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16. Abstract

The managed lane concept is currently being considered on major freeway projects in Texas cities. As a new concept in operating freeways it has a limited experience base, creating a knowledge vacuum in emerging key areas that are critical for effective implementation. Complicating the effort is the rapid progress of several freeway improvement projects in Texas for which managed lane operations are proposed. The operational experience both in Texas and nationally for managed lanes is minimal, particularly for extensive freeway reconstruction projects. The managed lane projects currently in existence involve retrofits of existing freeway sections within highly fixed access, geometric, operational configurations and established eligibility considerations. There are virtually no projects in operation from which to draw experiential data on the implementation of managed lane freeway sections with multiple operational strategies, including variations in eligible vehicle user groups by time of day.

Tools are available that document the impact of managed lane operations on the road users who make up the vehicle mix. Traffic simulation is a tool that affords the possibility of examining the operational impacts of a vast array of design alternatives for managed lanes; in the current research, the VISSIM simulation tool was used. Whereas such models are historically used to evaluate freeway and arterial design alternatives, with the user selecting the designs which produce the most significant benefits, the models themselves are flexible enough to test scenarios and provide performance data throughout the design and development process. This effort analyzes a variety of managed lane access and egress scenarios and makes weaving length recommendations for managed lanes access. The report provides maximum desirable weaving volume values, and gives additional guidance to assist engineers and planners in the determination of freeway ramp and managed lane access spacing.

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MANAGED LANES – TRAFFIC MODELING

by

Steven Venglar, P.E
Assistant Research Engineer.
Texas Transportation Institute

David Fenno, P.E.
Assistant Research Engineer
Texas Transportation Institute

Samir Goel
Texas Transportation Institute

and
Paul Schrader
Texas Transportation Institute

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The Texas A&M University System
College Station, TX 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation and it is not intended for construction, bidding, or permit purposes. The engineer in charge of this task of the project was Steven Venglar, Texas P.E. #84027. The engineers in charge of the overall research project were Beverly Kuhn, Texas P.E. #80308 and Ginger Daniels, Texas P.E. #64560.

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CHAPTER 1. MANAGED LANES MODELING INTRODUCTION

PURPOSE OF MANAGED LANES MODELING

The managed lanes concept has been defined by the Texas Department of Transportation (TxDOT) as "a facility that increases freeway efficiency by packaging various operational and design actions. Lane management operations may be adjusted at any time to better match regional goals." A fundamental aspect of managed lanes operation is the determination of which operations, or controls, are appropriate at any given time, and at what point it is necessary to change operations in order to maintain high efficiency within the managed lane.

Traffic modeling presents one means of performing experiments on the traffic volume, control, and geometric conditions found in the real world. Experiments can be performed on the exact same set of modeling conditions to determine which control most favorably influences the managed lane. Such experimentation is impossible under real-world conditions – no two "days" or "hours" of traffic flow are the same. Also, modeling can be performed in "greater than real time," often only restricted by the computer resources available. Again, restrictions from the real-world environment mean that all experimentation is done in "real time." In some cases, it may simply cost too much, or require too much manpower, to collect data for certain types of traffic condition studies. In these instances, models can easily and inexpensively simulate the traffic phenomena desired and report the results in the appropriate manner.

A variety of traffic analysis and simulation tools exist. When examining the structure and fundamentals of these models, it is possible to break them into two categories: macroscopic and microscopic. Macroscopic models rely on representations of aggregate vehicle behavior to determine traffic flow and quality within the model. Microscopic models actually simulate the behavior of individual vehicles and rely on rules of driver behavior to control vehicle position and speed. For purposes of modeling managed lanes, especially given restrictions such as vehicle occupancy for allowing entry to the managed lane, it will be necessary to use a microscopic traffic model in the current managed lanes study.

MODEL SELECTION

A variety of extant microscopic traffic models are applicable to the managed lanes concept being studied. As a minimum, the selected model must be capable of modeling interrupted flow facility operation (i.e., arterials and freeway frontage roads, if desired in the model), freeway operation (including lane changing and weaving), detailed freeway and arterial lane use designations, static and dynamic route assignment, user group/vehicle classification features, and high occupancy vehicle (HOV) lane operation. It is desired that the model be capable of explicitly (preferred) or implicitly modeling the impacts of user-defined criteria for route choice/assignment, including downstream congestion, vehicle occupancy, and willingness to pay tolls. The model must have a graphical, user-friendly interface (preferably Windows™ 95/98/ME/2000/NT) for ease of use, must run on a PC, and the results of the simulation must be presented or configured in such a way that descriptive statistics can be easily generated.

APPLICABLE MODELS

Among publicly or commercially available microscopic traffic simulation models, several are capable of fulfilling the minimum requirements for model functionality, including CORSIM (*1*), Paramics (*2*), VISSIM (*3*), Integration (*4*), and SimTraffic (*5*). When flexible/dynamic route assignment is introduced into the model selection process, CORSIM and SimTraffic are removed from contention. When explicit modeling of vehicle occupancy and willingness to pay tolls is considered, Integration is removed from the list of applicable models since it can accommodate only five classes of vehicle/occupancy and cannot explicitly model willingness to pay tolls.

Due to the specific nature of managed lanes modeling, only two models appear to be viable candidates for realistic managed lanes operational modeling: Paramics and VISSIM. Both models have options for introducing custom-programmed logic into the simulation, which is necessary for customized, condition-dependent control of access to the managed lanes. Though it would be most comprehensive to evaluate the proficiencies of both models for the current managed lanes application, the modeling development schedule and resources are prohibitive. As VISSIM could be obtained for roughly one-tenth of the cost of Paramics and required no external software to be fully functional and programmable for project purposes (i.e., Paramics would require separate purchase of a C compiler), the choice was made to use VISSIM.

FEATURES OF VISSIM

VISSIM is a microscopic traffic and transit simulation model. The model was developed in Germany to analyze complex traffic and transit operations including various levels of transit priority treatment and railroad preemption at signalized intersections. An English-language version has been available to U.S. users for over five years, and there is an expanding user base. VISSIM has a graphical user interface, which allows the user to create networks over scaled background aerial photography or CAD layouts. VISSIM's sophisticated vehicle simulation model allows the user to accurately analyze traffic/transit interactions such as curbside bus stops or complex traffic operations such as weaving sections and merges (*6*).

The program can analyze traffic and transit operations considering factors such as lane configuration, traffic composition, traffic signals, transit stops, weaving operations, variable message signs, and other traffic and control phenomena. For presenting simulation results, VISSIM generates numerous user-customizable output files. Information contained in these files can include detailed travel time and delay statistics, queue length statistics, detailed signal timing information, graphical output of space diagrams and speed profiles, and environmental indicators.

VISSIM contains an external signal state generator (known as VAP) that allows for the analysis of user-defined signal control logic. In the managed lanes cases being evaluated, VAP will be used to control access to the managed lanes based on managed lane performance (speed and/or occupancy within the managed facility), occupancy of the vehicle desiring entrance to the managed lane, and/or the willingness of a driver/vehicle to pay for high-occupancy toll (HOT) access to the managed lane.

CHAPTER 2. VISSIM MODEL CODING

Coding data for input into the VISSIM model is accomplished within the graphical user interface of the program. To facilitate drawing the links that form the roadway segments, it is possible to display a bitmap (.bmp) in the background of the workspace. Either roadway design files (converted to bitmaps) or aerial photography can be used, and result in a scaled model being constructed within VISSIM.

As with most traffic models, the primary input data for VISSIM is composed of roadway geometric information (lengths of roadway, number of lanes, lane use, turn bays, etc.), traffic volume data (peak-hour volume, intersection turning movement counts, traffic composition, vehicle occupancy, etc.), and traffic control information (signal presence and timing, signing, rules of the road, etc.). The following sections describe the source for data included in the managed lanes modeling and the process used to convert the managed lane and freeway design details and other information into VISSIM input files.

ROADWAY SEGMENTS

Within the VISSIM environment, it is incumbent upon the user to gain an understanding of the model and modeling process before attempting to code input data. As indicated in the VISSIM User's Manual (*7*), several guiding principles should be considered throughout model development, and the overall model scope and organization should be planned before implementation occurs. One key principle to ease of use on the PC, especially for larger models, is conservancy of modeled geometry. In other words, the model will perform better with fewer links and connecting structures.

Unlike more common (and earlier generation) models used in the U.S., the VISSIM model does not rely on a link-node structure, where links represent roadways and nodes represent junctions. Rather, links are used to represent roadways and are continuous (even through intersections), as long as the fundamental geometry (i.e., primarily, the number of lanes) remains constant. Where junctions and intersections occur, connectors are used to provide turning and/or merging/diverging vehicles with a path off of one link and onto another.

Freeway

Freeway sections within VISSIM are modeled as continuous links to the extent possible. The addition or subtraction of a lane due to lane drops/additions and exit/entrance ramps are cases where link breaks are necessary. If exit or entrance ramps merge/diverge from the freeway and no lane drop or lane addition is necessary, no link break is necessary for the mainlanes. For each freeway link, detail must be entered as to the basic properties of the link, including the number of lanes, the fact that it is a freeway (rather than an arterial) link, lane width, gradient, and other factors. Link identification is automatically incremented, and the length of the link is computed from the background scale within the user interface. As a rough rule of thumb, it is desirable to contain as many lanes as possible within the directional roadway section, as lane changing is only allowed within links that have multiple lanes. In other words, any lanes across which lane changing is allowed in the field or design plans must be contained within the cross section of one link. To more realistically represent roadway curvature, use intermediate points within a link to add curvature, and include geometric splines to longitudinally smooth the link.

Connectors are used to join together separate links that will ultimately constitute the travel lanes for one direction of flow along a given facility. When placing connectors, the manner of connection (i.e., lane continuity and connectivity) to adjacent upstream and downstream links is specified. Connectors are also used to allow for the junction of ramps with a freeway link. Again, the lane connectivity is specified. In the case of exit ramps, either turning percentages or routing decisions can be used to deliver the appropriate level of traffic to the ramp. For entrance ramps, the type of entrance ramp dictates how the merge with the freeway is coded. For forced merges, which do not have a supplemental or acceleration lane, yield rules are specified that make the ramp "yield" to the freeway in cases of vehicular conflict. For entrance ramps with a lane addition and/or a significant acceleration lane, the ramp is simply connected to the appropriate lane of the freeway.

Freeway lane drops and lane additions use connectors in a different manner than exit and entrance ramps. In the case of a lane drop, a connector is used to link the ending lane to its merge lane, and yield rules are specified. In the case of a lane addition, a connector simply links the diverging lane to the added lane; lane changing and driver behavior result in the utilization of the new lane.

To realistically model lane restrictions, such as for HOV lanes, lane closures can be erected on each individual link that prohibits certain classes of vehicles (i.e., non-HOVs for an HOV lane) from occupying the special use lane. To more realistically view underpasses and overpasses within the model viewer, it is possible to deactivate the animation for any link within the 2-D model space. For instance, at a freeway underpass the freeway link animation can be turned off for the link that passes under the crossing roadway's bridge. When viewing the simulation from above (i.e., in plan view) or in VISSIM's 3-D viewing mode, the freeway vehicles disappear at the crossing roadway, creating the illusion that they have passed under the bridge.

Frontage

Similar to link construction on the freeway, frontage roads are coded with as few links as possible. Links are only discontinued when it is necessary to add or drop lanes of extensive length from the frontage road itself. Right- and left-turn lanes or bays, where present in the design or field, are added using connectors off of the primary frontage road link. In most cases, it is possible to create the frontage road intersection with a crossing roadway without needing to break the frontage road link. Access to U-turn lanes is also made possible using connectors; in some cases the connector links directly to the frontage road, and in other cases the U-turn connector links to a separate link constructed to serve left-turning traffic.

Merge and diverge points for freeway ramps are accomplished using connectors that link to the roadway link constituting the ramp. Again, the frontage road link is kept continuous except where it is necessary to add or drop lanes from the frontage road to accommodate ramp merging or diverging.

Arterial

Crossing arterials should be coded as often as possible with single links. To fully account for queuing that occurs at the signalized interchanges along arterial approaches, arterials should be extended up to 1000 feet from signalized intersections (depending on queue length). As with the frontage roads, right- and left-turn bays and/or lanes are added to the primary link in each direction using connectors and separate turning links (if necessary).

Figure 1 depicts the geometric features of links and connectors, and how each is structured to create the necessary modeling environment. Note that within the figure, links without color are standard links, gray links are standard links that are declared "invisible" (i.e., not animated), and hatched links are connectors. In the figure, the crossing arterial passes under the freeway mainlanes.

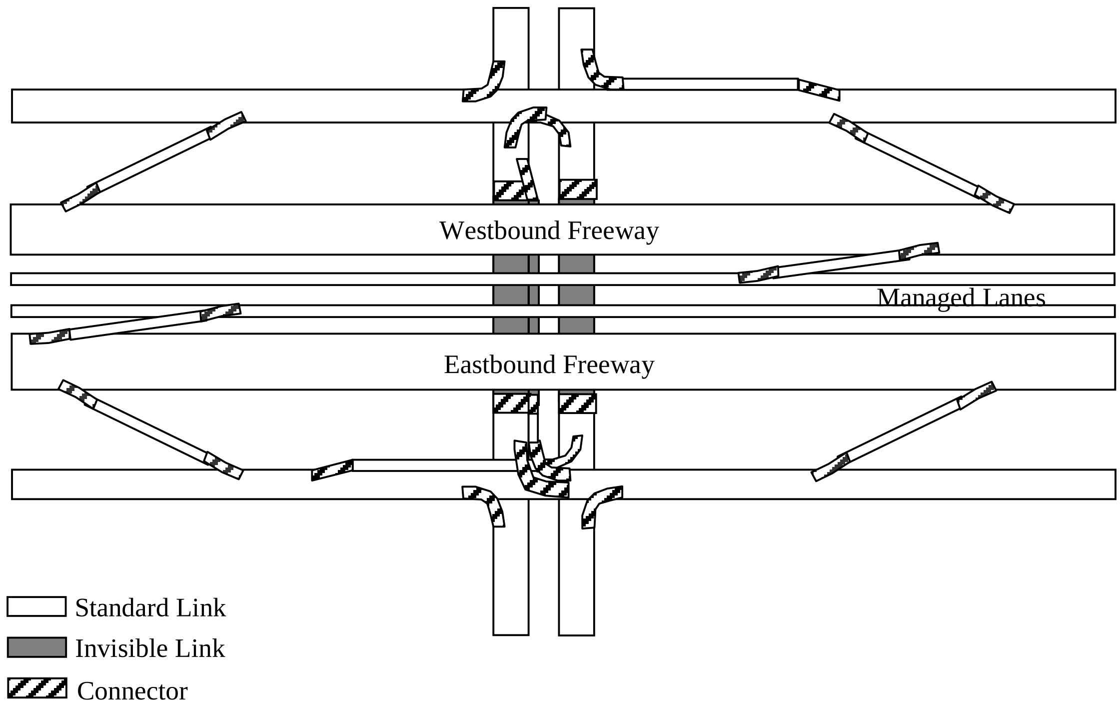

Figure 1. Geometric Elements of VISSIM Modeling.

TRAFFIC VOLUME

Traffic streams within VISSIM are coded using a hierarchical system that allows for a great deal of flexibility in defining individual vehicle and aggregate traffic flow characteristics. At the basic level, the VISSIM vehicle type input defines the acceleration, deceleration, occupancy, color, and other parameters for vehicles that will compose the traffic stream. A 2-D and 3-D template can be used to attach graphic quality to the vehicle, such as making a mid-size car look like a Ford Taurus. When all desired vehicle types are specified, vehicles with similar speeds and route choice behavior are collected into unique vehicle classes. Finally, traffic compositions are created to indicate the percentage of each vehicle type that is present in different traffic streams. For instance, a traffic composition for a freeway might have a greater percentage of heavy vehicles than an adjacent frontage road. Traffic volumes actually enter the model when a traffic volume is specified for network entry links. When specifying such an input volume, the composition is specified, along with the flow rate in vehicles per hour and the duration of the input.

Vehicle Mix

The ability to create vehicle types is an important feature of the VISSIM model, and a critical feature to managed lanes modeling. Realistic distributions of vehicle types allow more accurate representation of real-world vehicle operating characteristics within the traffic stream. Also, the ability to specify a variety of parameters for vehicle types allows some vehicles to be coded with multiple occupants, and other vehicles without. For use in the managed lanes modeling, passenger cars, pickups, and vans can be aggregated and organized into vehicle and occupancy categories SOV (single occupant vehicle), HOV 2 (high occupancy vehicle with two occupants), and HOV 3 (high occupancy vehicle with at least three occupants). Other vehicle categories may include bus (Bus), single unit truck (SU), and multi-unit, or semi, truck (MU).

Occupancy Specification and Distribution

The vehicle type input in VISSIM allows the user to specify vehicle occupancy – an essential element for determining whether or not vehicles will be eligible to enter the managed lane and/or HOV lane facilities along the Katy Freeway. For any given type of vehicle, separate types can be defined with occupancy as the only distinguishing characteristic. When traffic compositions are developed, a percentage of each type is specified, according to the expected occupancy distribution for that vehicle type.

Traffic Routing

Two general methods exist for determining where simulated vehicles travel within a modeled network: junction-specific allocation, such as turning movement specification; and origin-destination allocation, with static or dynamic routing (enabled with an add-on module to VISSIM). VISSIM is capable of both types of traffic routing through networks. At junctions, or intersections, specified percentages of vehicles on an approach can be "told" to turn left, go straight, turn right, etc. In addition, VISSIM can model vehicle allocation along pre-specified static routes or along dynamically defined routes, where vehicles can decide (if desired) between competing routes based on user-specified cost criteria.

For the managed lanes modeling, static routes can distribute vehicles in correct proportion along the frontage roads, arterials, and freeway. Access to the managed lane is made possible using a special static route (where options exist only to access the managed lane or stay on the freeway), to which access is permitted only if the managed lane is not congested and the vehicle meets selected entry criteria. Specialized or enhanced managed lane access control algorithms can be developed using VISSIM's VAP programming language.

TRAFFIC CONTROL

Traffic control within VISSIM occurs as a result of placing signals, signs, and/or markings along the links of the network. Signal, stop sign, and yield sign effects can be directly entered into the model, along with speed control signs.

Signals

Traffic signals are represented in VISSIM through signal heads that are placed in each lane of affected traffic. Signal control junctions (SCJs) are programmable representations of traffic signal controllers in the model. For each SCJ, signal control groups, or phases, are specified and organized with respect to one another to represent a signal-timing plan. Finally, signal heads are placed (usually with one head per lane) to control traffic according to background plan of the SCJ and signal groups. Signal phase time (or the amount of green, yellow, and red time) is specified for each group and can be easily edited using an interface window. Cycle length for each SCJ is specified to establish the background time duration of the overall signal pattern. Offset, or temporal relationship, between each SCJ and a master time clock or other SCJs is entered to allow for signal coordination. Complicated signal behavior can be programmed, including overlaps, which are possible by having a primary and secondary signal group driver for each signal head.

Signs

The impacts of regulatory signing are replicated in VISSIM by placing signs, or the "impact" of signs, at appropriate locations. Speed sign impacts can be implemented by using either localized speed restrictions (such as at sharp curves) or by imposing speed restrictions on all vehicles passing a point. Imposed restrictions can be selectively implemented by vehicle class, if desired, and are not removed until another speed restriction location is reached. Imposed speed restrictions and speed limitations on vehicles entering the network were used to reproduce appropriate speeds on the frontage roads and arterials within the model.

Stop signs and yield signs are modeled by specifying appropriate priority rule impacts at a specific location. The stopping or yielding point is defined, along with a gap sensor point and gap time specification for the traffic stream that the yielding/stopping vehicle is trying to enter. Almost any yielding and stopping behavior can be modeled. Discussion of common behaviors, such as right turn on red, is included in the VISSIM user manual (*7*).

Yield Points

Yielding behavior is not only used for stop and yield signing, but is also used to regulate a variety of other traffic phenomena. For instance, yield rules at lane drops define where the merging vehicles yield and what type of gap in the freeway traffic stream they desire for their merging maneuver.

MANAGED LANE MODELING

The introduction of managed lanes into the microscopic simulation process necessitates an investigation of the modeling process to ensure that the behavior and impacts of managed lane operation can be theoretically and practically accommodated within the modeling application. In the current case of using the VISSIM simulation model, the major roadway elements necessary to access, progress along, and depart from the managed lanes are contained within the model's standard geometric development tools. And, as occupancy can be specified for each vehicle type that is introduced into the model, it is possible to create a realistic distribution of vehicle occupancy across the modeled traffic stream.

Not explicitly available within the signing and signaling functions of the VISSIM model is the ability to selectively control access to the modeled managed lane facility, allowing only vehicles of multiple occupancy to access the managed lanes, and then only if the managed lanes are not congested. In addition, the level of occupancy required to access the managed lanes must be flexible enough to change throughout the day, allowing only very high occupancy vehicles (i.e., say, 3+) and vehicles of lower occupancy who are willing to pay a toll to enter the facility during periods of high managed lane traffic density. The pricing structure must be variable as well, so that toll rates can be raised to discourage managed lane use when congestion begins to appear.

Fortunately, an add-on module known as VAP can be included with VISSIM. VAP can be used to custom develop traffic controls, and code for managed lane access control was developed by project staff.

To ensure meaningful and appropriate results were generated for the current study, the VISSIM model was verified and calibrated for the managed lanes modeling cases being analyzed. As the study cases were freeway in nature, a target free flow saturation rate of 2400 passenger cars per hour per lane (pc/h/ln) was established based on the Highway Capacity Manual, or HCM (*8*). With limited experimentation, VISSIM was capable of producing a free flow saturation rate of 2280 pc/h/ln. As these results were within 5 percent of the maximum ideal value, they were judged acceptable and verified for study purposes. To calibrate the model, example problem 1 from the weaving chapter (i.e., Chapter 24) of the HCM (*8*) was used to develop calibration values, which were then used in a simulation of example problem 2. The VISSIM weaving and non-weaving speeds for this example problem were within 5 and 10 percent, respectively, of the HCM-reported results and, again, were judged acceptable for the research study purpose.

OTHER MODELING ACTIVITIES

Whereas VISSIM was selected to perform the analytical modeling of realistic managed lanes operation in this research study, it is unlikely that this tool will be used for all aspects of issue resolution during the planning and design of managed lanes. During planning and preliminary design, planners and engineers are more likely to use common analysis tools to design the basic access elements and other features of managed facilities. In particular, the HCM (*8*) and the Highway Capacity Software (HCS) (*9*) that is based on the HCM are widely used for such applications. To identify the managed lane access features and scenarios that are most appropriately analyzed using this tool (i.e., the HCS), the same analysis cases examined in

VISSIM will also be analyzed using the HCS (where appropriate). The "range of applicability" of the HCS to managed lane features and conditions will be established, and recommendations made for its use in basic managed lane analysis.

CHAPTER 3. MANAGED LANE MODELING SCENARIOS

The study corridor for managed lanes modeling is the Interstate 10 (Katy Freeway) corridor in Houston, Texas. Limits on the approximately 13-mile study section are the Barker Cypress interchange to the west and the Loop 610 interchange to the east. Two types of modeling were performed to provide insight into the operation of the freeway and managed lanes within the study corridor; a corridor model (including the freeway, managed lanes, and frontage roads) and a series of small models that address critical design and/or operations issues for managed lanes.

KATY FREEWAY CORRIDOR MODEL

Model Coverage and Input Data

Included within the corridor model are the freeway mainlanes, the managed lane facility (including a left-lane HOV lane and a barrier-separated lane), freeway entry and exit ramps, frontage roads, crossing roadways and highways, and the diamond interchanges or directional interchanges/ramps that access crossing and support facilities, including park-and-ride lots located in the corridor. Vehicle mix information as input into the Katy Freeway managed lanes model is based on eastbound and westbound vehicle classification counts performed by the Texas Transportation Institute on the Katy Freeway in December 1999. Details of the classification for the Freeway and current Katy HOV lanes are given in Table 1. In addition to the classifications shown in Table 1, additional vehicle classes were created for each automobile type (SOV, HOV 2, HOV 3) to account for the percentage of vehicles of each class whose occupants would be willing to pay tolls for access to the managed lanes (i.e., in a tolling or congestion/value pricing scenario).

Table 1. Vehicle Classification for Katy Freeway Managed Lanes Modeling.

Katy Freeway (current)		Katy HOV Lanes (current)	
Vehicle Type	**Percentage of Vehicle Mix**	**Vehicle Type**	**Percentage of Vehicle Mix**
SOV	88	SOV	
HOV 2	6	HOV 2	86
HOV 3+	0.5	HOV 3+	12
Bus	0.5	Bus	2
SU	2	SU	
MU	3	MU	

For the Interstate 10 managed lanes modeling, pretimed signals were used with optimized cycle length, phase duration, and offsets. Optimized settings were obtained from the PASSER III-98 interchange signal optimization program, with design volumes and geometry specified by TxDOT. Though VISSIM is capable of modeling actuated signal control, or interfacing with authentic or simulated external traffic signal controllers, pretimed control was selected for simplicity and to reduce the processor load of the simulation. In addition, current diamond interchange operation along the Katy Freeway is pretimed in nature.

Access Control Methodology for Managed Lanes

The Houston District of TxDOT specified the fundamental operations criteria for the managed lanes on the Katy Freeway when they indicated that managed lane speed should not fall below 50 mph. As it applies to managed lanes modeling, this criterion requires that vehicles, or even entire classes of vehicles, have only conditional access to the managed lanes facility. If managed lane operation is within the nominal operating criteria (i.e., speeds are above 50 mph), normal operations remain underway. In one possible peak-hour operations scenario for the Katy Freeway managed lanes, buses, HOV 3+, and HOV 2 vehicles are allowed to enter the lanes for free, and SOV vehicles can enter for a toll. Should managed lane speed fall below 50 mph, signing upstream of the managed lane access points would indicate that SOVs would no longer be allowed to access the managed facility (i.e., they would have to remain on the general-purpose lanes of the Katy Freeway).

Within the VISSIM model, VAP code was created to implement selective access restrictions to the managed facility. A pair of detectors was located within and upstream of the entry/exit weave for each of the three freeway access points into the managed facility. In a simple "if.. then" logic construction, the VAP code obtained the managed lane detector speed information and determined if speeds were less than 50 mph. If so, the VAP code assigned tolled SOV vehicles to take a pre-specified route that left them on the general-purpose lanes rather than allowing them to use a route that gave them access to the ramp (or access control point/merge area for a concurrent flow, non-barrier separated managed facility) onto the managed facility. Pricing impacts could also have been programmed into the VAP code (based on ratios of tolled SOVs willing to accept different toll levels), though such code was not developed as part of this project effort.

It should be noted that this flexible access control technique utilizing VAP cannot be used in VISSIM when there is uncontrolled access between the general-purpose lanes and a concurrent flow managed lane. Within the model, uncontrolled access to a managed lane would be implemented by simply not allowing non-candidate vehicle types to enter the managed lane. As VAP does not allow the run-time manipulation of lane restrictions, there exists no means of changing the lane to disallow certain vehicles when managed lanes operating criteria are not being met. As the Katy Freeway did not have uncontrolled access to the non-barrier separated managed lanes, this modeling restriction did not impact the current research.

Model Utility

VISSIM model construction for the 13-mile managed lane facility proposed for the Katy Freeway (along with the freeway and frontage roads) allowed researchers to gain a thorough understanding of how the managed lane facility integrated with the transportation network elements within the corridor. TxDOT may use the model during the planning and design of the managed lanes within the freeway alignment to examine alternative operating scenarios and/or alternative designs for managed lane features and access treatments. When the Katy Freeway model was complete, researchers focused their attention on developing "critical issue models" to examine fundamental features of managed lanes and their operation. These models constitute the research team's modeling efforts in managed lane development and research, and are based on the geometric features and flow conditions found in the proposed Katy Freeway corridor plan.

CRITICAL ISSUE MODELS

The development of modeling scenarios for the critical design and/or operations issues models are fundamentally linked to issues or features of managed facilities that may not be adequately covered by existing analytical procedures and techniques. A list of issues was identified with input from the Houston District of TxDOT, the TTI Advisory Panel for the project, and the task leaders of research activity within the managed lane study. The issues are listed below, and next to the issue name is whether or not that topic item is or is not covered adequately using current techniques (i.e., analytical traffic engineering tools, state and/or nationwide design standards):

- freeway weaving (freeway entrance to managed lane entrance) – not covered adequately;
- freeway weaving (managed lane exit to freeway exit) – not covered adequately;
- vehicle stream separation for managed lane access – not covered adequately;
- weaving within managed lanes (entrance/exit auxiliary lane) – covered adequately;
- entrance merge (i.e., from a park-and-ride lot ramp) – covered adequately; and
- exit diverge (i.e., to a park-and-ride lot ramp) – covered adequately.

To model each of the critical issues not covered by current analytical techniques, the Katy Freeway was used as a realistic base scenario from which experimental modeling activities were conducted. The objective of this experimental approach was to identify boundary conditions and ranges of operation for a variety of design and operational parameters that affect managed lanes. Ultimately, the constraints and conditions identified through this effort were incorporated into the design and operations recommendations of the research effort.

In particular, researchers examined "rules of thumb" from HOV design and guidelines manuals in the current research examination of freeway weaving and vehicle stream separation. The generic guidelines from three HOV design guides are included below:

- weaving distance minimum of 500 ft per freeway lane (*10*);
- weaving distance per lane 500 ft minimum, 1000 ft desired (*11*); and
- 2500 ft or more is suggested between an entrance or exit ramp and a slip ramp (*12*).

In addition to modeling the above critical items using VISSIM, the HCS was also used where the analytical case met the criteria (length, volumes, etc.) for applying HCS procedures. Where appropriate, results from the HCS were compared with results from VISSIM for the same scenarios, and "ranges of applicability" of the HCS for each issue were identified. However, researchers anticipated that the HCS would only be applicable for a limited number of analyses (or portions thereof) as the cross-freeway weaving being examined in the current research was beyond the scope of the weaving and ramp analysis modules in the HCM and HCS.

Scenario Development

Table 2 contains modeling scenario information for the two weaving analysis design/operation issues. For each of the modeling scenarios created, measures of effectiveness (MOEs) were generated and compared for VISSIM and the HCS. Results from this set of scenarios were used to identify minimum and desirable weaving distances between freeway and managed lane access points. Indirectly, this information could also be used to develop minimum and desirable spacing between managed lane access and major interchanges, and to identify desirable separation distances between managed lane access points (though longer spacing will often be employed to provide more positive control over managed lane access).

The range of scenarios represented in Table 2 constitutes only the initial set of scenarios that were evaluated over the course of the project. It is anticipated that the model will be used to experiment with other managed lane design, control, and operation parameters as the managed lane research project progresses. These future scenarios may include enforcement design, sign location, and other topics of concern.

Table 2. Critical Weaving Issue Modeling Scenarios for Managed Lane Modeling.

<table>
<tr><th>Issue</th><th>Case</th><th colspan="2">Variables*</th></tr>
<tr><td rowspan="2">Freeway Entrance Ramp to Managed Lane Access Point</td><td>I. (w/o intermediate exit ramp)</td><td rowspan="2">Cross-Freeway <u>Weaving Distances</u>
1500’ 3500’
2000’ 4000’
2500’ 4500’
3000’ 5000’</td><td rowspan="2">Percent of First Ramp Traffic Weaving <u>Across Freeway</u>
10
30
50
70</td></tr>
<tr><td>II. (w/ intermediate exit ramp)</td></tr>
<tr><td rowspan="2">Managed Lane Exit Point to Freeway Exit Ramp</td><td>III. (w/o intermediate entrance ramp)</td><td rowspan="2"><u>Volume Levels</u>
Medium (v/c ≈ .6)
High (v/c ≈ .9)</td><td rowspan="2">Truck Percent of First <u>Ramp Traffic Stream</u>
5
10</td></tr>
<tr><td>IV. (w/ intermediate entrance ramp)</td></tr>
</table>

* All combinations of each variable applied to each case, for a total of 512 analysis scenarios

Though some managed lane facilities can be found on the right-hand side of the corridor’s general-purpose lanes, it is much more common to find the managed lanes to the left of the general-purpose lanes. And, since freeway entrance and exit ramps are typically right-side access points, a cross-freeway merge is necessary for vehicles entering the freeway that wish to ultimately reach the managed lanes. The converse situation is also true for vehicles exiting the managed facility, which must then perform a cross-freeway merge to reach the desired freeway exit ramp.

As mentioned previously, typical "rules of thumb" for cross-freeway merging allow a minimum of 500 ft, and a desired 1000 ft, per lane along the freeway to perform such maneuvers. On larger freeway facilities with five lanes or more, the distance for this maneuver stretches from 2500 ft at the minimum to 5000 ft desirable. With typical interchange spacing of 1 mile, this means that there exists a very high probability that at least one freeway entrance or exit ramp will be located between a freeway entrance ramp and the downstream managed access point (or between a managed lane egress point and the next downstream freeway exit ramp). Thus, it was necessary to not only analyze the freeway entrance to managed lane entrance cross-freeway weave (see Figure 2), but to also analyze the cross-freeway merge in conjunction with an intermediate freeway entrance or exit ramp (see Figure 3). Similarly, an analysis was made of the managed lane exit weave to the next downstream freeway exit ramp, both without (see Figure 4) and with (see Figure 5) an intermediate freeway entrance or exit ramp. Because of the similarities between these analysis scenarios (i.e., the managed lanes exit weave simply being the converse of a managed lanes entrance weave), it was anticipated that the results of the four developed case studies would serve to verify and reinforce one another. Weaving distance lengths for the four case studies were based on the bounds of the "rules of thumb" for cross-freeway weaving, and input volumes were derived from experimentation with the VISSIM model and observation of speed and volume under different loading conditions.

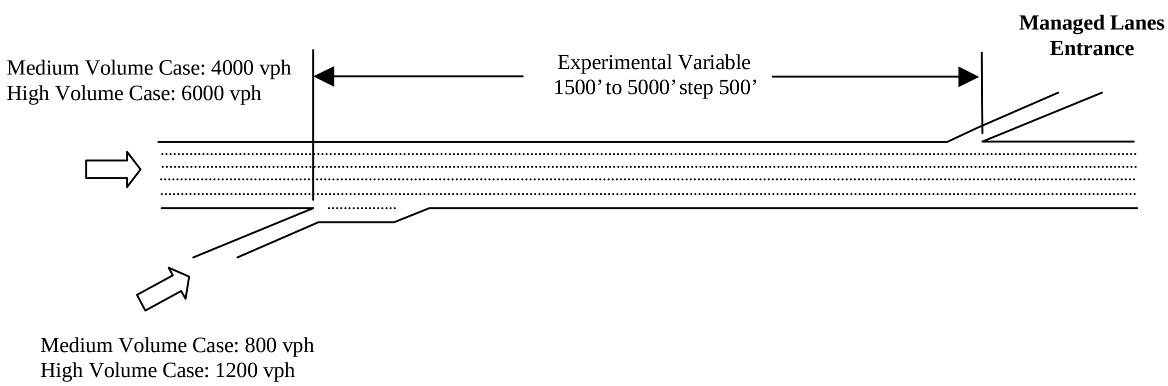

Figure 2. Case I – Freeway Entrance to Managed Lanes Entrance.

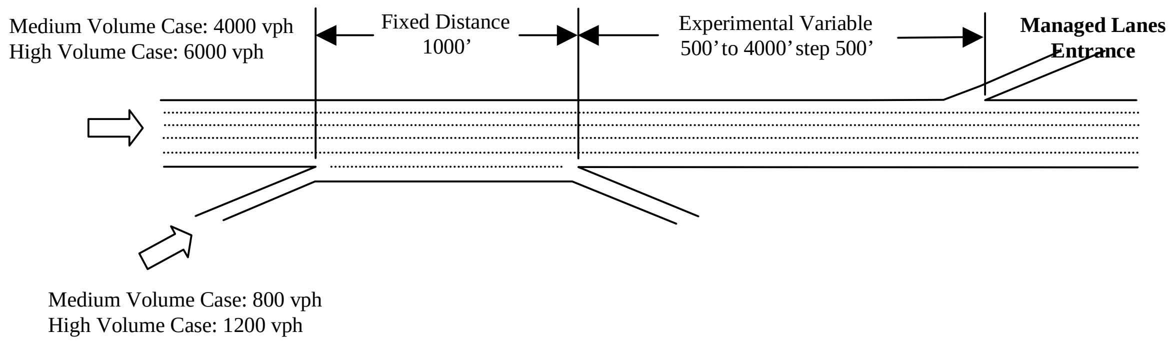

Figure 3. Case II – Freeway Entrance to Managed Lanes Entrance w/ Intermediate Weave.

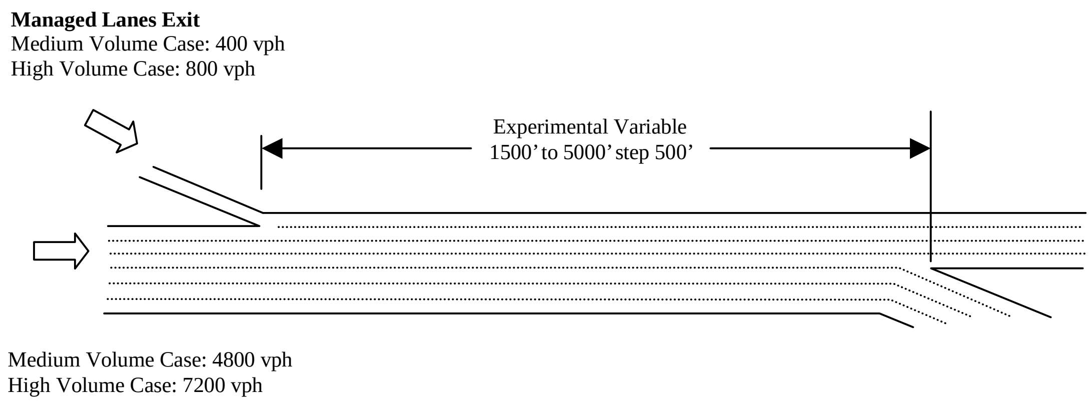

Figure 4. Case III – Managed Lanes Exit to Freeway Exit.

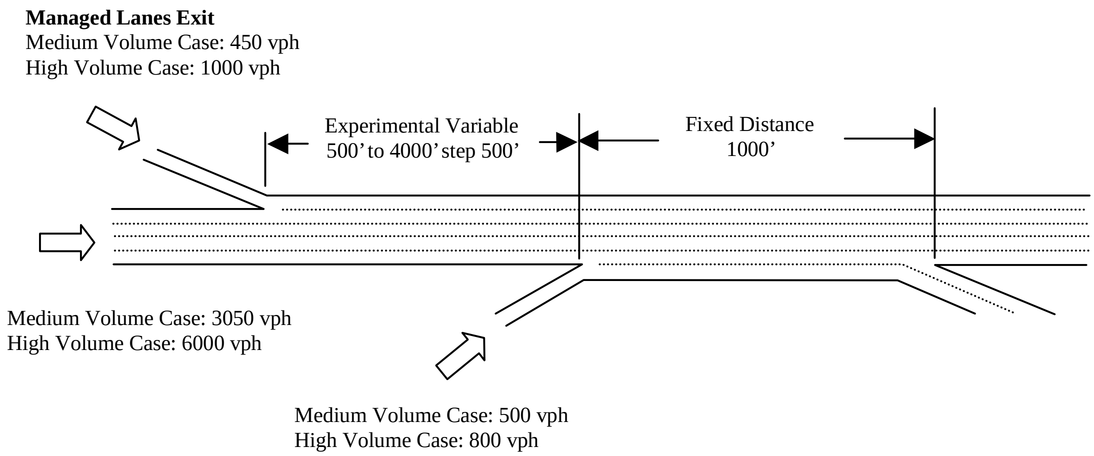

Figure 5. Case IV – Managed Lanes Exit to Freeway Exit w/ Intermediate Weave.

In addition to cross-freeway weaving for accessing and exiting managed lanes, the selective separation of freeway mainlane vehicles into the appropriate lane for accessing managed lanes is also a critical issue that is not adequately addressed by current design and operations analysis standards and procedures. Table 3 highlights the various modeling scenarios that will be used to analyze traffic stream separation for managed lane access. Generic geometric details of the intra-freeway weaving scenarios can be found in Figure 6. Note that within the figure the beginning point of selective separation is demarcated as the sign location (i.e., indicating the downstream presence of an entrance to the managed lanes facility). This point can conceptually be interpreted as the point where drivers of any vehicle class (i.e., bus, HOV, SOV paying toll, truck, etc.) are able to determine that they are eligible candidates for entry into the managed lane/lanes and begin to maneuver to the left freeway lane so that they can access the managed lanes.

Table 3. Traffic Stream Separation Issue Modeling for Managed Lanes.

Issue	Variables*	
Traffic Stream Separation for Access to Managed Lanes	Percent Trucks in Managed Lane Traffic Stream 0 5 10 15	Percent Buses in Managed Lane Traffic Stream 5 10 15
	Volume Levels Medium (v/c ≈ .6) High (v/c ≈ .9)	Distance to Managed Access 2640’ 10560’ 5280’ 13200’ 7920’ 15840’

* All combinations of each variable applied to each case, for a total of 144 analysis scenarios

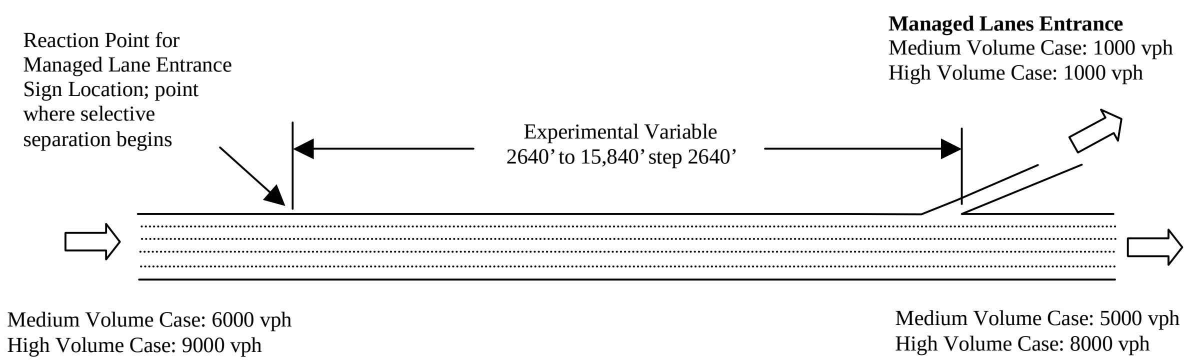

Figure 6. Selective Separation of Vehicles for Accessing Managed Lane Facilities.

HCS Applicability to Cross-Freeway Weaving Analysis

Both VISSIM and the HCS were used to analyze the cross-freeway weaving that occurs from vehicles accessing a freeway via an entrance ramp and then maneuvering across the mainlanes to reach a downstream managed lanes exit. Limitations quickly emerged, however, in the application of the HCS to this problem. First, the weaving module within the freeway section of the HCS can only be used to analyze weaving sections of up to 2500 feet in length. For weaving lengths greater than 2500 feet, the HCS requires that the section be divided into two, separate (ramp) analytical sections. Fundamentally, the HCS assumes that weaving impacts are minimal where weaving maneuvers occur over distances greater than 2500 feet – an assumption/ hypothesis that this modeling effort is designed to test. Also, as found in the weaving discussion in the HCM (*8*), weaving procedures are designed to analyze weaving that occurs between entrance and exit ramps located on the same side of the freeway facility. They are not directly applicable to the cross-freeway weaving found in this project's managed lane scenarios.

The ramp analysis module of the HCS was also applied to the entrance-to-managed-access weave problem. In this case, the required separation of the weaving section into two separate sections – an entrance ramp merge and an exit ramp diverge – raised concerns about the continuity of the analysis. Furthermore, results indicated – and a review of the HCM (*8*) Chapter 25 equations confirm – that the ramp procedures produce the same results for any number of freeway mainlanes greater than three. The procedure also produced the same results for varying weaving distances, as it is primarily concerned with the availability of gaps in the lane into which the ramp is merging and the next adjacent lane. It is noted that this simply indicates that the HCS and HCM are not applicable to the multi-lane cross-freeway weaving being analyzed; it does not indicate any limitation on the HCS and HCM for their intended scope of use. Due to these limitations, however, the decision was made to focus solely on VISSIM as the analytical tool for cross-freeway and intra-freeway weaving analysis of managed lanes for this research.

Freeway Entrance to Managed Access Weaving Results

Preliminary analytical results from VISSIM for the two cases (i.e., Case I and Case II) involving a weave from a freeway entrance ramp to a managed lane access point on the other side of the freeway indicated that congestion was occurring in unanticipated locations. A careful review of VISSIM input parameters revealed that the cause of the congestion was a quantity known as the "lane change" distance, which is specified for each connector. As connectors were used to join both mainlane and ramp segments together, it was possible for connectors linking two mainlane freeway segments together to have the same lane change distance specified as the connector from the mainlanes to an adjacent exit ramp.

The net result of the overlap in lane change distance specification was intense lane changing and congestion on the freeway mainlanes a distance upstream equal to the entered lane change distance. A simple solution to this problem was to specify different lane change distances for the mainlane to mainlane connector and the adjacent mainlane to ramp connector. Follow-up on this issue with the software distributor (*7*) revealed that the next release (i.e., VISSIM version 3.6; 3.5 is being used for the current investigation) of the VISSIM program would include a distribution of lane changing distances rather than a single, pre-specified value.

When preliminary analysis and testing were complete, researchers began the process of systematically performing VISSIM runs and processing the results. As VISSIM is stochastic in nature, multiple runs were performed for all subsets of each of the four cases. Tabular results from all model runs for freeway entrance to managed lane entrance weaving (i.e., Cases I and II) can be found in Appendix A. Results from analysis Case I, a simple cross-freeway weave, are described in four figures: medium volumes with 5 percent heavy vehicles, medium volumes with 10 percent heavy vehicles, high volumes with 5 percent heavy vehicles, and high volumes with 10 percent heavy vehicles. Case II, a complex cross-freeway weave, is also described with four figures (with the same volume and percent trucks combinations).

Figure 7 details results for the combination of medium freeway volume (a nominal volume to capacity - v/c - ratio through the section of 0.6) and 5 percent trucks. Figure 8 details results for the combination of medium freeway volume (a nominal v/c ratio through the section of 0.6) and 10 percent trucks. Figure 9 details results for the combination of high freeway volume (a nominal v/c ratio through the section of 0.9) and 5 percent trucks. Figure 10 details results for the combination of high freeway volume (a nominal v/c ratio through the section of 0.9) and 10 percent trucks. Discussion follows the presentation of the four figures.

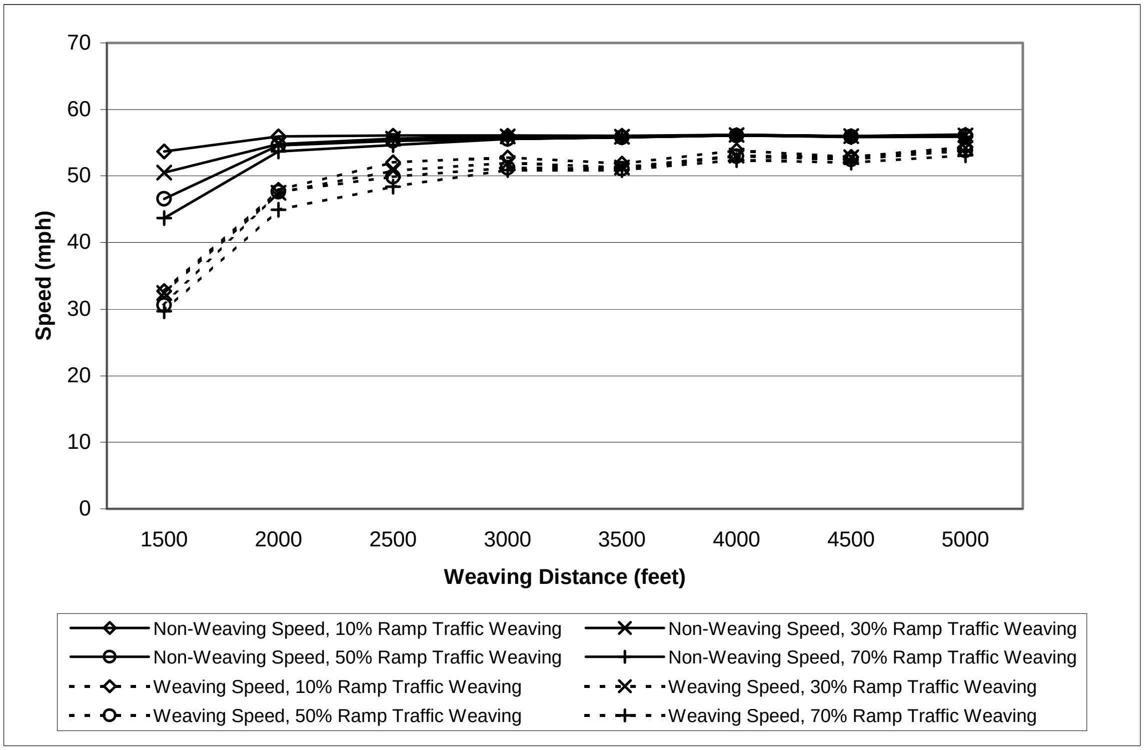

Figure 7. Case I Entrance Weave Results – Medium Volume and 5% Trucks.

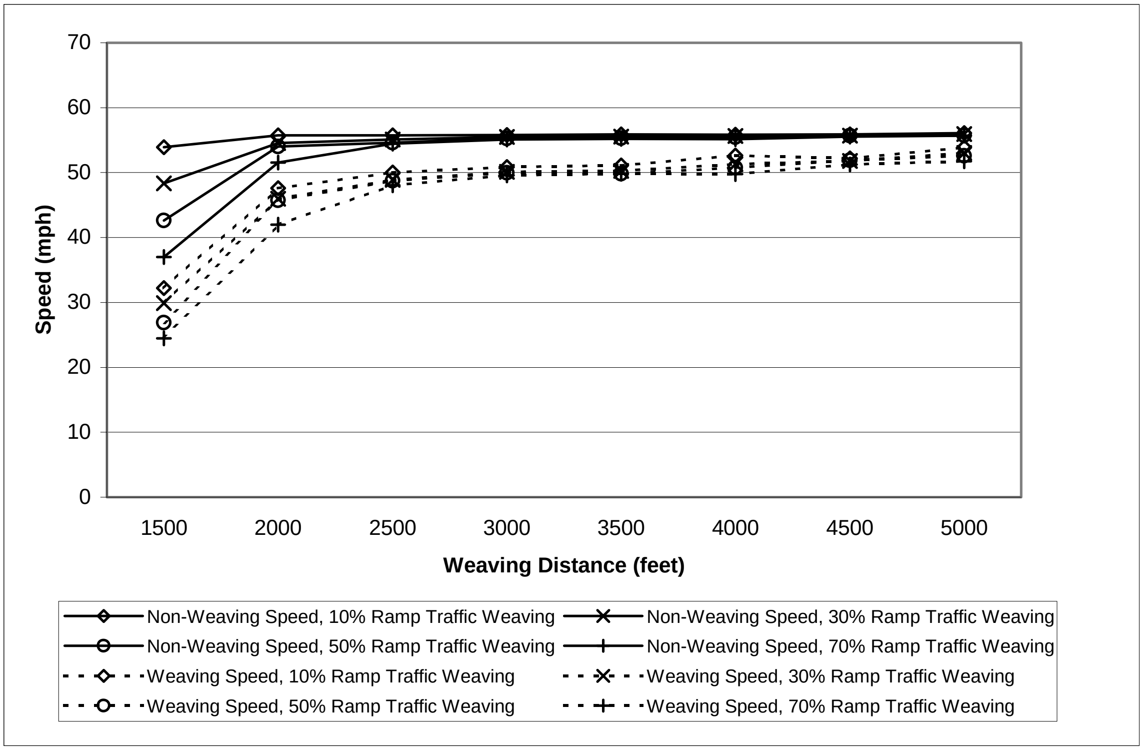

Figure 8. Case I Entrance Weave Results – Medium Volume and 10% Trucks.

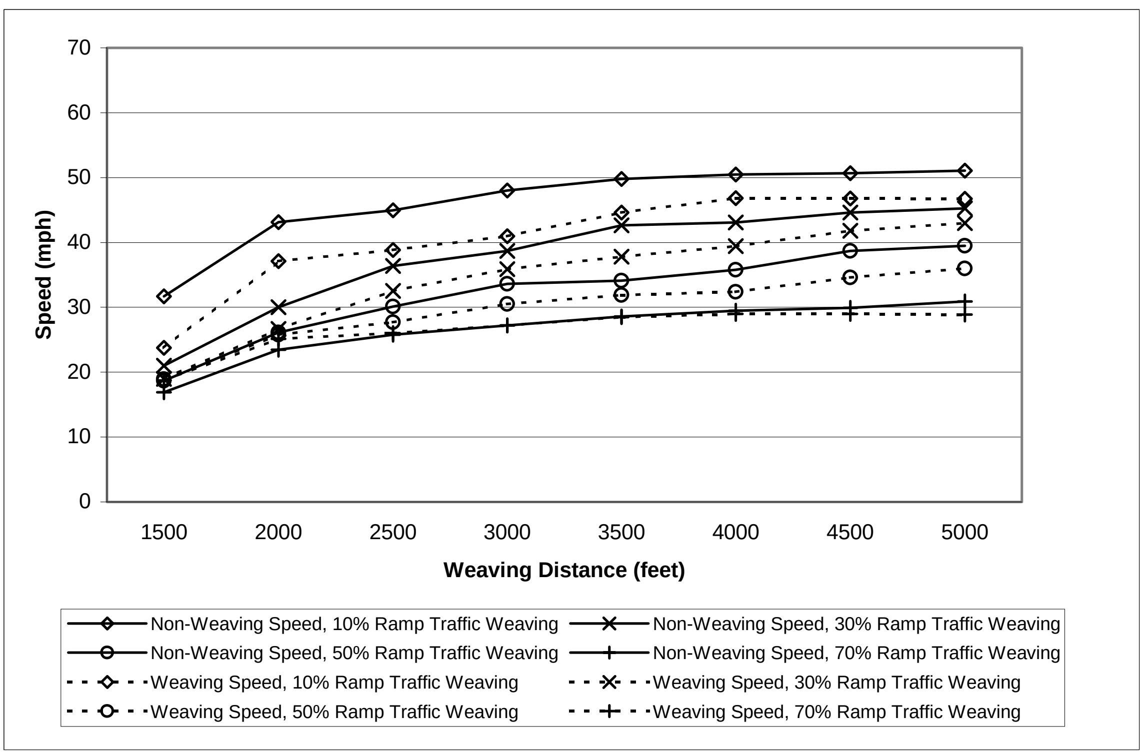

Figure 9. Case I Entrance Weave Results – High Volume and 5% Trucks.

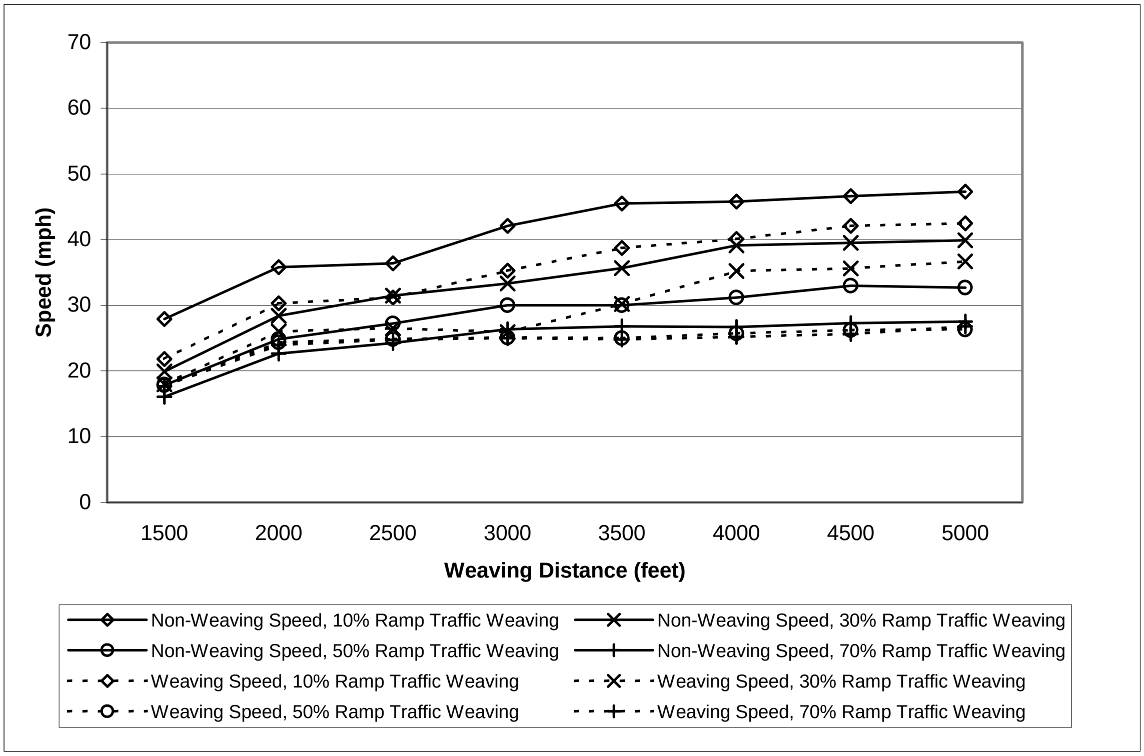

Figure 10. Case I Entrance Weave Results – High Volume and 10% Trucks.

Review of Figure 7 and Figure 8 reveals the impact of increased heavy vehicle percentage on weaving and non-weaving vehicle performance. These heavy vehicle impacts are more pronounced at shorter weaving distances, as indicated by the greater variability and approximately 8 percent speed reduction for the 1500 foot weaving distance. Figure 7 and Figure 8 also indicate that weaving and non-weaving speeds stabilize for weaving distances of 3000 feet and greater.

Comparisons of Figure 9 and Figure 10 to Figure 7 and Figure 8, respectively, indicate the impacts of higher volumes and weaving-related congestion on weaving section performance. The variability in speed between weaving and non-weaving vehicles is consistently greater for the high-volume cases. Also, the results for different percentages (i.e., 10, 30, 50, and 70 percent) of entrance ramp weaving traffic are both significantly lower in speed performance and cover a much broader range (i.e., exhibit much greater variability). For the high-volume results, speed performance stabilizes for weaving distances greater than 3500 to 4000 feet. Note that four lane-change maneuvers are necessary in Case I, and that the freeway entrance ramp is 500 feet long.

Case II, or complex entrance weave, results are found in Figure 11 through Figure 14. Figure 11 details results for the combination of medium freeway volume (a nominal v/c ratio through the section of 0.6) and 5 percent trucks. Figure 12 details results for the combination of medium freeway volume (a nominal v/c ratio through the section of 0.6) and 10 percent trucks. Figure 13 details results for the combination of high freeway volume (a nominal v/c ratio through the section of 0.9) and 5 percent trucks. Figure 14 details results for the combination of high freeway volume (a nominal v/c ratio through the section of 0.9) and 10 percent trucks. Discussion follows the four figures.

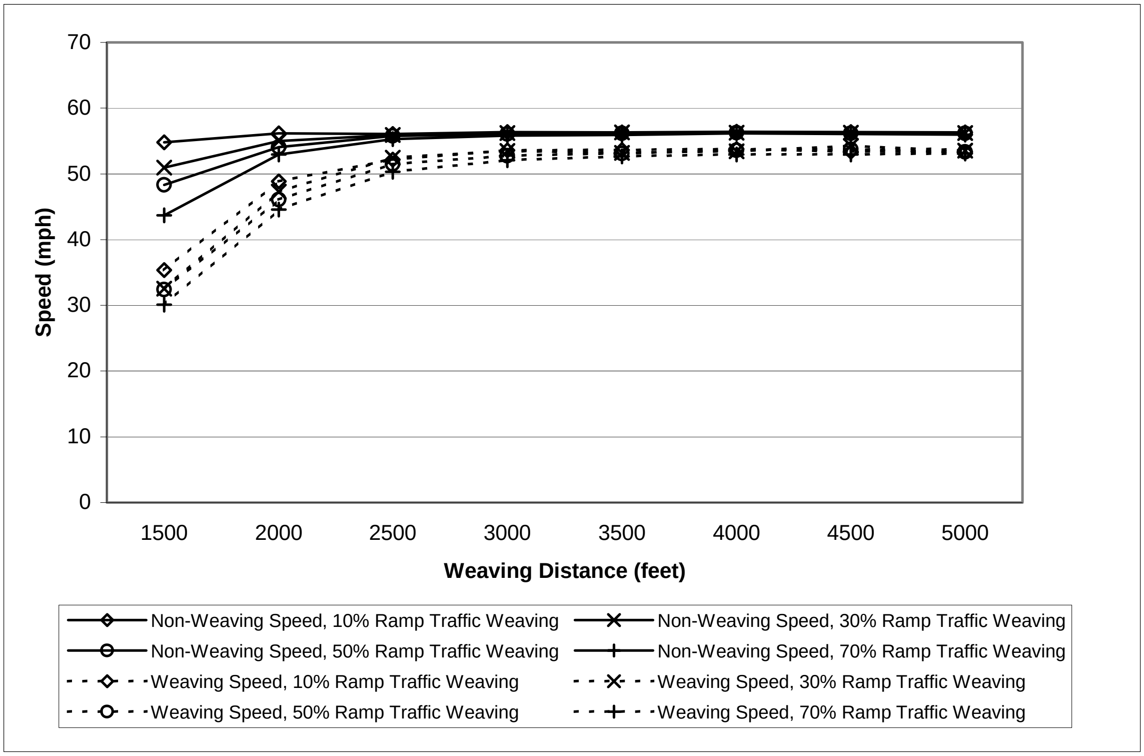

Figure 11. Case II Complex Entrance Weave Results – Medium Volume and 5% Trucks.

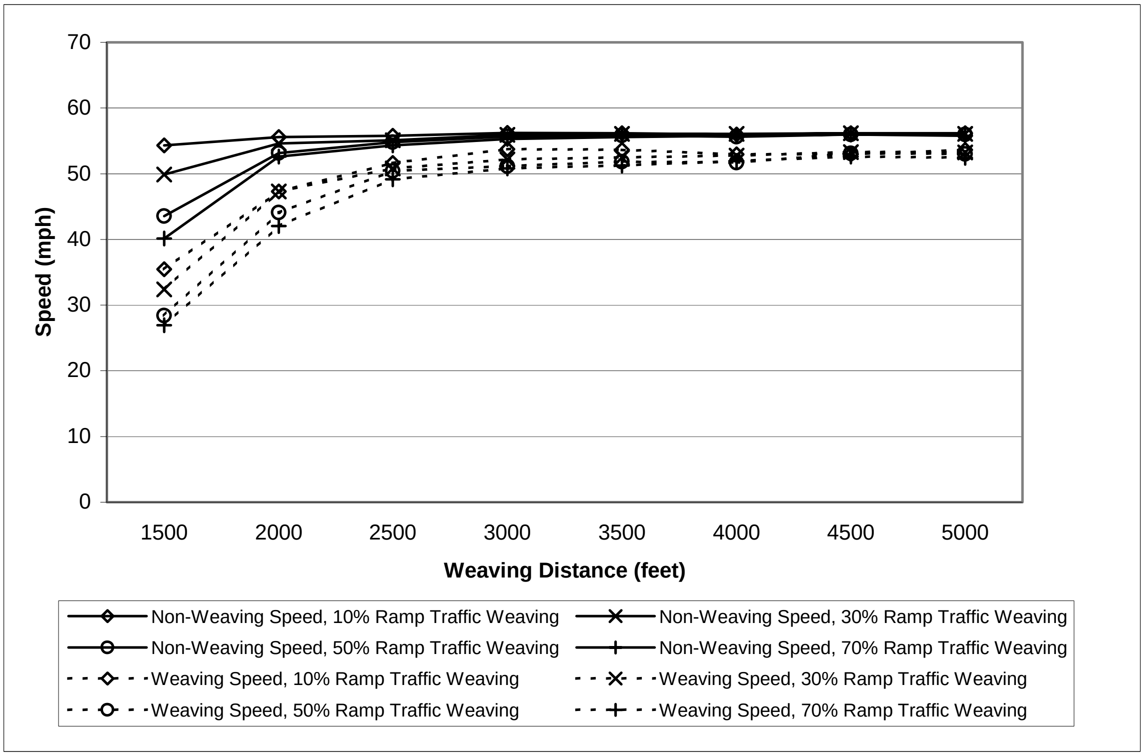

Figure 12. Case II Complex Entrance Weave Results – Medium Volume and 10% Trucks.

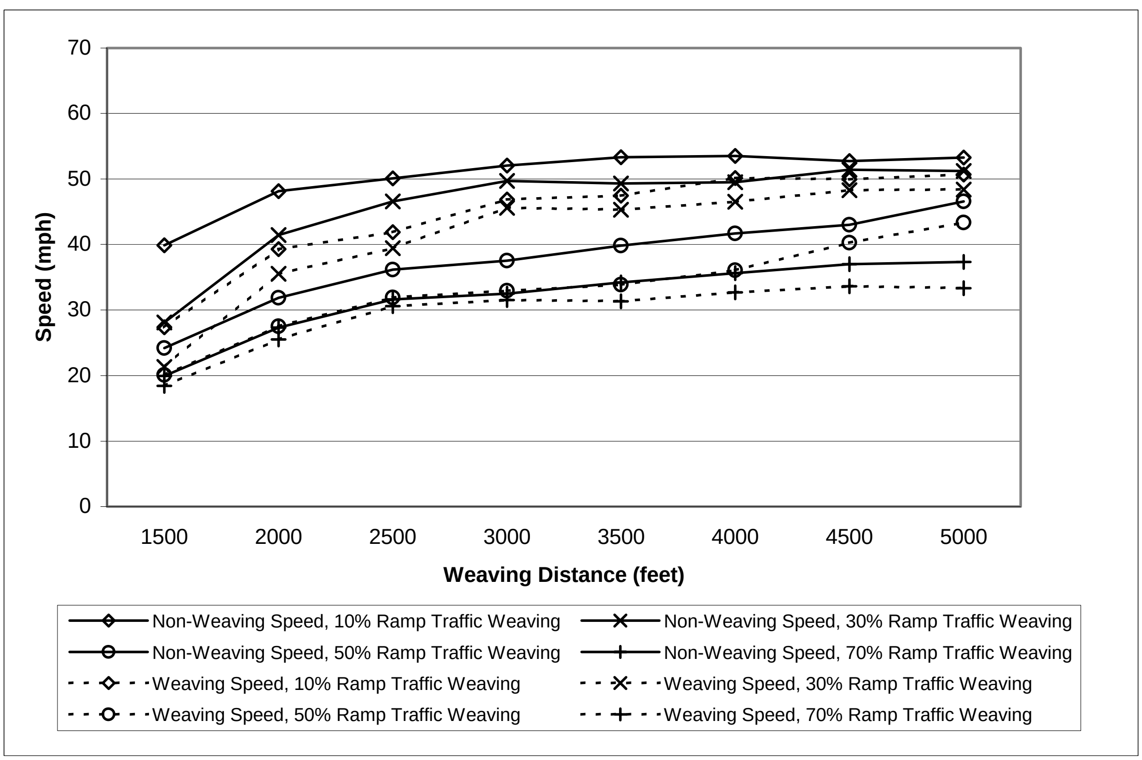

Figure 13. Case II Complex Entrance Weave Results – High Volume and 5% Trucks.

Figure 14. Case II Complex Entrance Weave Results – High Volume and 10% Trucks.

As with Figure 7 and Figure 8, Figure 11 and Figure 12 reveal the impact of increased heavy vehicle percentage on weaving and non-weaving vehicle performance. These heavy vehicle impacts are more pronounced at shorter weaving distances, as indicated by the greater variability and reduced speed for the 1500 foot weaving distance. For the more complex weave found in Case II, Figure 11 and Figure 12 indicate that weaving and non-weaving speeds stabilize for weaving distances between 3000 and 3500 feet and greater.

Mimicking the Case I results, comparison of Figure 13 and Figure 14 to Figure 11 and Figure 12, respectively, indicate the impacts of higher volumes and weaving-related congestion on weaving section performance. The variability in speed between weaving and non-weaving vehicles is consistently greater for the high-volume cases. Also, the results for different percentages (i.e., 10, 30, 50, and 70 percent) of entrance ramp weaving traffic are both significantly lower in speed performance and cover a much broader range (i.e., exhibit much greater variability). For the high-volume results, speed performance stabilizes for weaving distances greater than 3500 to 4000 feet. Note that Case II requires a vehicle to make five lane changes to accommodate the freeway entrance to managed lanes entrance maneuver.

Managed Lane Exit to Freeway Exit Weaving Results

Case III contains a managed lane exit weave to a downstream freeway exit ramp; this case is the exit ramp weave complement to the entrance weave found in Case I. Case IV is a more complex weaving situation than the one found in Case III, as it contains a freeway entrance ramp between the managed lanes exit ramp and the freeway exit ramp. Case IV is the exit weave complement to Case II. Unlike Case II, Case IV locates its complex weave at the downstream end of the weaving section. This was not the situation in Case II, where the complex weave was at the upstream end of the overall managed lanes cross-freeway weave. Because of the downstream location of the complex weave, and the congestion that is contained within the complex weave, Case IV results are much different in nature than Case II.

Tabular results for all Case III and Case IV simulations can be found in Appendix B. Case III results are contained in four figures, with each figure representing a different combination of medium or high volumes and 5 percent or 10 percent heavy vehicles (See Figure 15 through Figure 18). Case IV results are similarly contained in four figures (See Figure 19 through Figure 22). Discussion follows both the Case III and Case IV sets of figures.

Like the entrance ramp cross-freeway results, the exit ramp cross-freeway results found in Figures 15 and 16 indicate that under medium volume conditions, non-weaving and weaving freeway flow stabilize for relatively modest weaving distances. Operation stabilizes for the cross-freeway exit weave and 5 percent trucks at 2500 feet, and for 10 percent trucks at 3000 feet. Under high-volume conditions, such as those represented in Figure 17 and Figure 18, freeway operation stabilizes at weaving distances of 3500 feet and greater. Note that a minimum number of three lane changes must occur for the cross-freeway managed lanes exit to freeway exit weave.

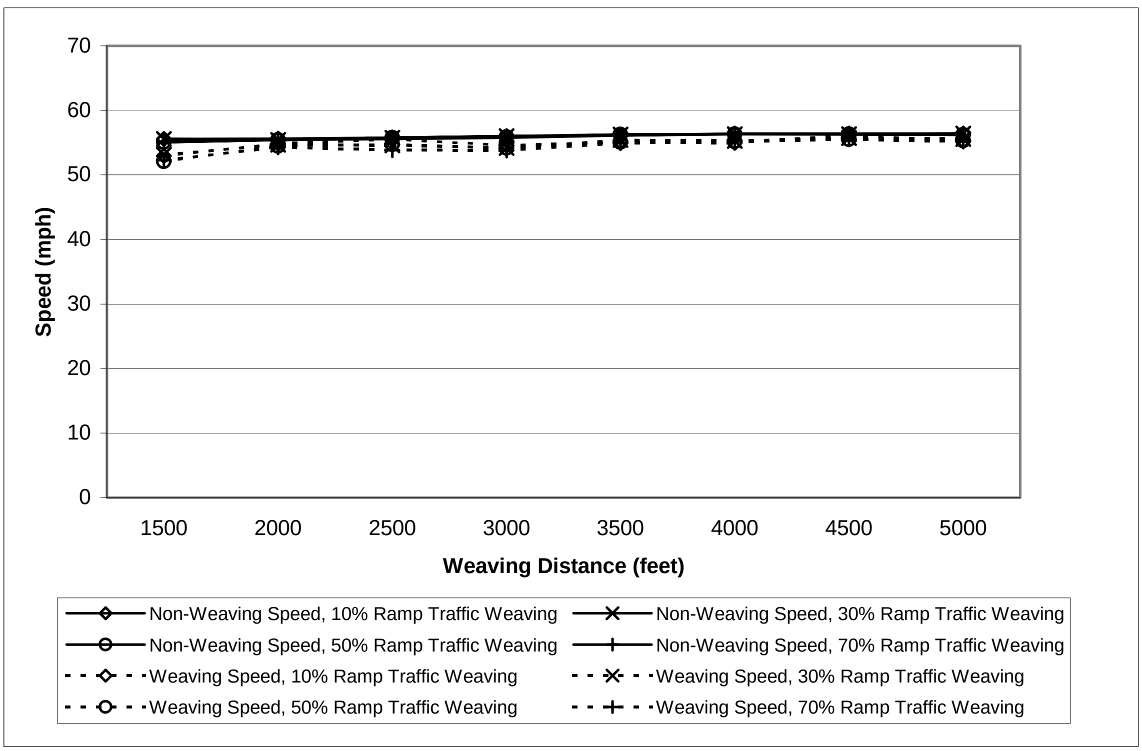

Figure 15. Case III Exit Weave Results – Medium Volume and 5% Trucks.

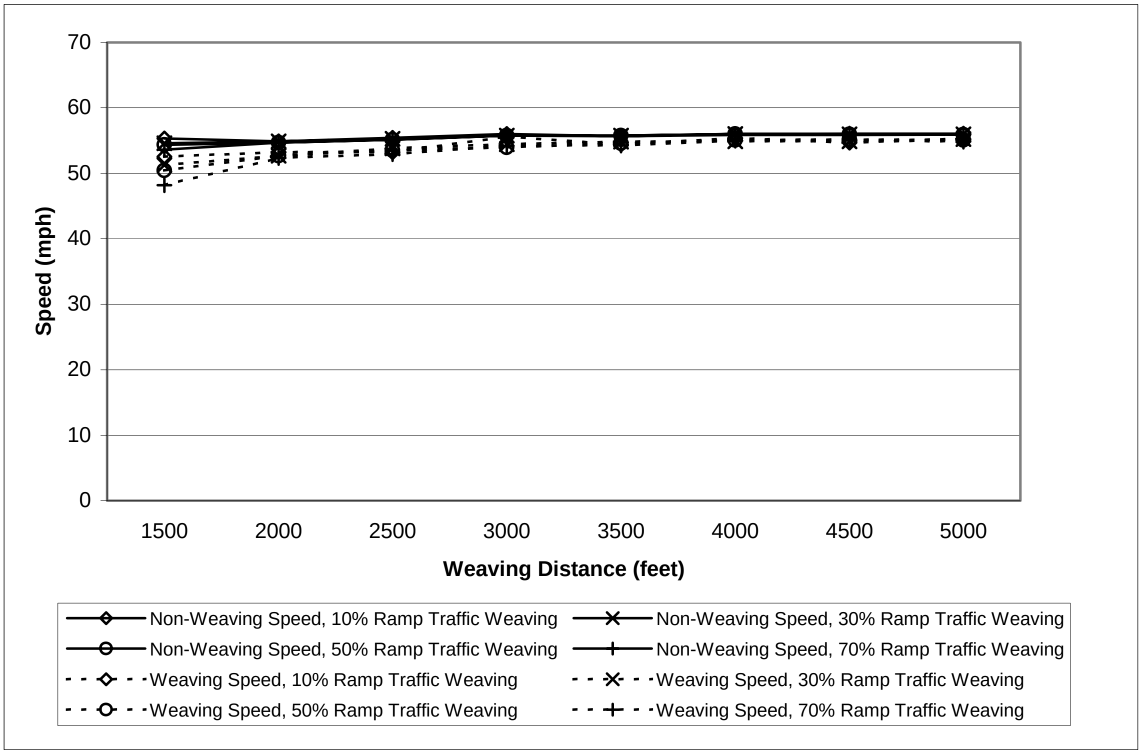

Figure 16. Case III Exit Weave Results – Medium Volume and 10% Trucks.

Figure 17. Case III Exit Weave Results – High Volume and 5% Trucks.

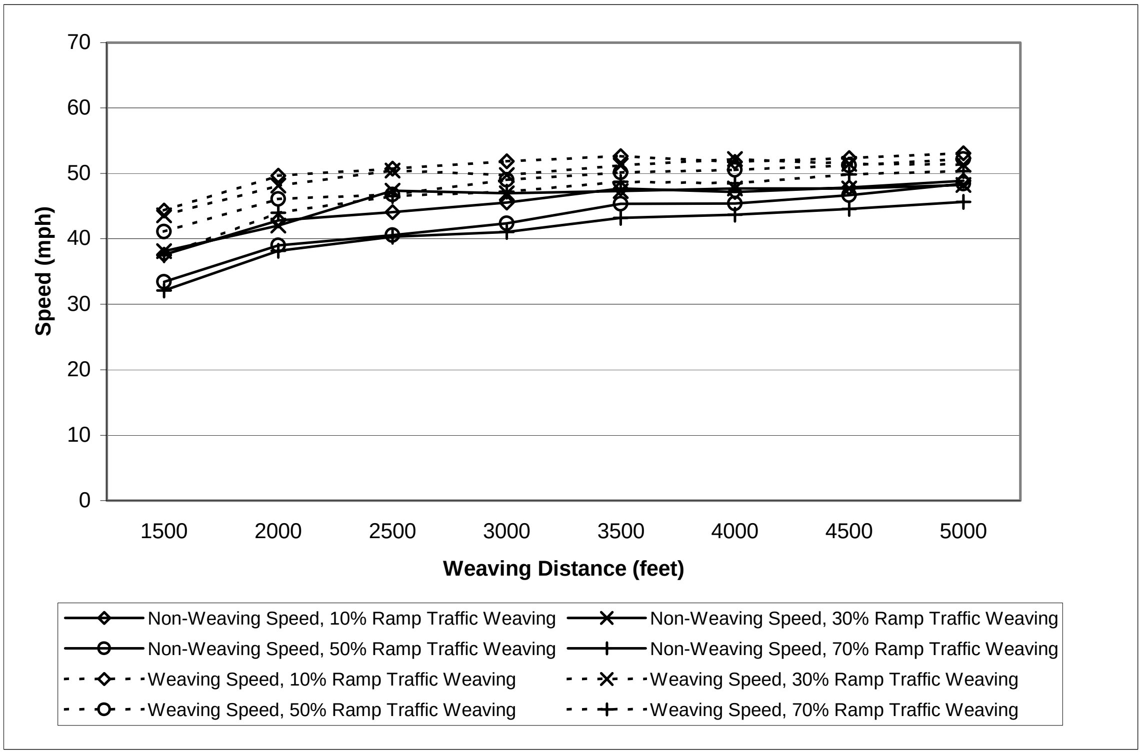

Figure 18. Case III Exit Weave Results – High Volume and 10% Trucks.

The impacts of congestion found earlier (See Figure 9 and Figure 10) are mimicked in Figure 17 and Figure 18, as they exhibit greater variability between non-weaving and weaving vehicle speeds. Also visible are the performance degrading impacts of the modeled increases in ramp traffic weaving percentages.

Figure 19 and Figure 20 verify earlier results concerning required weaving distances for cross-freeway maneuvers. A stabilization of non-weaving and weaving freeway flow is observed at 3000 feet and greater distances for medium volumes with 5 percent and 10 percent heavy vehicles. Note that a minimum number of four lane changes are necessary for the cross-freeway managed lane exit to freeway exit weave.

Figure 19. Case IV Complex Exit Weave Results – Medium Volume and 5% Trucks.

Figure 20. Case IV Complex Exit Weave Results – Medium Volume and 10% Trucks.

Figure 21. Case IV Complex Exit Weave Results – High Volume and 5% Trucks.

Figure 22. Case IV Complex Exit Weave Results – High Volume and 10% Trucks.

High-volume Case IV results are shown in Figure 21 and Figure 22. Unlike all previous results, these figures show a decrease in speed performance with increasing weaving distance. This counter-intuitive result occurs because of the simulation experiment design, and not because there exists an inverse relation between weaving performance and weaving distance. Unlike the complex entrance weave found in Case II, the Case IV experiment locates its complex weave at the downstream end of the overall weaving section. As a result, congestion-related speed reductions and queuing occur on the mainlanes along the length of the overall weaving section. Thus, the longer the weaving distance the longer vehicles are mired in congestion, and the lower the speed. Because of the inconclusive nature of the complex exit weave results under high volume conditions, the results of Figure 21 and Figure 22 will be used only to identify congestion-related weaving concerns; they will not be used in making recommendations for weaving distance requirements for managed lane cross-freeway maneuvers.

Traffic Stream Separation Analysis Results

Selective separation, or the repositioning of mainlane vehicles that are destined for the managed lanes, results in vehicles destined for the managed lanes taking advantage of gaps in the traffic stream to maneuver to the correct lane position – in this case, the left freeway lane – so that they can ultimately access the managed portion of the facility. The VISSIM modeling experiment was designed with varying percentages of buses and trucks in the traffic stream, and with varying distances between the point that vehicles began their selective separation maneuver and the location of the managed facility access point.

The impacts of bus percentage, truck percentage and maneuver (i.e., intra-freeway weaving) distance under both medium- and high-volume conditions can be seen in the figures presented in this section and in the tabular results shown in Appendix C. For clarity and discussion purposes, results have been summarized into five figures. Figure 23 presents weaving and non-weaving speed results for a 15 percent truck and 15 percent bus vehicle mix; Figure 24 presents weaving and non-weaving speed results for a 15 percent truck and 5 percent bus vehicle mix; Figure 25 presents weaving and non-weaving speed results for a 0 percent truck and 15 percent bus vehicle mix; and, Figure 26 presents weaving and non-weaving speed results for a 0 percent truck and 5 percent bus vehicle mix. Finally, Figure 27 provides weaving and non-weaving speed results for all truck and bus percentage vehicle mix combinations for an intra-freeway selective separation weaving distance of two miles.

As observed in Figure 23 through Figure 26, freeway weaving and non-weaving speed performance is related to the selective separation weaving distance. Consistent with expectations, greater selective separation weaving distance exhibits improved performance. Also as expected, non-weaving speeds are consistently higher than weaving speeds, as the non-weaving – or through – vehicle population was not required to discover and maneuver into gaps in adjacent lanes in order to reach the leftmost, managed facility access lane. For medium-volume levels, selective separation results stabilize at distances greater than and equal to 1 mile. For high-volume levels, selective separation results stabilize at distances between 1.5 and 2 miles and greater. Figure 27 indicates that the impact of truck percentage on performance (indicted by the downward steepness of the results line from left to right) is more substantial than the impact of bus percentage, which is shown by the spread of data points for each truck percentage within each group of results (medium-volume non-weaving, medium-volume weaving, high-volume non-weaving, and high-volume weaving). Again, such results are expected as the truck vehicle class is both larger and slower to accelerate/decelerate than buses.

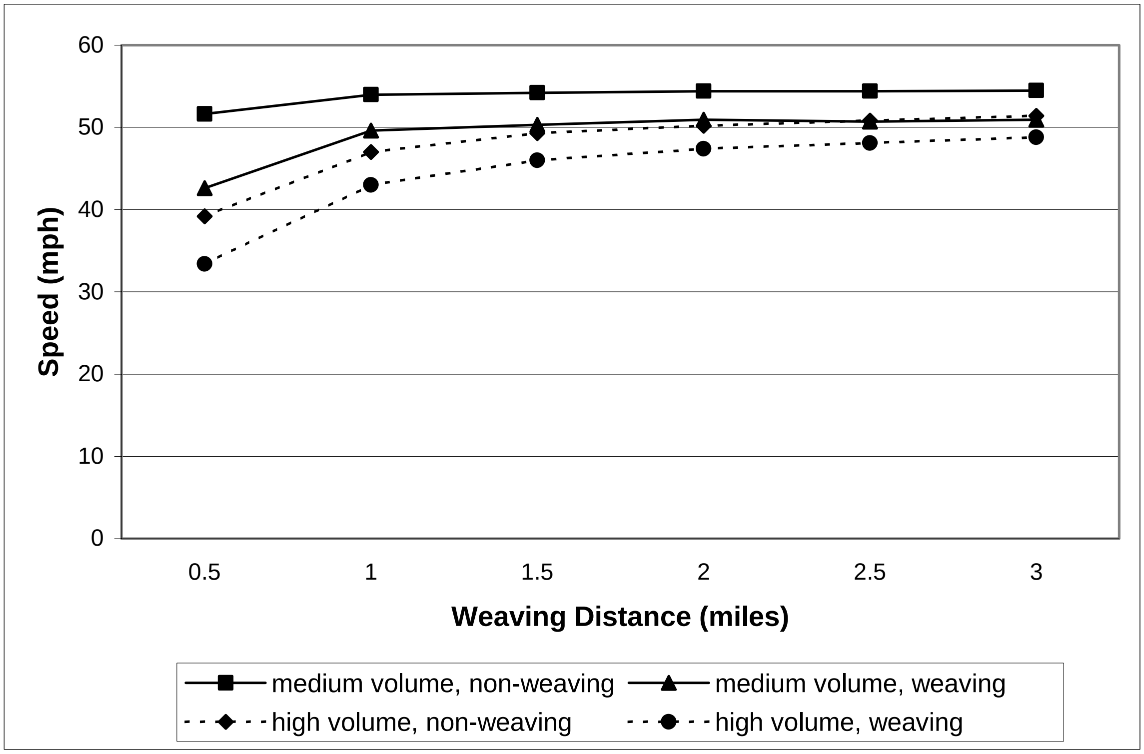

Figure 23. Selective Separation – Medium and High Volume, 15% Truck and 15% Bus.

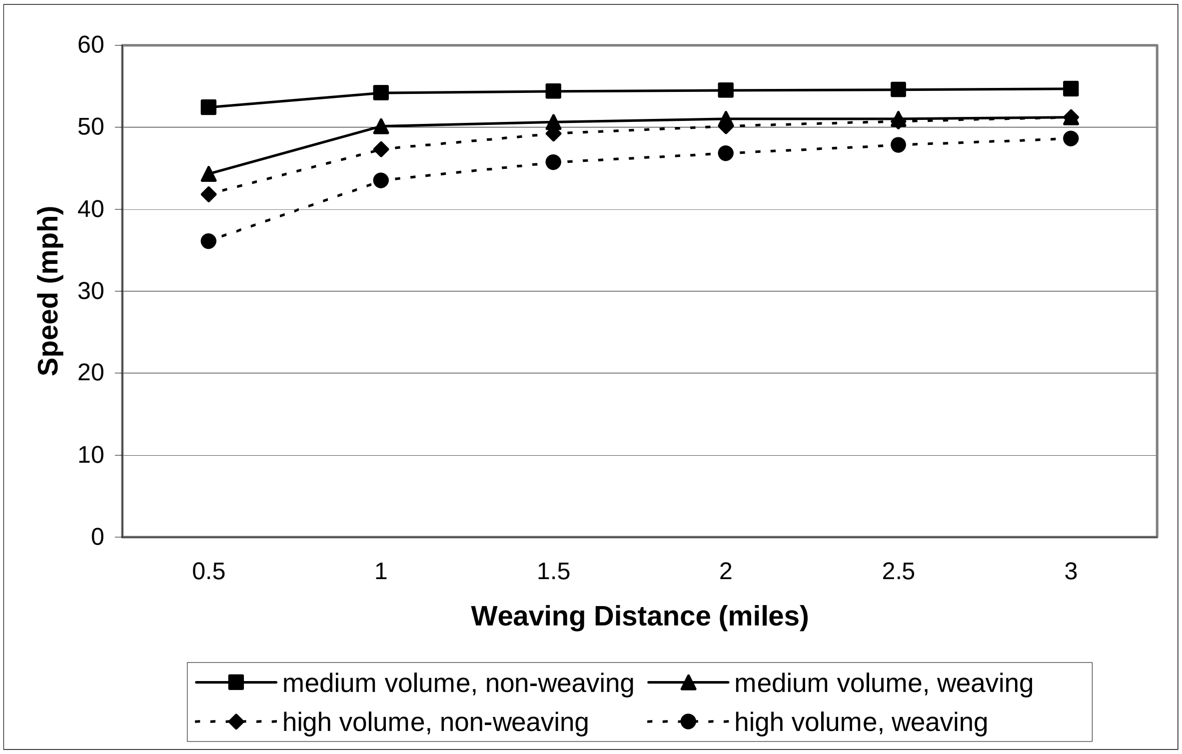

Figure 24. Selective Separation – Medium and High Volume, 15% Truck and 5% Bus.

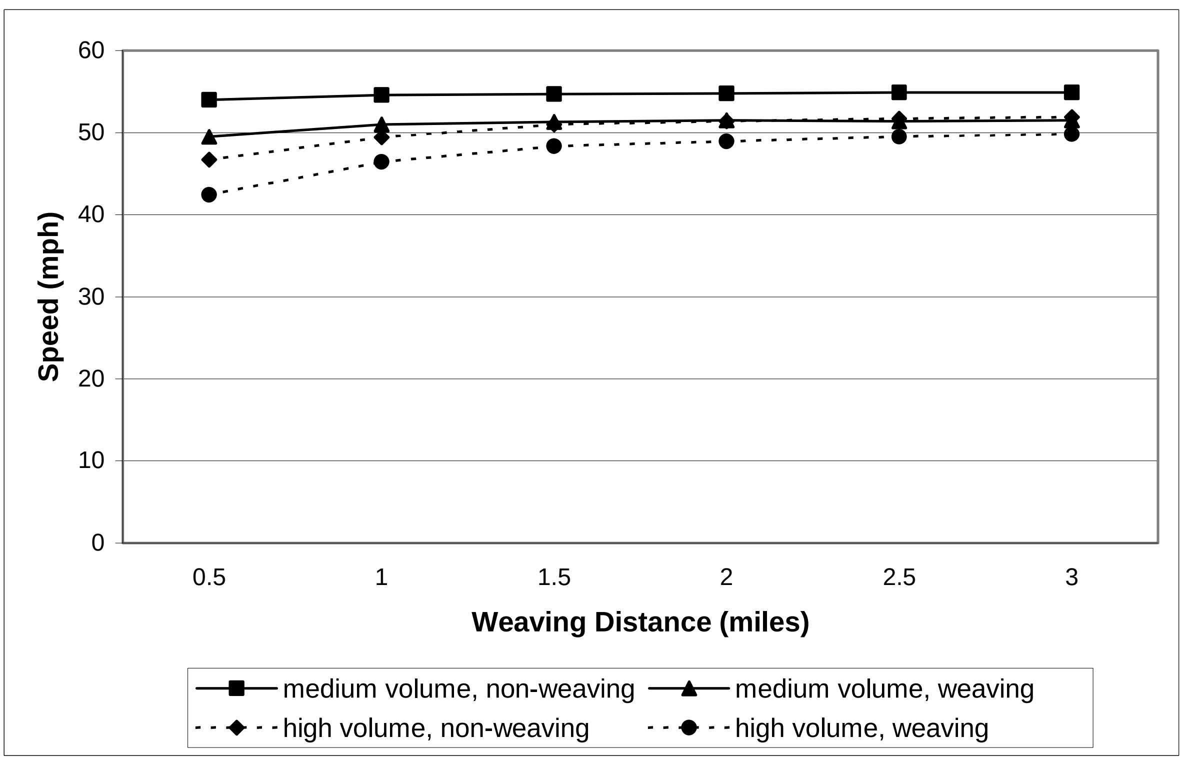

Figure 25. Selective Separation – Medium and High Volume, 0% Truck and 15% Bus.

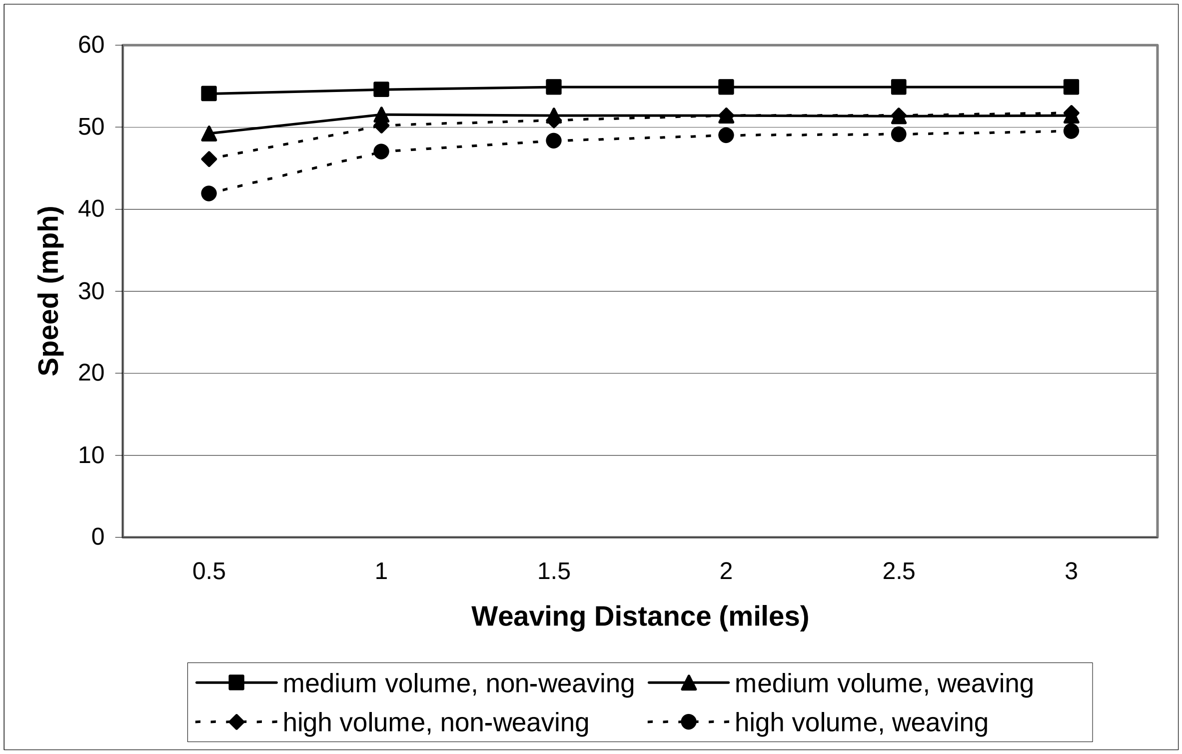

Figure 26. Selective Separation – Medium and High Volume, 0% Truck and 5% Bus.

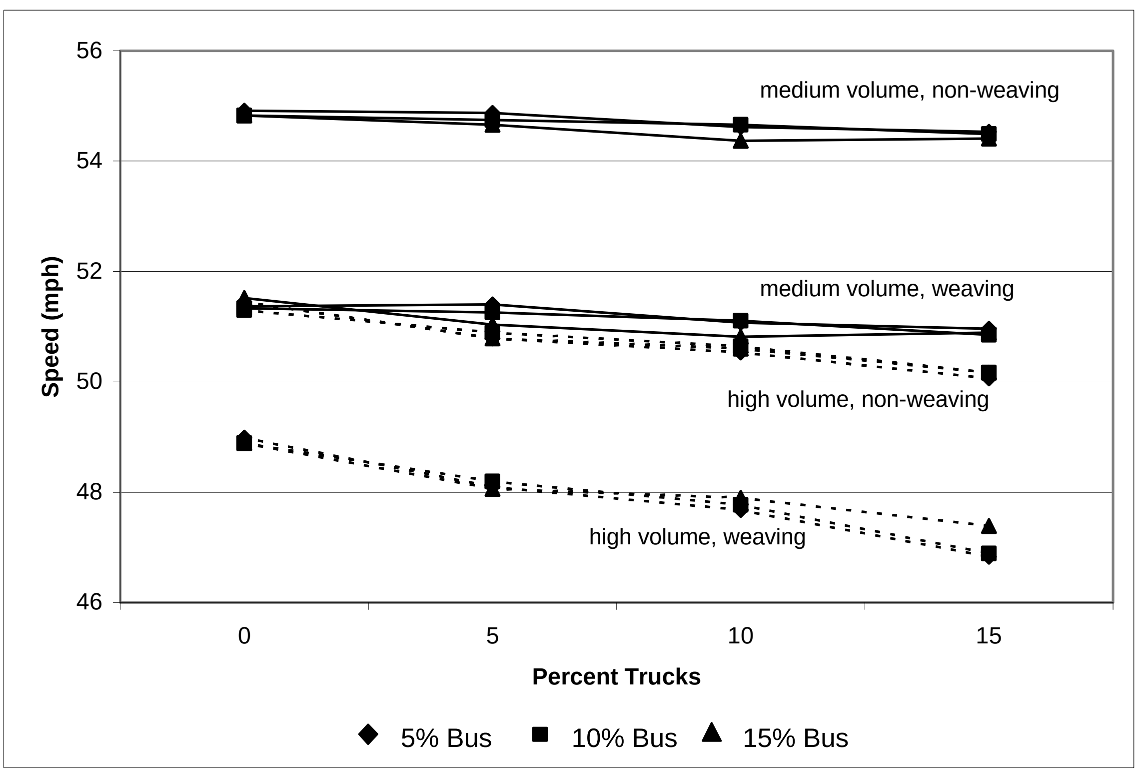

Figure 27. Selective Separation – Two-Mile Weave Distance.

CHAPTER 4. RECOMMENDATIONS

For ease of distribution of managed lanes research results, the recommendations of the managed lanes modeling effort are summarized in list format:

1. Standard analysis techniques, especially the Highway Capacity Manual and Highway Capacity Software, are appropriate for isolated entrance, exit ramp, and one-sided weaving section analysis where these features must be studied within corridors with managed lanes applications. More complex issues, such as cross-freeway weaving and intra-freeway weaving, are most appropriately and practically studied using simulation.

2. The simulation tools CORSIM and Integration offer sufficient data input flexibility to accommodate a variety of managed lane simulation modeling issues, including complex geometrics, signalization/control, and some routing capabilities. However, where multiple vehicles classes and selective real-time control and routing must be modeled, the simulation tools Paramics and VISSIM are most applicable.

3. Typical managed lane design guidelines specify either minimum – 500 feet – and desirable – 1000 feet – weaving distances per lane, or a preferred minimum distance – 2500 feet – between a freeway entrance or exit and a managed lanes facility entrance or exit. The current research updates and places conditionality on these generic guidelines. A recommended weaving distance application table (Table 4) has been developed for anticipated conditions in the design year. The managed facility designer has the option of:

   (1) specifying medium or high volume in the design year (based on HCM level of service – LOS),
   (2) allowing for or not allowing for up to a 10 mph [derived from Exhibit 3-62 of (*13*)] reduction in operating speed due to managed lane related weaving, and
   (3) having or not having intermediate ramp/ramps between the freeway entrance/exit and the managed lanes entrance/exit.

Table 4. Weaving Distances for Managed Lane Cross-Freeway Maneuvers.

Design Year Volume Level	Allow up to 10 mph Mainlane Speed Reduction for Managed Lane Weaving ?	Intermediate Ramp (between freeway entrance/exit and managed lanes entrance/exit) ?	Recommended Minimum Weaving Distance Per Lane (feet)
Medium (LOS C or D)	Yes	No	500
		Yes	600
	No	No	700
		Yes	750
High (LOS E or F)	Yes	No	600
		Yes	650
	No	No	900
		Yes	950
Note: The provided weaving distances are appropriate for freeway vehicle mixes with up to 10 percent heavy vehicles; higher percentages of heavy vehicles will require increasing the per lane weaving distance. The value used should be based on engineering judgment, though a maximum of an additional 250 feet per lane is suggested.			

4. For general managed lane planning purposes, the recommended minimum and desirable distances between a freeway entrance/exit ramp and a managed lanes entrance/exit are 2500 feet and 4000 feet, respectively. The minimum distance applies in cases where a speed reduction of up to 10 mph is acceptable and freeway volumes are moderate. For high-freeway volumes, especially in cases where an intermediate ramp is present between the freeway entrance/exit and the managed lanes entrance/exit, 4000 feet of cross-freeway weaving distance is appropriate.

5. Under moderate volume freeway conditions (i.e., LOS C or D), a maximum weaving volume of 450 vehicles per hour is recommended between any given freeway entrance and the next, downstream managed lanes entrance (and conversely, for any given managed lanes exit and the next, downstream freeway exit). Under high-volume freeway conditions, a maximum weaving volume of 350 vehicles per hour is recommended for the same conditions. In corridors where freeway ramp location, spacing and origin-destination patterns cause managed-lane related weaving volumes that exceed these values, it is recommended that direct access from park and ride/transit facilities to the managed lanes be provided.

6. To preserve freeway quality of service in the vicinity of managed lanes entrance and exit ramps, it is recommended that for moderate freeway volumes in the design year, a transition distance of 1 mile be allowed for vehicles to selectively maneuver from their initial position in any freeway lane to the leftmost (or rightmost) freeway lane so that they can access a managed lane facility. Under high-volume freeway conditions in the design year, a transition distance of 1.5 to 2 miles is appropriate. For both moderate and high-volume freeway conditions, the presence of ramps within the transition distance requires that the given value be increased. Note that these distances are the required transition distances once drivers have already determined whether or not they are

candidates for the managed facility. Sign locations should be designed based on driver perception and decision distances that are added onto the values given here. Also note that the transition distance values given here provide sufficient upstream warning so that mainlane speeds are not significantly impacted by the selective separation weaving vehicles; if lesser transition distances are used, mainlane and weaving vehicle speed will be reduced.

REFERENCES

1. <http://www.fhwa-tsis.com/tsis/tsiscontent> ITT Industries Systems Division (under contract to the Federal Highway Administration). Copyright 1997-2000. Site and page accessed on 3/5/2001.

2. <http://www.paramics-online.com> Quadstone Limited. Copyright 2000. Site accessed on 3/5/2001.

3. <http://www.itc-world.com/SimTools.htm> Innovative Transportation Concepts. Copyright 1999. Site and page accessed on 3/5/2001.

4. Van Aerde, M. Integration© Release 2.10 for Windows: User's Guide-Volume I: Fundamental Model Features. Copyright M. Van Aerde 1984-1998. July 1998.

5. <http://www.trafficware.com/simtraffic.htm> Trafficware. Copyright 1999. Site and page accessed on 3/5/2001.

6. <http://www.itc-world.com/VISSIMinfo.htm> Innovative Transportation Concepts. Copyright 1999. Site and page accessed on 3/5/2001.

7. VISSIM 3.50 User Manual. PTV Planung Transport Verkehr AG (PTV AG), Karlsruhe, Germany, Copyright 1991-2000. December 2000. (Distributed in North America by Innovative Transportation Concepts, LLC, Corvallis, Oregon.)

8. 2000 Highway Capacity Manual, Transportation Research Board, National Research Council, Washington, DC, 2000.

9. Highway Capacity Software, McTrans Center for Microcomputers in Transportation, University of Florida, 2000.

10. High Occupancy Vehicle (HOV) Guidelines for Planning, Design, and Operations. Division of Traffic Operations, Department of Transportation (Caltrans), Business, Transportation and Housing Agency, State of California, July 1991, pp. 4-6.

11. Fuhs, C.A. High Occupancy Vehicle Facilities: A Planning, Design, and Operation Manual. Parsons Brinckerhoff, Quade and Douglas, Incorporated, New York, NY, 1990, p. 4-3-21.

12. Turnbull, K. and Capelle, D. HOV Systems Manual. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, February 1998, pp. 6-49.

13. A Policy on Geometric Design of Highways and Streets, American Association of State Highway and Transportation Officials, Washington, D.C., 2001, p. 241.

APPENDIX A – MANAGED LANES ENTRANCE WEAVE RESULTS

Case I – Medium Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	53.7	50.5	46.6	43.7	32.7	32.4	30.6	29.7
2000	55.9	54.8	54.6	53.6	47.9	47.5	47.6	44.9
2500	56.0	55.6	55.2	54.6	52.0	50.8	49.9	48.4
3000	56.1	55.9	55.5	55.5	52.7	51.9	51.2	50.9
3500	56.0	55.9	55.8	55.8	51.9	51.3	51.1	50.9
4000	56.2	56.2	56.1	56.1	53.8	53.0	52.9	52.4
4500	56.0	56.0	55.9	55.8	52.9	52.8	52.5	52.0
5000	56.2	56.1	56.0	55.9	54.4	54.2	53.8	53.1

Case I – Medium Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	53.9	48.3	42.6	37.0	32.2	29.9	26.9	24.4
2000	55.7	54.6	54.0	51.5	47.6	46.0	45.7	42.0
2500	55.7	55.1	54.6	54.5	50.0	48.9	48.8	48.0
3000	55.8	55.5	55.2	55.1	50.9	50.1	50.0	49.6
3500	55.9	55.5	55.3	55.2	51.1	50.3	49.8	49.8
4000	55.9	55.6	55.4	55.1	52.7	51.3	50.8	49.8
4500	55.9	55.7	55.7	55.5	52.2	51.8	51.9	51.3
5000	56.1	55.9	55.8	55.7	53.9	53.0	52.6	51.8

Case I – High Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	31.7	21.0	18.7	16.9	23.7	19.0	18.9	18.8
2000	43.1	30.0	26.1	23.5	37.1	26.7	25.8	25.2
2500	44.9	36.4	30.1	25.8	38.9	32.5	27.7	26.0
3000	48.0	38.7	33.6	27.2	41.0	35.9	30.5	27.2
3500	49.8	42.6	34.1	28.6	44.6	37.8	31.9	28.5
4000	50.5	43.1	35.8	29.5	46.8	39.4	32.4	29.0
4500	50.7	44.6	38.7	29.9	46.8	41.8	34.6	29.0
5000	51.0	45.2	39.5	30.9	46.7	43.0	36.0	28.9

Case I – High Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	27.9	19.9	17.8	16.1	21.8	18.0	17.9	17.7
2000	35.8	28.4	24.8	22.6	30.3	26.0	24.4	24.0
2500	36.4	31.5	27.2	24.3	31.2	26.5	24.8	24.8
3000	42.1	33.3	30.0	26.3	35.3	25.9	25.1	25.0
3500	45.5	35.7	30.0	26.8	38.7	30.2	25.0	24.8
4000	45.8	39.1	31.2	26.7	40.1	35.2	25.7	25.2
4500	46.6	39.5	33.0	27.3	42.1	35.6	26.2	25.6
5000	47.3	39.9	32.7	27.5	42.5	36.7	26.3	26.8

Case II – Medium Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	54.8	50.9	48.3	43.7	35.4	32.6	32.4	30.1
2000	56.2	55.0	54.1	53.0	48.9	47.3	46.1	44.6
2500	56.1	55.9	55.8	55.3	52.2	52.5	51.5	50.3
3000	56.3	56.2	56.1	55.8	53.6	53.5	52.8	52.1
3500	56.3	56.3	56.2	55.9	53.6	53.2	53.1	52.7
4000	56.4	56.3	56.3	56.2	53.8	53.4	53.6	52.9
4500	56.4	56.3	56.2	56.1	53.4	54.2	53.7	52.9
5000	56.3	56.2	56.1	56.0	53.3	53.6	53.3	53.1

Case II – Medium Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	54.3	49.9	43.6	40.1	35.5	32.4	28.4	27.0
2000	55.6	54.6	53.2	52.6	47.3	47.3	44.1	42.0
2500	55.8	55.1	54.8	54.3	51.6	50.8	50.4	49.2
3000	56.2	55.9	55.7	55.3	53.7	52.2	51.1	50.8
3500	56.2	56.1	55.8	55.6	53.6	52.5	51.8	51.2
4000	56.0	56.1	55.6	55.8	52.9	52.8	51.7	51.9
4500	56.2	56.2	56.0	56.0	52.9	53.3	53.1	52.6
5000	56.1	56.1	56.0	55.8	53.6	53.3	53.0	52.4

Case II – High Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	39.9	28.1	24.2	19.9	27.4	21.3	20.1	18.5
2000	48.1	41.4	31.8	27.3	39.3	35.5	27.5	25.5
2500	50.1	46.6	36.2	31.6	41.9	39.4	31.9	30.6
3000	52.1	49.7	37.5	32.5	46.9	45.6	32.9	31.5
3500	53.3	49.3	39.8	34.2	47.5	45.3	33.9	31.3
4000	53.5	49.5	41.7	35.6	50.1	46.5	36.0	32.7
4500	52.7	51.4	43.0	37.0	49.9	48.3	40.3	33.6
5000	53.3	51.2	46.5	37.3	50.7	48.4	43.3	33.3

Case II – High Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	35.8	25.9	21.2	19.4	23.6	20.2	18.8	17.9
2000	41.3	35.5	27.9	26.0	31.5	28.4	25.2	25.0
2500	45.9	40.5	34.0	30.8	37.6	34.4	30.6	28.5
3000	49.4	42.6	35.0	32.0	41.0	35.1	31.0	29.4
3500	50.5	43.8	37.5	32.9	42.9	37.5	33.9	30.9
4000	49.4	46.4	37.3	34.2	43.3	41.3	34.0	32.4
4500	49.9	46.3	38.1	34.6	43.8	41.0	33.8	34.0
5000	51.3	47.7	38.9	35.1	43.0	41.0	33.2	33.6

APPENDIX B – MANAGED LANES EXIT WEAVE RESULTS

Case III – Medium Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	55.6	55.6	55.1	55.1	52.9	53.2	52.1	52.3
2000	55.6	55.4	55.4	55.4	54.8	54.7	54.5	54.3
2500	55.8	55.8	55.8	55.6	55.5	54.6	54.8	53.8
3000	56.0	56.0	55.9	55.8	54.6	54.2	54.2	53.8
3500	56.1	56.2	56.2	56.1	55.1	55.4	55.1	55.0
4000	56.4	56.3	56.3	56.3	55.0	55.3	55.2	55.3
4500	56.4	56.3	56.3	56.2	56.2	55.7	55.5	55.5
5000	56.4	56.4	56.2	56.2	55.2	55.6	55.3	55.2

Case III – Medium Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	55.3	54.6	54.3	53.6	52.5	51.3	50.4	48.2
2000	54.9	54.9	54.7	54.7	53.2	52.7	52.7	52.4
2500	55.4	55.3	55.1	55.1	53.2	53.8	53.5	52.9
3000	56.0	55.8	55.8	55.8	55.6	54.4	53.9	54.2
3500	55.6	55.8	55.8	55.6	54.4	54.8	54.6	54.3
4000	56.0	56.0	56.0	55.9	55.4	54.9	55.1	55.0
4500	56.1	56.0	56.0	55.9	54.7	54.9	55.1	55.1
5000	56.1	56.0	55.9	55.9	55.2	55.2	55.1	54.8

Case III – High Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	46.1	43.3	42.1	40.2	48.2	46.4	46.6	44.2
2000	49.8	48.2	47.7	45.2	51.9	49.5	50.2	49.3
2500	50.7	49.9	49.4	47.9	53.4	51.7	50.7	50.6
3000	50.6	50.1	49.0	48.3	53.1	52.2	51.8	51.5
3500	51.4	52.7	52.1	50.5	53.1	53.6	52.7	51.8
4000	52.5	51.9	51.6	50.0	54.1	53.3	52.6	52.2
4500	53.8	53.0	51.3	50.2	53.8	53.7	53.1	52.8
5000	53.4	52.8	52.2	51.8	54.7	53.5	53.5	52.9

Case III – High Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	37.5	38.1	33.4	32.1	44.3	43.6	41.1	37.5
2000	42.8	42.0	39.0	38.2	49.6	48.2	46.1	44.0
2500	44.1	47.4	40.6	40.3	50.7	50.4	46.8	46.5
3000	45.5	47.0	42.4	41.1	51.9	49.7	49.0	47.2
3500	47.7	47.3	45.4	43.2	52.6	51.2	50.1	48.7
4000	47.1	47.7	45.4	43.7	51.7	52.2	50.5	48.5
4500	47.8	47.7	46.7	44.5	52.4	51.5	51.2	49.8
5000	48.9	48.2	48.4	45.6	53.1	51.3	52.2	50.3

Case IV – Medium Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	56.7	56.4	55.9	55.6	48.3	47.8	48.3	47.4
2000	56.9	56.7	56.7	56.7	53.5	53.6	53.6	53.6
2500	56.7	56.7	56.7	56.7	55.1	54.9	54.5	53.8
3000	57.0	57.0	57.0	57.0	55.5	55.5	55.2	55.4
3500	56.9	56.8	56.8	56.8	54.9	55.3	55.7	55.6
4000	57.0	56.9	56.9	56.9	55.7	54.4	54.6	54.8
4500	57.0	56.9	56.9	56.9	57.5	55.9	55.7	55.6
5000	56.9	56.9	56.8	56.8	56.1	55.5	55.4	55.1

Case IV – Medium Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	56.4	55.6	55.1	54.6	45.9	43.3	44.1	43.8
2000	56.9	56.9	56.7	56.5	52.5	53.8	53.3	52.6
2500	56.6	56.6	56.6	56.6	52.8	53.5	52.9	52.8
3000	56.8	56.8	56.7	56.7	55.2	55.1	54.4	54.7
3500	56.7	56.7	56.7	56.7	54.2	54.4	53.4	53.5
4000	56.9	56.8	56.8	56.8	54.9	54.8	54.4	54.3
4500	57.0	56.9	56.9	56.8	56.8	55.9	55.8	55.7
5000	56.9	56.9	56.8	56.7	55.5	55.7	55.6	55.5

Case IV – High Volume, 5% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	47.4	40.6	37.0	31.3	41.8	37.6	34.7	29.9
2000	47.4	45.8	42.7	38.6	44.7	42.9	40.3	34.8
2500	41.6	39.5	37.0	34.5	44.6	41.9	38.2	36.4
3000	41.2	33.0	28.8	26.4	43.0	34.9	31.5	28.8
3500	40.7	31.1	27.3	23.2	42.3	34.6	32.6	28.2
4000	39.9	28.7	24.5	21.9	40.6	33.4	29.5	25.9
4500	40.0	27.9	22.3	20.0	40.1	31.4	26.3	24.9
5000	39.2	26.3	23.2	18.8	39.7	30.9	27.9	24.5

Case IV – High Volume, 10% Heavy Vehicles

Distance	Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)				Non-Weaving Speed (Results for Indicated percent Ramp Traffic Weaving)			
	10%	30%	50%	70%	10%	30%	50%	70%
1500	46.0	40.2	32.9	29.4	41.0	37.1	30.8	28.0
2000	44.5	42.9	39.5	36.2	41.2	38.0	34.7	31.6
2500	38.6	37.7	35.7	33.4	40.0	38.8	35.5	34.2
3000	34.8	31.8	27.6	25.1	36.9	34.6	29.7	26.7
3500	31.9	27.9	25.0	23.7	34.5	30.8	29.5	26.7
4000	30.6	27.2	22.6	19.4	33.4	30.5	26.3	22.1
4500	29.6	23.5	21.2	17.0	32.8	26.2	24.2	21.0
5000	30.0	24.5	20.3	17.8	31.6	28.2	23.8	20.7

APPENDIX C – SELECTIVE SEPARATION WEAVING RESULTS

Medium Volume - 0.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	34.3	87.1	54.1	4632	37.9	79.2	49.2	964
5	5	34.7	86.1	53.5	4630	39.0	77.0	47.8	962
10	5	35.1	85.1	52.9	4636	39.4	76.2	47.3	965
15	5	35.4	84.4	52.4	4632	42.1	71.3	44.3	964
0	10	34.3	87.1	54.1	4632	37.9	79.2	49.2	964
5	10	34.5	86.6	53.8	4633	38.0	79.0	49.1	963
10	10	34.7	86.1	53.5	4634	39.2	76.6	47.6	964
15	10	35.9	83.2	51.7	4631	42.6	70.5	43.8	964
0	15	34.4	86.9	54.0	4637	37.7	79.6	49.5	965
5	15	35.0	85.4	53.0	4636	41.0	73.2	45.5	965
10	15	35.2	84.9	52.7	4632	42.2	71.1	44.2	964
15	15	36.0	83.0	51.6	4633	43.8	68.5	42.6	963

High Volume - 0.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	40.3	74.1	46.1	7115	44.5	67.5	41.9	876
5	5	42.2	70.8	44.0	6697	47.3	63.5	39.4	826
10	5	43.4	68.8	42.8	6511	49.8	60.3	37.4	806
15	5	44.4	67.3	41.8	6230	51.7	58.1	36.1	777
0	10	39.8	75.1	46.6	6969	44.3	67.8	42.1	855
5	10	42.7	70.0	43.5	6578	48.6	61.8	38.4	818
10	10	42.9	69.7	43.3	6343	48.8	61.5	38.2	788
15	10	43.9	68.1	42.3	6141	51.1	58.7	36.5	761
0	15	39.7	75.3	46.7	6906	44.0	68.2	42.4	846
5	15	41.6	71.8	44.6	6560	47.6	63.1	39.2	816
10	15	42.6	70.1	43.6	6480	49.2	61.0	37.9	805
15	15	47.4	63.0	39.2	5905	55.8	53.8	33.4	728

Medium Volume - 1 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	67.6	87.9	54.6	4633	71.8	82.8	51.5	962
5	5	67.7	87.8	54.5	4629	72.7	81.8	50.8	963
10	5	68.0	87.4	54.3	4596	73.2	81.3	50.5	960
15	5	68.1	87.3	54.2	4627	73.8	80.6	50.1	963
0	10	67.3	88.3	54.9	4631	72.0	82.6	51.3	962
5	10	67.7	87.8	54.5	4633	72.5	82.0	51.0	964
10	10	68.0	87.4	54.3	4634	73.0	81.5	50.6	962
15	10	68.2	87.2	54.1	4632	73.8	80.6	50.1	964
0	15	67.6	87.9	54.6	4637	72.4	82.2	51.0	964
5	15	67.8	87.7	54.5	4637	72.7	81.8	50.8	962
10	15	68.4	86.9	54.0	4631	74.4	79.9	49.7	964
15	15	68.4	86.9	54.0	4631	74.5	79.8	49.6	964

High Volume - 1 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	73.6	80.8	50.2	7170	78.6	75.7	47.0	884
5	5	76.2	78.0	48.5	6547	82.2	72.4	44.9	816
10	5	76.8	77.4	48.1	6503	83.1	71.6	44.5	805
15	5	78.1	76.1	47.3	6205	85.0	70.0	43.5	773
0	10	74.5	79.8	49.6	7040	79.6	74.7	46.4	866
5	10	76.1	78.1	48.5	6618	81.9	72.6	45.1	819
10	10	77.1	77.1	47.9	6330	83.8	71.0	44.1	788
15	10	78.4	75.8	47.1	6189	86.2	69.0	42.9	770
0	15	74.7	79.6	49.4	7011	79.7	74.6	46.4	863
5	15	75.6	78.6	48.8	6542	82.2	72.4	44.9	815
10	15	76.7	77.5	48.1	6282	83.0	71.7	44.5	784
15	15	78.6	75.6	47.0	6012	86.0	69.2	43.0	739

Medium Volume - 1.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	100.2	88.4	54.9	4636	106.8	82.7	51.4	962
5	5	100.6	88.0	54.7	4631	106.9	82.7	51.3	961
10	5	100.8	87.8	54.6	4634	107.9	81.9	50.9	961
15	5	101.1	87.6	54.4	4628	108.4	81.5	50.6	963
0	10	100.3	88.3	54.8	4636	106.7	82.8	51.4	961
5	10	100.6	88.0	54.7	4634	107.2	82.4	51.2	964
10	10	100.7	87.9	54.6	4634	107.8	82.0	50.9	962
15	10	101.4	87.3	54.2	4633	108.5	81.4	50.6	960
0	15	100.5	88.1	54.7	4636	106.9	82.7	51.3	965
5	15	100.7	87.9	54.6	4637	107.9	81.9	50.9	962
10	15	101.0	87.7	54.4	4633	108.4	81.5	50.6	961
15	15	101.4	87.3	54.2	4630	109.1	81.0	50.3	959

High Volume - 1.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	108.3	81.7	50.8	7187	113.6	77.8	48.3	887
5	5	109.0	81.2	50.4	6830	115.4	76.6	47.6	845
10	5	110.6	80.0	49.7	6424	118.0	74.9	46.5	795
15	5	111.8	79.2	49.2	6137	120.1	73.6	45.7	760
0	10	107.9	82.0	51.0	7094	113.2	78.1	48.5	871
5	10	109.3	81.0	50.3	6670	116.3	76.0	47.2	823
10	10	110.7	80.0	49.7	6461	118.4	74.6	46.4	803
15	10	111.0	79.8	49.5	6277	118.4	74.6	46.4	784
0	15	107.8	82.1	51.0	7048	113.7	77.7	48.3	866
5	15	109.8	80.6	50.1	6539	116.4	75.9	47.2	810
10	15	110.9	79.8	49.6	6233	118.7	74.4	46.2	778
15	15	111.5	79.4	49.3	6235	119.3	74.1	46.0	778

Medium Volume - 2.0 mile signing									
		to Mainlanes				to Managed Lane			
%Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	129.1	88.4	54.9	4635	138.3	82.7	51.4	959
5	5	129.2	88.3	54.9	4627	138.2	82.8	51.4	961
10	5	129.8	87.9	54.6	4637	139.1	82.2	51.1	959
15	5	130.0	87.8	54.5	4627	139.4	82.0	51.0	963
0	10	129.3	88.3	54.8	4635	138.4	82.6	51.3	959
5	10	129.5	88.1	54.7	4634	138.6	82.5	51.3	961
10	10	129.7	88.0	54.7	4638	139.0	82.3	51.1	963
15	10	130.1	87.7	54.5	4632	139.7	81.9	50.9	958
0	15	129.3	88.3	54.8	4637	137.9	82.9	51.5	963
5	15	129.7	88.0	54.7	4638	139.2	82.2	51.0	959
10	15	130.4	87.5	54.4	4632	139.8	81.8	50.8	959
15	15	130.3	87.6	54.4	4629	139.6	81.9	50.9	962

High Volume - 2.0 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	137.8	82.8	51.4	7235	145.0	78.9	49.0	892
5	5	139.6	81.8	50.8	6719	147.7	77.4	48.1	828
10	5	140.3	81.4	50.5	6508	149.0	76.8	47.7	805
15	5	141.6	80.6	50.1	6208	151.7	75.4	46.8	773
0	10	138.2	82.6	51.3	7044	145.3	78.7	48.9	867
5	10	139.3	81.9	50.9	6704	147.4	77.6	48.2	828
10	10	140.0	81.5	50.6	6218	148.7	76.9	47.8	776
15	10	141.3	80.8	50.2	6166	151.5	75.5	46.9	764
0	15	137.8	82.8	51.4	7070	145.3	78.7	48.9	868
5	15	139.6	81.8	50.8	6709	147.8	77.4	48.1	829
10	15	140.0	81.5	50.6	6197	148.4	77.1	47.0	817
15	15	141.3	80.8	50.2	6008	149.9	76.3	47.4	738

Medium Volume - 2.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	162.6	88.4	54.9	4630	174.1	82.5	51.3	957
5	5	162.8	88.3	54.9	4631	173.9	82.6	51.3	963
10	5	163.2	88.1	54.7	4636	174.7	82.3	51.1	958
15	5	163.6	87.9	54.6	4632	175.0	82.1	51.0	962
0	10	162.7	88.4	54.9	4630	173.9	82.6	51.3	957
5	10	162.8	88.3	54.9	4634	174.5	82.4	51.2	960
10	10	163.1	88.2	54.8	4658	174.5	82.4	51.2	955
15	10	164.0	87.7	54.5	4634	175.2	82.0	51.0	963
0	15	162.8	88.3	54.9	4636	173.8	82.7	51.4	963
5	15	163.3	88.1	54.7	4630	174.0	82.6	51.3	957
10	15	163.5	87.9	54.6	4634	174.5	82.4	51.2	957
15	15	164.3	87.5	54.4	4634	176.0	81.7	50.7	960

High Volume - 2.5 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	173.7	82.8	51.4	7234	181.7	79.1	49.1	892
5	5	174.2	82.5	51.3	6707	182.2	78.9	49.0	826
10	5	175.4	82.0	50.9	6413	185.2	77.6	48.2	795
15	5	176.2	81.6	50.7	6262	186.6	77.0	47.8	780
0	10	172.9	83.2	51.7	7130	180.8	79.5	49.4	878
5	10	174.0	82.6	51.3	6681	183.2	78.4	48.7	823
10	10	175.1	82.1	51.0	6432	184.5	77.9	48.4	797
15	10	175.9	81.7	50.8	5994	186.2	77.2	47.9	735
0	15	172.9	83.2	51.7	7081	180.5	79.6	49.5	869
5	15	173.8	82.7	51.4	6540	183.1	78.5	48.8	812
10	15	175.3	82.0	50.9	6292	185.0	77.7	48.3	783
15	15	175.8	81.8	50.8	6145	185.7	77.4	48.1	765

Medium Volume - 3.0 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	195.8	88.6	55.0	4640	209.5	82.9	51.5	896
5	5	196.1	88.5	55.0	4629	209.8	82.8	51.4	963
10	5	196.6	88.2	54.8	4635	210.3	82.6	51.3	957
15	5	197.1	88.0	54.7	4627	210.8	82.4	51.2	961
0	10	195.9	88.6	55.0	4631	210.0	82.7	51.4	957
5	10	196.3	88.4	54.9	4632	209.8	82.8	51.4	961
10	10	196.4	88.3	54.9	4635	210.1	82.7	51.3	963
15	10	197.3	87.9	54.6	4632	211.7	82.0	50.9	962
0	15	196.2	88.4	54.9	4632	209.6	82.8	51.5	963
5	15	196.2	88.4	54.9	4632	210.2	82.6	51.3	957
10	15	197.0	88.1	54.7	4635	210.8	82.4	51.2	957
15	15	197.7	87.8	54.5	4632	211.9	81.9	50.9	961

High Volume - 3.0 mile signing									
		to Mainlanes				to Managed Lane			
% Trucks	% Buses	Travel Time	Speed kph	Speed mph	# Vehicles	Travel Time	Speed kph	Speed mph	# Vehicles
0	5	208.3	83.3	51.7	7028	217.7	79.8	49.5	865
5	5	209.3	82.9	51.5	6687	219.3	79.2	49.2	824
10	5	209.3	82.9	51.5	6421	221.3	78.5	48.7	794
15	5	210.4	82.5	51.2	6292	222.0	78.2	48.6	785
0	10	208.5	83.2	51.7	7066	217.8	79.7	49.5	868
5	10	209.0	83.0	51.6	6819	219.0	79.3	49.2	844
10	10	209.3	82.9	51.5	6338	221.3	78.5	48.7	788
15	10	210.8	82.3	51.1	6100	221.8	78.3	48.6	755
0	15	207.5	83.6	51.9	7101	216.7	80.1	49.8	868
5	15	209.4	82.9	51.5	6619	219.4	79.1	49.2	819
10	15	209.3	82.9	51.5	6382	220.3	78.8	49.0	791
15	15	209.8	82.7	51.4	6041	220.9	78.6	48.8	744