1500 vph for the left and right lanes, respectively. The LOS was calculated to be ‘B’ for merge and diverge segments on GPLs. LOS was also calculated for segments with a gradient factor on GPLs. The LOS for 2% up-grade and 4% down-grades was found to be B for the recommended lengths on GPLs. The average speeds on level grade provided by HCS in the ramp influence area of diverge segment was 57.5 mph compared to 55.63 mph for speeds of all vehicles in VISSIM. For the merge segment, average speeds calculated by the HCS in the ramp influence area was 63.2 mph compared to 61.23 mph for the speeds of vehicles in VISSIM.

5.5. Sensitivity Analysis

Speed-flow plots of heavy vehicles were studied in the GPLs of merge, link and, diverge segments for SDRF values varying from 0.2 to 0.8. Figure 7 shows the speed-flow plots of heavy vehicles for various SDRF values on the diverge segment. From the figure it can be observed that for heavy vehicles when volume exceeded 280 tph, speeds reduced below 50 mph for SDRF values of 0.5 and higher. Taking safety into consideration, a SDRF value of 0.4 from the plot was found to generate realistic diverge behavior for trucks exiting the GPLs using an off-ramp. For merge segments, similar speed-flow plots with SDRF values were observed. A SDRF value of 0.2 was found to simulate acceptable speeds in the merge segment. Heavy vehicles exiting the TOLs using the slip ramp did not reduce or slow down passenger vehicles while entering the merge segment of GPLs. This finding is consistent with the research study by Srividya et al. (8) to generate realistic merge behavior on the freeway. The SDRF sensitivity analysis for the link segment showed that the default SDRF value of 0.6 generated acceptable speeds for vehicles on the GPLs.

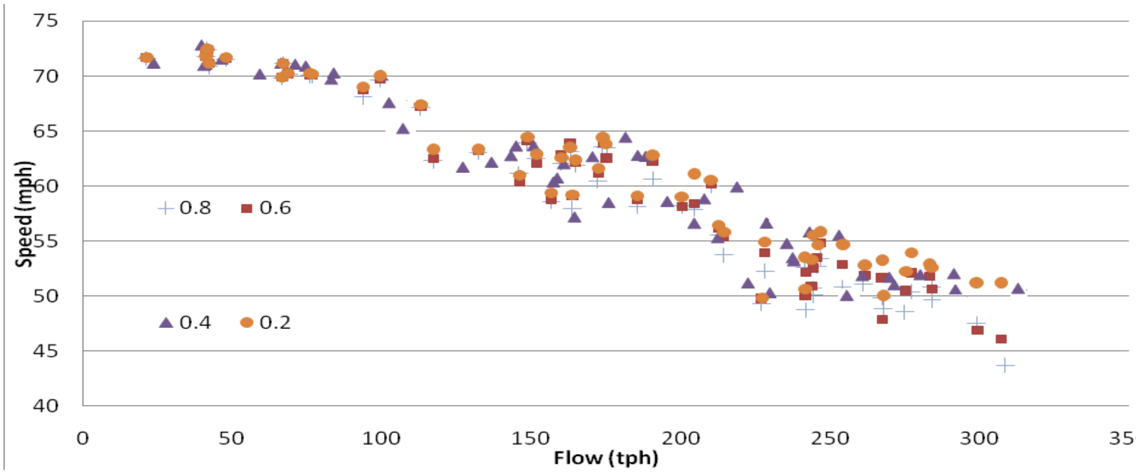


Figure 9. Heavy vehicles speed-flow plots for different SDRF sensitivity values, vehicles on the diverge section of GPL.

6. CONCLUSIONS AND RECOMMENDATIONS

This study analyzed the slip ramp spacing for safe and efficient operation of the GPLs and TOLs. Research indicated that the distance needed for trucks to merge with/also merge from traffic is greater than that to accelerate/decelerate; therefore, this distance controls the length of the acceleration/deceleration lanes. Higher traffic flow rates can be achieved with no significant drop in the speed if additional merge, link, and diverge lengths are provided. Part 1 of the TOL merge segment showed no signs of congestion for any of the design lengths tested. The average length of a merge segment should be 1000 feet. The diverge lane length should be 1000 feet, and the link segment for trucks requires 900 feet for heavy vehicle volume of 320 tph. The total distance from slip ramp to off-ramp can range from 2,900 feet to 3,500 feet. The results for Part 2, evaluating slip ramps after the interchange, followed a similar trend, with an increase in operating speeds resulting from increases in segment lengths. Speed-flow characteristics of heavy vehicles were analyzed on the slip ramps. The results showed that the speeds were acceptable for ADG design lengths on the merge segment of TOL and on the slip ramps of both Part 1 and Part 2.

Analysis of gradient factor of the key segments shows that for 4% up grade, a significant drop in speeds were found. The speeds recorded on the segments were not acceptable. Heavy vehicles were unable to reach acceptable speeds of 50 mph for the tested design cases. Speeds of heavy vehicles were improved when climbing lanes were installed on the merge, link, and diverge segment. Speeds were below 50 mph in the segments for 3% upgrade. Lengths of 1200 ft, 1250 ft, and 1000 ft for merge, link, and diverge, respectively, are to be used on a 3% grade if the speed limit for the heavy vehicles on the climbing lane is below 50 mph. Speeds of heavy vehicles were found to be acceptable on a 2% gradient with climbing lanes. The recommended design lengths for 2% upgrade of merge, link, and diverge are 1200 ft, 1250 ft, and 1000 ft respectively. Climbing lanes should be used to improve the speeds of heavy vehicles on GPL segment on up-grade. Analysis of 4% negative gradient showed that ADG recommended design lengths failed. Speeds were recorded low for both heavy vehicles and passenger vehicles. The recommended design lengths for merge, link, and diverge are 850 ft, 1200 ft, and 925 ft respectively for a truck volume of 320 tph. Operations degrade for traffics flow between 280 and 320 trucks per hour and between 2,500 and 3,000 general purpose vehicles per hour. LOS was found to be 'B' for the recommended merge, link and diverge segments for level, 2% up- and 4% downgrades on GPL. The speeds for vehicles on merge and diverge segments on GPL was found to be similar in both HCS and VISSIM softwares. From the sensitivity analysis, It can be concluded that SDRF value of 0.2 for merge and 0.4 for diverge segments simulated realistic merging and diverging behavior of vehicles on GPL. The default value of 0.6 for SDRF generated realistic driving behavior on the link segment. To maintain homogeneity in speeds of heavy vehicles and to reduce the congestion on the merge segment of a GPL, the speed limits on slip ramps should be the same as those on GPLs.

7. ACKNOWLEDGEMENTS

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SECTION

2. CONCLUSIONS

This work studied slip ramp spacing for safe and efficient operation of the GPLs. Research shows that distance needed for trucks to weave in traffic is greater than that to accelerate or decelerate; therefore, the weaving distance controls the length of the acceleration/deceleration lanes. Higher traffic flow rates can be achieved with no significant drop in the speed if additional merge, link, and diverge lengths are provided. Part 1 of the TOL merge section showed no signs of congestion for any of the design lengths tested. The average length of a merge section should be 1000 feet. The lengths of the diverge lanes should be 1000 feet, and the weaving section for trucks requires 900 feet for heavy vehicle traffic of 320tph. The total distance from slip ramp to off-ramp should be 2,900 feet to 3,500 feet. The results for Part 2, evaluating slip ramps after the interchange, followed a similar trend, with an increase in operating speeds resulting from increases in segment lengths.

Analysis of gradient factor of the key segments shows that for 4% up grade, a significant drop in speeds were found. The speeds recorded on the segments were not acceptable. Heavy vehicles were unable to reach acceptable speeds of 50 mph for the tested design cases. Speeds of heavy vehicles were improved when climbing lanes were installed on the merge, link, and diverge segment. Speeds were below 50 mph in the segments for 3% upgrade. Lengths of 1200 ft, 1250 ft, and 1000 ft for merge, link, and diverge respectively are to be used on a 3% grade if the speed limit for the heavy vehicles on the climbing lane is below 50 mph. Speeds of heavy vehicles were found to be acceptable on a 2% gradient with climbing lanes. The design lengths for 2% upgrade of merge, link, and diverge are 1200 ft, 1250 ft, and 1000 ft respectively generated acceptable speeds with the least slip ramp spacing. Climbing lanes should be used to improve the speeds of heavy vehicles on GPL segment on up-grade. Analysis of 4% negative gradient showed that ADG recommended design lengths failed. Speeds were recorded low for both heavy vehicles and passenger vehicles. The design lengths of merge, link, and diverge are 850 ft, 1200 ft, and 925 ft, respectively, for a truck volume of 320 tph generated acceptable speeds. Operations degrade for traffics flow between 280 and 320 trucks per hour and between 2,500 and 3,000 general purpose vehicles per hour. Based on the analysis common lengths of 900 feet , 1200 feet, and 1000 feet for merge, link, and diverge respectively are recommended for level and 4% downgrade. A combination of 1000 feet, 1300 feet, and 1100 feet is recommended for upgrade with climbing lanes. LOS was found to be ‘B’ for the recommended merge, link and diverge segments for level, 2% up- and 4% downgrades on GPL. The speeds for vehicles on merge and diverge segments on GPL was found to be similar in both HCS and VISSIM softwares. From the sensitivity analysis, It can be concluded that SDRF value of 0.2 for merge and 0.4 for diverge segments simulated realistic merging and diverging behavior of vehicles on GPL. The default value of 0.6 for SDRF generated realistic driving behavior on the link segment. To maintain homogeneity in speeds of heavy vehicles and to reduce the congestion on the merge segment of a GPL, the speed limits on slip ramps should be the same as those on GPLs.

VITA

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