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16. Abstract

Current funding constraints and difficulty in gaining environmental and public approval for large-scale construction projects has forced the Texas Department of Transportation (TxDOT) to continue considering alternative solutions to roadway widening to mitigate congestion. One area for potentially improving freeway performance is ramp locations. Current ramp treatments only address point demand. Applying managed lanes operational strategies to ramps could maximize existing capacity, manage demand, offer choices, improve safety, and generate revenue. This project investigates the application of these demand management strategies to mainlane ramps and managed lane ramp operations during the peak period; i.e., “managed ramps.” Such strategies could include peak-period use of both mainlane or managed lanes entrance and exit ramps by user group, possibly influencing mode choice, enhancing mobility, improving safety in a freeway corridor, and helping ensure the integrity and free-flow operations of a managed lanes facility. This research: (1) investigated under what conditions should managed ramps be considered for both mainlanes and managed lanes based on relevant factors including target users in the corridor, congestion level, ramp spacing/density, ramp volumes, accident history, etc.; (2) assessed the impacts and benefits of managed ramps; and (3) developed general guidelines and best practices for operating and enforcing managed ramps.

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DISCLAIMER

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The United States government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

The highway system in the United States is a critical component of American life. It provides extensive and flexible personal mobility to American citizens and efficient freight movement to support the domestic economy (*1*). However, a variety of factors interfere with this system's ability to provide these services. The growth of vehicle miles traveled continues at an accelerated rate (*2*), to the extent that it outpaces the growth across the country in the number of lane miles (*1*). Additionally, congestion in urban areas is increasing and occurs during longer parts of the day and delays more travelers every year (*3*). These trends are especially evident in Texas where increasing population growth has led to an increase in congestion in all major urban areas (*3*). This population growth places enormous demands on the already burdened transportation infrastructure, particularly the freeway systems.

Transportation agencies realize that they cannot accomplish construction of sufficient freeway lane capacity to provide free-flow conditions during peak travel periods in developed urban areas due to cost, land consumption, neighborhood impacts, environmental concerns, and other factors. Like other transportation agencies nationwide, the Texas Department of Transportation (TxDOT) is searching for methods to better manage traffic flow, mitigate the adverse effects of congestion, and thus improve the efficiency of existing and proposed networks.

MANAGED LANES STRATEGIES

Transportation agencies across the country are successfully using managed lanes as one method to better manage traffic flow. The theory behind managed lanes is to set aside certain freeway lanes and to use a variety of operating strategies to move traffic more efficiently in those lanes. As a result, travelers have an option when traveling on a congested freeway. Using managed lanes can allow a transportation agency to leverage existing capacity and move both people and goods in the most efficient manner possible. The managed lanes concept is a tool that is available to the transportation community and may be used as part of a comprehensive plan to achieve regional goals.

The term "managed lanes" has different meanings to different agencies. In some agencies, the term is commonly thought of as high-occupancy vehicle (HOV) lanes while in others it might refer to high-occupancy toll (HOT) lanes. Still other agencies may use an even broader definition which may include HOV lanes, value-priced lanes (including HOT lanes), and exclusive or special use lanes (such as express, bus-only, or truck-only lanes). TxDOT uses the following as a definition for managed lanes:

> "A managed lane facility is one 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" (*4*).

The definition is very general, and yet it reflects the complexity and flexibility of the managed lanes concept. The definition allows each district across the state to determine what "managed lanes" means for their jurisdiction. Thus, it respects the needs of the community without requiring the application of a specific strategy that does not meet those needs. Moreover, it encourages flexibility, realizing that the needs of a region may change over time, thereby requiring a different managed lanes operational strategy.

Figure 1 is a diagram that illustrates the potential lane management strategies that fall into this broad definition of managed lanes. On the left of the diagram are the applications of a single operational strategy – pricing, vehicle eligibility, or access control – and on the right are the more complicated managed lanes facilities that combine more than one of the strategies. The multifaceted facilities on the far right of the diagram are those that incorporate or combine multiple lane management strategies.

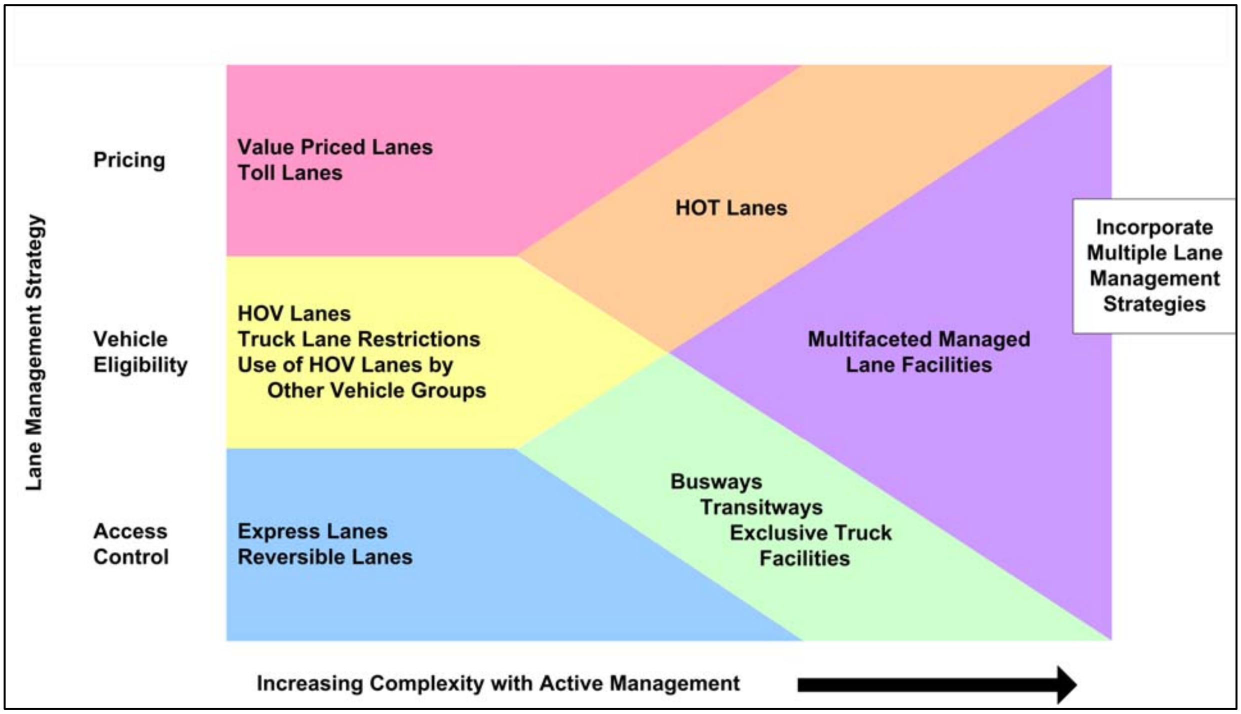


Figure 1. Lane Management Strategy Complexity (5).

Managed lanes operational strategies can maximize existing capacity, manage demand, offer choices, improve safety, and generate revenue. The key to successfully operating managed lanes is the ability to alter the operations of the lanes in ways that keep traffic flowing. This strategy provides flexibility, not only in the day-to-day operations of the lanes, but in situations where isolated incidents such as a major accident call for the lanes to be open to more or different user groups.

CURRENT RAMP MANAGEMENT STRATEGIES

Historically ramp management strategies refer to ramp metering and ramp closures. These strategies with special use treatments and ramp terminal treatment are the most commonly accepted methods of ramp management strategies. Ramp metering is the most extensively used strategy. A ramp meter is simply a device (similar to a traffic signal), which regulates the flow of traffic entering a freeway. Ramp metering was first implemented in 1963 on the Eisenhower Expressway (I-290) in Chicago, Illinois. This first application involved a police officer who would stop traffic on an entrance ramp and release vehicles one at a time at a predetermined rate. This approach had the objective of providing safer and smoother merging into freeway traffic without disrupting the mainlane flows. Since then, agencies had systematically deployed ramp meters in many urban areas including:

- Los Angeles, California;
- Minneapolis-St. Paul, Minnesota;
- Seattle, Washington;
- Denver, Colorado;
- Phoenix, Arizona;
- Houston, Austin, Dallas, and San Antonio in Texas;
- Columbus, New York;
- Detroit, Michigan;
- Toronto, Canada; and
- Portland, Oregon.

In some instances, cities have withdrawn the use of ramp meters for various reasons, although many studies indicate that ramp metering is a successful strategy (*6*).

In recent years ramp metering has again been at the forefront of operational options, with plans for deployment in various European countries including Belgium, the Netherlands, France, the United Kingdom, and Germany (*7*), as well as in Minneapolis, Cleveland, Denver, Los Angeles, the Pennsylvania Turnpike, and Salt Lake City in the United States. To encourage carpooling and high-occupancy vehicles, many states currently provide separate bypass lanes on the ramps (*7, 8, 9*). The California Department of Transportation (Caltrans) manual also provides guidelines for proper signs to use with HOV and carpool bypass lanes on ramps (*7*). As another example, the Washington Department of Transportation *Design Manual* states; "Consider HOV bypass lanes with ramp meters" (*8*). Some states also use metering on freeway-to-freeway connectors and mainlanes (*8*).

One example of ramp closures in Texas was located in Corpus Christi on State Highway (SH) 358, also known as South Padre Island Drive (SPID). Unsafe weaving conditions were created when vehicles entering at the Kostoryz Road on-ramp to westbound SH 358 weaved through vehicles exiting at the Ayers off-ramp and the freeway-to-freeway off-ramp from SH 358 to SH 286 (Cross-town Expressway). This weaving problem occurred during a 30-minute morning peak. It should be noted that most of the traffic from Kostoryz Road was westbound through traffic at SPID. This weaving resulted in several accidents on SPID. A gate was installed at the Kostoryz Road on-ramp to westbound SH 358 (SPID). The drop-down electromechanical gate was operated on a timer. When the ramp was closed, the westbound SPID portion of Kostoryz Road on-ramp traffic was diverted to the Ayers on-ramp and had to go through a traffic signal. Any SH 286-bound traffic from Kostoryz also had an easier access from the frontage road to SH 286. Ramp closure significantly reduced accidents on SPID and improved traffic flow. Another example of ramp closure is in El Paso on the Paisano ramp on westbound Interstate 10 (IH-10). Vehicles entering the freeway using this ramp during peak traffic conditions experienced merging problems, and congestion was a problem on IH-10 within the proximity of the ramp. Although TxDOT considered ramp metering, they decided to use a ramp closure strategy. A gate was thus installed on the ramp.

APPLYING MANAGED LANES STRATEGIES TO RAMPS

One of the areas for potentially improving freeway performance is at ramp locations. The current ramp treatments discussed above only address point demand. Simply put, ramp management is the application of control devices, such as traffic signals, signing, and gates, to regulate the number of, and rate by which, vehicles enter or leave the freeway. The concept of managed ramps would be to apply any of the myriad of managed lanes operational strategies along a corridor to optimize the use of the overall freeway facility. For example, agencies could use tolling to manage ramp access with no regard to vehicle occupancy. During the peak period, agencies could also restrict the use of specific entrance or exit ramps to HOVs and/or transit. The HOT lane strategy might also be applicable where HOVs and transit would use specific ramps at no charge, and single-occupant vehicles (SOVs) pay a toll. If the conditions are appropriate, agencies may prohibit heavy trucks from using particular ramps during certain periods of the day or may be the only vehicles allowed to use particular ramps. Furthermore, agencies could apply these strategies to managed lanes access points if they become so congested that they negatively impact both the mainlanes and the managed lanes. Such operational strategies as discussed above could help maximize existing capacity, manage demand, offer choices, enhance mobility, improve safety, and generate revenue within the freeway corridor itself.

RESEARCH AGENDA

The objectives of this research project were to:

- Assess under what conditions agencies should consider managed ramps for both mainlanes and managed lanes based on relevant factors including target users in the corridor, congestion level, ramp spacing/density, ramp volumes, accident history, and other factors that may play a role in this determination.
- Assess the impacts and benefits of managed ramps.
- Develop general guidelines and best practices for operating and enforcing managed ramps.

Researchers undertook a two-year approach of research to satisfy the stated objectives. The research approach consisted of eight tasks that represented a logical sequence of needs assessment, research, evaluation, and product development.

CHAPTER 2: LITERATURE REVIEW

BACKGROUND

Increasing population in Texas has placed enormous demands on the transportation infrastructure, particularly the freeway systems. There is a growing realization that agencies cannot construct sufficient freeway lane capacity to provide free-flow conditions during peak travel periods in developed urban corridors due to cost, land consumption, neighborhood impacts, environmental concerns, and other factors. To meet this growing demand, TxDOT has begun utilizing operational strategies offered by managed lane facilities.

As discussed previously, a managed lane facility is one that increases freeway efficiency by packaging various operational and design actions. Operating agencies may adjust lane management operations at any time to better match regional goals. Managed lanes are intended to provide peak period free-flow travel to certain user groups. Currently the managed lanes users typically access managed lanes facilities by the same ramps utilized for general-purpose lanes. In order to support a more efficient operation of managed lanes facilities as well as the freeway as a whole, managed ramp strategies are being examined. Managing ramps includes the applications of managed lane strategies to the ramps themselves.

Managed lane operational strategies include HOV lanes, value-priced lanes or HOT lanes, exclusive-use lanes such as bus or truck lanes, separation and bypass lanes, dual-use lanes, and lane restrictions. Managed lanes support increased efficiency of traffic on existing roadways and generally meet the following transportation systems management goals outlined in the *Guide for the Design of High Occupancy Vehicle Facilities* (*10*), which were originally developed for HOV lanes:

- improve operating level of service (LOS) for high-occupancy vehicles, both public and private, thereby maximizing person-moving capacity of roadway facilities;
- provide fuel conservation;
- improve air quality by reducing pollution caused by delay and congestion; and
- increase overall accessibility while reducing vehicular congestion (*10*).

MANAGED LANE STRATEGIES

The following sections provide a description of the various types of managed lanes operational strategies deployed in Texas and across the country.

High-Occupancy Vehicle Lanes

HOV lanes, first implemented in the Washington, D.C., and northern Virginia areas in 1969, increase the person-moving capacity of the existing infrastructure (*11*). HOV lanes, simply put, are separate lanes that are restricted to vehicles with a specified occupancy and may include carpools, vanpools, and buses (*12*). Most HOV facilities require that vehicles have two or more (2+) occupants to legally use the facility; however, some facilities require three or more (3+) occupants during peak travel times (*13*). HOV lanes can be implemented on either arterials or freeways. When implemented on freeways, the following three types of facilities are used—separated roadway, concurrent flow lanes, and contraflow lanes (*10*). Additionally, the separated roadway facility may be either a two-way facility or a reversible-flow facility.

The number of operating HOV lanes agencies are proposing and implementing throughout North America is steadily increasing. This trend indicates that HOV lanes are a widely accepted strategy for addressing traffic mobility in metropolitan areas. However, HOV facilities are not appropriate for all situations, and agencies should evaluate and monitor each facility to ensure the facility meets the goals and expectations of the community (*14*). Expectations and objectives for a successful HOV lane include moving people, benefiting transit, and improving overall roadway efficiency. Constraints that may affect the successful implementation of strategies involving HOV lanes include adverse impact on general-purpose lanes, cost-effectiveness, public acceptance, and the environmental impact of implementation (*12*).

Value-Priced Lanes and High-Occupancy Toll (HOT) Lanes

A HOT lane is an HOV lane that allows vehicles with lower occupancy to have access to the lane by paying a toll. Variations of HOT lanes are value-priced, value express, and fast and intertwined regular (FAIR) lanes, which may or may not be occupancy driven depending on the region or state. Value express lanes, as implemented by the Colorado Department of Transportation (CDOT), are similar to HOT lanes (*15*). In most cases, value express lanes and

FAIR lanes are toll lanes. However, some jurisdictions use these terms to describe strategies similar to a HOT lane.

The idea behind HOT lanes is to improve the HOV lane utilization by selling unused lane capacity *(12)*. In a study for the CDOT, Urban & Transportation Consulting, et al., found that a successful HOT lane should have the following assumptions:

- HOT lanes should be incorporated with HOV lanes that are currently in existence or to be constructed.
- There must be recurring congestion where the HOT lanes could help drivers avoid congestion by paying a toll.
- HOT lanes cannot take away an existing mainlane in order to be created.
- HOT lanes are not self-supporting *(15)*.

The key to successful HOT lanes is to manage the number of vehicles to maximize the use of the HOV lane without exceeding capacity and creating congestion. One way to manage a HOT lane is through the use of dynamic toll pricing. The toll is a variable toll that changes as often as every five minutes, with the price of the toll increasing with the level of congestion. As the toll increases, the number of motorists willing to pay the toll will decrease, thereby managing lane use *(16)*. Concerns regarding HOT lanes include legality, equity, societal issues, and public acceptance *(17, 18)*.

Exclusive Lanes

The operational strategy of exclusive lanes provides certain vehicles, usually designated by vehicle type, an exclusive operational lane. The most common types of vehicles designated for this strategy are buses and large trucks. Buses are often given exclusive lanes to provide an incentive for riders by decreasing delay, whereas trucks are separated in an attempt to decrease the effects of trucks on safety and reduce conflicts by the physical separation of truck traffic from passenger car traffic.

It should be noted that until recently, very few truly exclusive facilities existed, and many of those facilities actually restricted trucks and/or buses to specified lanes and allowed other vehicles to use any lane *(19)*. In recent years, agencies have implemented a number of truly exclusive busways in various metropolitan areas. A busway is a bus-only roadway that is separated from the rest of the traffic. The busway, which acts like a “surface subway,” allows buses to receive traffic signal preference, thus bypassing stoplights, or to cross over intersections on overpasses (*20*). Transportation agencies may consider busways a cost-effective alternative to either subways or light rail and are implementing them in a number of cities. Advantages of busways include flexibility, self-enforcement, incremental development, low construction costs, and implementation speed (*21*).

Although exclusive truck facilities are often discussed as a strategy, a true exclusive truck facility has not been implemented. The type of managed truck lane most often implemented is a restriction as opposed to an exclusive facility. Theoretically, truck facilities could have positive impacts on noise and air pollution, fuel consumption, and other environmental issues. Creating and maintaining an uninterrupted flow condition for diesel-powered trucks will result in a reduction of emissions and fuel consumption when compared to congested, stop-and-go conditions. However, the creation of a truck facility may also shift truck traffic from more congested parallel roadways, thereby shifting the environmental impacts. Non-truck traffic may also increase on automobile lanes due to latent demand. Feasibility studies for exclusive truck lanes have also been conducted in Virginia, California, the United Kingdom, and the Netherlands (*20*).

Separation and Bypass Lanes

The separation or bypass lane is a treatment for a specific section or segment of roadway. Several areas have successfully used this management strategy that often addresses a roadway segment that has the following characteristics: weaving area, a significant grade, high percentage of truck traffic, and/or congestion. Weaving areas are segments of freeway formed when a traffic diverge area closely follows a merge area. Operationally, weaving areas are of concern because the “crossing” of vehicles creates turbulence in the traffic streams. Trucks limit the visibility and maneuverability of smaller vehicles attempting to enter and exit the freeway system. An indication of the barrier effect is an over-involvement of trucks in weaving area crashes, rear-end collisions, and side collisions. Some studies show that this problem may be magnified when a differential speed limit is present (*22*, *23*).

Dual Facilities

Dual facilities are managed lane strategies that have physically separated inner and outer roadways in each direction. The inner roadway is reserved for light vehicles or cars only, while the outer roadway is open to all vehicles. The New Jersey Turnpike has a 35-mile segment that consists of interior (passenger car) lanes and exterior (truck/bus/car) lanes within the same right-of-way. For 23 miles, the interior and exterior roadways have three lanes in each direction. On the 10-mile section that opened in November 1990, the exterior roadway has two lanes, and the interior roadway has three lanes per direction. Each roadway has 12-ft lanes and shoulders, and barriers separate the inner and outer roadways. The mix of automobile traffic is approximately 60 percent on the inner roadways and 40 percent on the outer roadways (*24*).

These facilities, referred to as dual-dual segments, were implemented to relieve congestion. Other truck measures that the New Jersey Turnpike Authority (NJTA) has implemented on the turnpike are lane restrictions and ramp shoulder improvements. The restriction implemented in the 1960s does not allow trucks in the left lane of roadways that have three or more lanes by direction. On the dual-dual portion of the turnpike from Interchange 9 to Interchange 14, buses can use the left lane. The resulting effect is that the left lane becomes a bus lane with the right lane(s) occupied by trucks. The NJTA rates compliance for truck lane restrictions as high (*22*).

Lane Restrictions

Lane restrictions are a management strategy that limits certain types of vehicles to specified lanes. The most common type of lane restriction addresses truck traffic. A large presence of trucks, both in rural and urban areas, can degrade the speed, comfort, and convenience experienced by passenger car drivers. Some states, to minimize these safety and operational effects, have implemented truck lane restrictions or have designated exclusive truck lane facilities.

Agencies must consider a number of operational considerations when implementing this type of managed lane strategy. Engineers design highways for a mix of vehicle types; however, an increased presence of large trucks on a roadway may result in serious degradation of flow quality for the following reasons:

- trucks are significantly heavier than passenger cars,

- trucks are considerably longer than other vehicles, and
- trucks have lower rates of deceleration and acceleration (*25*).

In urban areas, the demand on the highway system has grown much more rapidly than the corresponding increases in available capacity. This increase in demand has led to high levels of congestion and an increased awareness for traffic operations. Correspondingly, studies concerning the effect of trucks on highway operations have also increased (*26*).

RAMP STRATEGIES

The Federal Highway Administration's (FHWA) *Ramp Management and Control Handbook* (*27*) introduces ramp management and identifies ramp closure, ramp metering, special use treatment, and ramp terminal treatments as different forms of ramp management strategies. The handbook, which also discusses facility design, signing, performance evaluation, and institutional issues, found that ramp metering is the most prevalent form of ramp management.

Ramp Metering

Most urban freeways are multilane facilities that carry heavy traffic during peak periods. Ramp meters (also called flow signals) are traffic signals that control traffic at entrances to freeways (*28*, *29*, *30*, *31*). Agencies install ramp meters to address three primary operational objectives (*30*, *31*):

- control the number of vehicles allowed to enter the freeway,
- reduce freeway demand, and
- break up the platoons of vehicles released from an upstream traffic signal.

The purpose of the first two objectives is to ensure that the total traffic entering a freeway section remains below the operational bottleneck capacity of that section. A secondary objective of ramp metering is to introduce controlled delay (cost) to vehicles wishing to enter the freeway and, as a result, reduce the incentive to use the freeway for short trips during rush hour. The purpose of the third objective is to provide a safe merge operation at the freeway entrance.

Traffic demand at a single on-ramp is usually a small component of the total freeway demand. Therefore, metering a single ramp and even a few ramps may not be sufficient to achieve the first objective. In addition, drivers affected by a small ramp metering system perceive such a system to be unduly taxing them, favoring those who have entered the freeway at uncontrolled ramps at upstream freeway sections. Thus, agencies should install ramp metering on a sufficiently wide section of a freeway if it is to achieve all its expected benefits and keep motorists happy.

Ramp Closure

Agencies seldom use ramp closure to provide relief for freeway bottlenecks. Most agencies use this management strategy only under special circumstances. The following paragraphs present two examples of ramp closure from Texas.

As discussed previously, the first example of ramp closure is an on-ramp located in Corpus Christi, Texas, on SH 358, also known as South Padre Island Drive, as shown in Figure 2. Ramp closure significantly reduced accidents on SPID and improved traffic flow. This gate was removed recently because a major construction project is under way to provide a permanent solution to the problem.

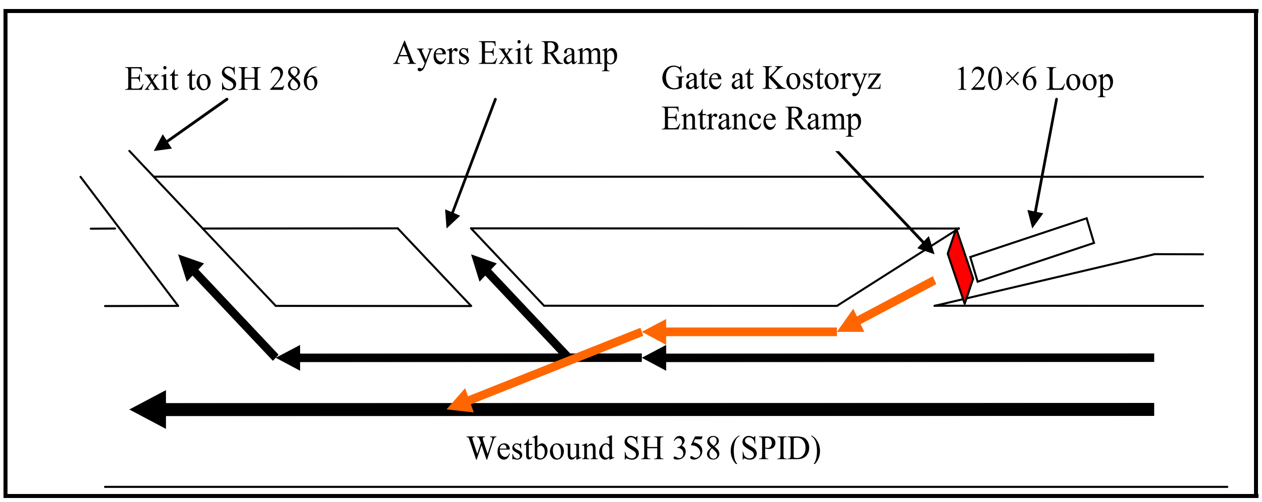


Figure 2. SH 358 Ramp Closure – Corpus Christi, TX.

The second example of ramp closure is in El Paso, Texas, on the Paisano on-ramp on westbound IH-10, as pictured in Figure 3. Vehicles entering the freeway using this ramp during peak traffic conditions experienced merging problems due to congestion on IH-10 within the proximity of the ramp. Although TxDOT considered ramp metering, it later decided to use a ramp closure strategy. TxDOT installed a gate on the ramp several few years ago; however, TxDOT has yet to commence operating the gate pending FHWA approval (which required additional research). This gate can be manually operated from the El Paso traffic management center (TransVista).

Figure 3. IH-10 Ramp Closure – El Paso, TX.

Exclusive Truck Ramps

The use of exclusive truck ramps is a ramp strategy transportation departments and planners are discussing more frequently. Trucks have longer acceleration and deceleration rates than automobiles and require a longer, more gradually sloped ramp than that for a cars-only ramp. Some ramps currently in existence are unsuitable for trucks. One such ramp is the exit 10 ramp on IH-68 in West Virginia. This ramp has a 7 percent grade and is not recommended for most truck traffic. In some instances agencies have provided alternate ramps for trucks. Another area where agencies are considering truck ramps is at freeway-to-freeway interchanges in areas that have grade issues or heavy truck traffic.

One type of truck ramp currently in use is the truck bypass ramp or lane. One example of this type of strategy is IH-405 at the IH-5 interchange in California. This highly congested interchange has a northbound split and a southbound merge. In the 1970s, Caltrans built truck bypass lanes on IH-5 near three high-volume interchanges, including the interchange at IH-405.

The lanes were built to physically separate trucks from other traffic and to facilitate weaving maneuvers in the interchange proper (*24*).

Another truck bypass facility exists on a section of northbound IH-5 near Portland, Oregon, at the Tigard Street interchange; it is similar to some of the California facilities. The bypass lane requires trucks to stay in the right lane, exit onto a truck roadway, and reenter traffic downstream of the interchange. Passenger cars are also allowed to use the bypass facilities. A significant grade on the mainlanes of IH-5 generates the need for this facility. Without the truck roadway, larger vehicles would be forced to climb a grade and then weave across faster-moving traffic that is entering the mainlanes from their right. The resulting speed differentials caused by trucks performing these maneuvers created operational as well as safety problems prior to the implementation of the bypass facility. Truck speeds are now typically 50 mph in the merge area; prior to implementation of the bypass lane, truck speeds were 20 to 25 mph. There were no specific cost data available for construction of the bypass lane (*24*).

CHAPTER 3: LEGISLATIVE ISSUES

In this chapter, the research team provides a brief summary of potential conflicts in the research related to ramp management and pricing. The following sections present details of these conflicts. Upon reviewing the material provided, the program coordinator directed the research team to move forward with scenarios involving exclusive use and pricing as they may provide insight into needed changes in the legislation if they prove effective.

TOLL PROJECTS

Section 201.001(b) of the Transportation Code, which is part of *Chapter 201 - General Provisions and Administration*, defines a toll project as the following:

> ". . . one or more tolled lanes or a highway or an entire toll highway constructed, maintained, or operated as part of the state highway system and any improvement, extension, or expansion to the highway" (*32*).

The subsections following this definition specifically mention ramps as either a component of a toll project or a component of a non-tolled facility that is necessary for the efficient operation and maintenance of a toll project (*33*, *34*). Thus, current Texas law clearly considers ramps as part of an overall toll project.

MANAGED LANES STRATEGIES

The Transportation Code provides definitions of various managed lanes strategies under *Chapter 224 - Acquisition, Construction, and Maintenance*. Under this chapter, exclusive lanes and restricted lanes are specifically noted as allowable congestion mitigation projects and facilities (*35*). Exclusive lanes are defined as a lane or section of a highway which is restricted to use by one or designated motor vehicle classifications (*36*). Restricted lanes are defined as being either a high-occupancy vehicle lane, a toll lane, or an exclusive lane (*37*).

A different section of the Transportation Code (*38*) further discusses HOV lanes and their implementation on Texas roadways, including their use by motorcycles and low-emissions vehicles that do not have the required minimum number of occupants.

A separate section of the Transportation Code describes in more detail exclusive lanes, specifically noting the requirements for their implementation (*39*). The requirements that may potentially impact this research are:

- the requirement that two or more lanes are adjacent to the proposed exclusive lane for use by those vehicles not allowed to use the exclusive lane, or
- the requirement that a multilane facility is adjacent to the proposed exclusive lane for use by those vehicles not allowed to use the exclusive lane.

In addition to these two requirements, an exclusive lane designated by the Texas Transportation Commission should help enhance safety, mobility, or air quality (*40*).

TOLL LANES

The Transportation Code provides the Texas Transportation Commission with the authority to allow TxDOT to charge a toll for the use of one or more lanes of a state highway, including an HOV lane or an exclusive lane as defined previously (*41*). Specific restrictions on charging tolls on specific lanes govern how TxDOT implements this law. For example, TxDOT may not charge a toll for the use of an exclusive lane unless if: (1) the lanes or multilane facility adjacent to the exclusive lane (as required in the exclusive lane section noted above) is tolled, or (2) a vehicle authorized to use the tolled exclusive lane is also authorized to use the non-tolled adjacent lanes or multilane facility (*42*).

Further restrictions are in place regarding the use of toll lanes, as outlined in a separate section. Specifically, TxDOT may not operate a non-tolled state highway or a segment of a non-tolled state highway as a toll project unless it meets one of several factors. These factors are as follows:

- the facility was designated a toll project before the contract to construct was awarded;
- the facility was open to traffic as a turnpike project on or before 1 September 2005;
- the facility was designated a toll project in a metropolitan planning organization (MPO) plan or program on or before 1 September 2005;
- the facility when reconstructed will have an equal or greater number of non-tolled lanes as it did prior to reconstruction;

- a facility is built adjacent to the tolled facility such that the combined number of non-tolled lanes on both facilities is equal to or greater than the number of non-tolled lanes prior to construction;
- the facility was open as an HOV lane on 1 May 2005; or
- the Texas Transportation Commission converts a facility to a toll facility through a three-step process if it determines that the conversion will improve mobility or is the most feasible and economic means to accomplish necessary expansion, improvements, or extensions to that portion of the state highway system (*43*, *44*).

Furthermore, the current law also states that an HOV lane may be operated as a tolled lane only if the operating entity allows vehicles with the specified minimum number of occupants to use the lane without paying the toll (*45*).

POTENTIAL CONFLICTS OF RESEARCH

Essentially, the research in this project investigated the potential for applying restrictions to ramp usage, potentially creating conflicts with existing Texas laws. Two potential conflicts were with the exclusive use of a ramp or the pricing of a ramp. It is unclear whether the designation of a ramp for HOV use only would create a potential conflict. The following sections briefly describe the potential conflicts of the research. The program coordinator, project director, and the Project Monitoring Committee directed the research team to move forward with the research despite any potential conflicts discussed in the following sections which may arise with managed ramp applications in the future.

Exclusive Use

The question arises as to whether a ramp designated as an exclusive ramp for use by designated vehicle classifications qualifies as an exclusive lane as defined in the Transportation Code (discussed previously in this chapter). Some operational scenarios consider the exclusive use of a ramp by a designated vehicle class, such as all cars or all trucks. If this designation constitutes an exclusive use, then the requirements for adjacent lanes or an adjacent facility for the non-restricted vehicles may become an issue for implementation. The legislation needs to clarify whether the frontage road and unrestricted ramps upstream and downstream of the exclusive ramp would satisfy the requirements of the law.

Pricing

Several of the operational scenarios assess the feasibility of using pricing to manage ramp access. If the pricing of an existing ramp to a non-tolled facility constitutes a tolled lane, then the restrictions on toll lane implementation, specifically as it relates to existing capacity, may have implications on the research. However, it is evident that a newly constructed ramp that is priced would be allowed under the law.

CHAPTER 4: OPERATIONAL STRATEGY SELECTION

The research team recently completed a thorough investigation of the potential operational strategies that could prove beneficial to ramp management. The following sections include a summary of the process the project team used to conduct the review of candidate strategies and the resulting strategies selected for modeling.

MANAGED LANES GOALS

The research team first identified potential goals for managed lanes operational strategies in an effort to select appropriate goals for ramp management. Primarily, the overall goals for the implementation of managed lanes can be divided into five distinct categories: mobility, safety, community, financial, and homeland security. TxDOT uses managed lanes to improve the overall quality of life for transportation system users and to ensure the long-term viability of the community. The following sections provide a description and rationale behind these categories.

Mobility

Mobility goals of managed lanes focus upon such wide topics as demand and accessibility. The strategies deployed under this goal aim to improve the mobility of the facility or the entire transportation system in the region.

Safety

Safety goals are designed to reduce the frequency and severity of collisions and conflicts between users and vehicles on a particular facility or along a corridor. No managed lanes implementation should compromise the safety of a facility experienced under previous operations.

Community

Community goals are generally those goals which aim to help maintain or improve the economic sustainability and viability and quality of life of a local community based on the interests of its constituents.

Financial

Financial goals, much like their name implies, are those that aim to address the financial realities of infrastructure expansion with limited funding, and the financing methods by which an agency pursues the development of projects.

Homeland Security

Homeland security goals aim to develop a transportation system that can effectively and efficiently support emergency operations in the event of natural disasters or homeland security related incidents.

Table 1 below highlights the different mobility, safety, community, financial, and homeland security goals that may be associated with managed lanes operational strategies. The research team reviewed these goals and determined that while these goals are associated with managed lanes facilities on major freeways, they also apply to managed lanes strategies applied to freeway ramps for the purpose of ramp management. For example, managing ramps using alternative strategies can enhance *mobility* by providing congestion relief and improving accessibility at either point locations or along an entire corridor. They can modify travel demand and may enhance alternative modes depending on the implemented strategy. Furthermore, they may enhance *safety* by reducing congestion along a corridor and/or at ramp locations where weaving increases the potential for incidents.

Applying managed lanes strategies to ramps could meet *community* goals by reducing the environmental impacts of congestion. If pricing is applied to ramp management, then it may help meet the *financial* goals of the region by generating revenue to help improve the benefit-cost ratio of a project. Finally, ramp management implementation can support *homeland security* goals if agencies apply specific strategies during incidents to support emergency management and/or disaster management operations.

Table 1. Possible Managed Lanes Goals (Adapted from *46*).

Goal Category	Possible Managed Lanes Goals
Mobility Goals	• Provide a transportation system that can handle current and future demand • Increase mobility and accessibility by offering travel options • Provide additional facility capacity • Optimize existing managed lanes capacity • Provide congestion relief • Modify travel demand • Enhance alternative modes • Improve accessibility
Safety Goals	• Improve the safety of corridor travel • Maintain the level of safety on a facility
Community Goals	• Minimize environmental impacts • Preserve neighborhoods • Maintain an urban form • Maintain land use patterns
Financial Goals	• Develop financially self-sustaining transportation improvements • Maximize the benefit-cost ratio of infrastructure investment
Homeland Security Goals	• Enhance and support emergency management operations • Enhance and support disaster management operations

CANDIDATE MANAGED LANES STRATEGIES, RELATED GOALS, AND OBJECTIVES

A variety of managed lanes operational strategies exist that have the potential to meet the aforementioned goals. As described in Table 2, these operational options are categorized by lane management strategy or a combination of multiple lane management strategies. The research team assessed these strategies and determined that all of them have potential application to ramps and ramp management. However, the overall effectiveness of these strategies may vary depending on a number of factors. These factors may include, but are not limited to,

- the existing conditions of the general-purpose lanes,
- the specific problems and issues impacting performance at ramp locations,
- the willingness of travelers to accept managed ramps,
- the preexistence of managed lanes in the region, and
- the overall goals and objectives of TxDOT and partner agencies regarding mobility, congestion, and transportation project finance.

Table 2. Managed Lanes Strategies (Adapted from *46*).

Lane Management Strategy	Example Managed Lanes Strategy	Description
Pricing (P) Refers to management that uses prices to regulate demand.	Value-Priced Express Toll Lanes	Separated lanes with limited access where all vehicles pay a toll that is set at a variable rate to achieve specific operating objectives (e.g., higher travel speeds than non-toll lanes).
	Express Toll Lanes Non-Value-Priced	Separated lanes with limited access where all vehicles pay a fixed toll.
Vehicle Eligibility (V) Refers to management based on vehicle type or user group.	High-Occupancy Vehicle Lanes	Lanes that only allow vehicles that meet or exceed a required number of occupants.
	Truck-Restricted Lanes	Lanes of the roadway in which large trucks are restricted.
Access Control (A) Limited or controlled access allows management of the flow and throughput of traffic on a facility.	Express Lanes (non-tolled)	Separated lanes with limited access and no toll charged.
Pricing + Vehicle Eligibility (P + E)	High-Occupancy Toll Lanes	HOV lanes that allow vehicles that do not meet the occupancy requirement to use the lanes for a fee or toll.
Vehicle Eligibility + Access Control (V + A)	Exclusive Transitways	Lanes or roadways that exclusively serve buses.
	Exclusive or Dedicated Truck Lanes	Dedicated lanes in which only large trucks are permitted.
Pricing + Vehicle Eligibility + Access Control (P + V + A)	Multifaceted Managed Lanes Facilities	Multiple lane management strategies are used in various combinations to actively manage demand.

After agreeing that these strategies have potential for ramp applications, the research team then assessed the goals and objectives for the previously described lane management strategies. As illustrated in Table 3, each lane management strategy category can meet many of the goals listed in Table 1. How these strategies meet the goals depends on the same factors noted previously.

For this task, the research team assessed these goals as they might apply to ramps and ramp management. As with the overall goals, the researchers determined that the same goals and related objectives that generally apply to managed lanes strategies could also apply to strategies for managing ramps. Furthermore, the application of managed lane strategies at ramps can help address operational problems at a specific location or can be applied at a series of ramps to achieve corridor level benefits. Once again, the potential for meeting these goals lies with the specific lane management strategy implemented at either isolated ramps or along an entire corridor.

Table 3. Lane Management Strategies and Goals (Adapted from *47*).

Lane Management Strategy	Typical Managed Lanes Goals															
	Provide a Transportation System that Can Handle Current and Future Demand	Increase Mobility and Accessibility by Offering Travel Options	Provide Additional Facility Capacity	Optimize Existing Managed Lanes Capacity	Improve Congested Roadways	Modify Travel Demand	Enhance Alternative Modes	Improve Accessibility	Improve the Safety of Corridor Travel	Maintain Level of Safety on a Facility	Minimize Environmental Impacts	Preserve Neighborhoods	Maintain Land Use Patterns	Develop Transportation Improvements That are Financially Self-Sustaining	Maximize the Benefit-Cost Ratio of Infrastructure Investment	Enhance and Support Emergency and Disaster Management Operations
P	▲	▲	▲	▲	▲	▲	▲			▲	▲			▲	▲	▲
V	▲	▲	▲	▲	▲	▲	▲		▲	▲	▲	▲	▲			▲
A	▲	▲	▲	▲	▲	▲	▲			▲	▲					▲
P + V	▲	▲	▲	▲	▲		▲			▲	▲	▲	▲	▲	▲	▲
V + A	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲			▲
P + V + A	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲

Additionally, the research team established ramp-related objectives that fit within the five categories. These objectives are provided in Table 4. The applications of the various lane management strategies to ramps can meet both the goals in the previous table as well as the ramp-specific goals. The team used these goals to assess the candidate strategies for ramp application to ensure that any unique ramp-related issues are addressed with selected operational options.

Table 4. Possible Managed Ramp Goals.

Goal Category	Possible Managed Ramp Goals
Operational / Mobility Goals	• Prevent freeway from breaking down in bottleneck location • Provide priority access to special class of user to general-purpose facility • Overcome geometry deficiency to particular class of vehicles • Overcome ramp storage problems • Provide priority access to special class of user destined for managed lanes facility • Promote "balanced" flow in corridor • Enhance and support incident management • Delay the onset of congestion on the freeway corridor
Safety Goals	• Reduce vehicle crashes in merge and weaving areas • Reduce vehicle conflicts in merge and weaving areas • Channelize vehicles with different operating characteristics ramps that can better support vehicle operating characteristics • Reduce the potential for rear-end collisions at ramps where congestion frequently occurs
Community Goals	• Balance perception of penalizing short vs. long trips • Promote the use or discourage the use of certain facilities, ramps, or adjacent roadway(s) by certain vehicle users (i.e., trucks) • Serve as an alternative to installing ramp meter signals at a specific location • Enhance TxDOT's ability to operate the corridor in an integrated fashion with other transportation providers in the community
Financial Goals	• Generate revenue for particular ramp or facility • Delay the need to widen a freeway facility by maximizing the use of all the available capacity in the corridor through better operations
Homeland Security Goals	• Enhance and support emergency management operations • Ensure access to a managed lane facility to aid in the rapid deployment of emergency vehicle and disaster relief resources during an emergency event

Agencies can link candidate managed lanes strategies to specific objectives they desire to achieve. These goals and objectives can help a transportation agency clearly identify which managed lanes operational strategies best suit the region. Table 5 presents managed lanes strategies and the related typical objectives they work to achieve. These relationships among the strategies, goals, and objectives are based on surveys of practitioners and experts *(46)*.

The research team evaluated these objectives and again determined that they are applicable to ramp management, though their impact depends upon the specific strategy implemented.

Table 5. Lane Management Strategies and Objectives (Adapted from *47*).

Lane Management Strategy	Typical Managed Lanes Objectives																				
	Increase Vehicle-Carrying Capacity	Increase Person-Carrying Capacity	Increase Goods-Carrying Capacity	Maintain Free Flow Speed	Maintain or Improve Level of Service	Reduce Travel Time	Increase Trip Reliability	Provide Travel Alternatives	Reduce Peak Period Vehicle Trips	Improve Express Bus Service	Provide Transmodal Connectivity and Accessibility	Minimize Traffic Crashes Involving Large Trucks	Minimize Traffic Crashes	Improve Air Quality from Mobile Sources	Address Environmental Justice Concerns	Encourage Transit Oriented Development	Fund New Transit and Managed Lanes Improvements	Produce Enough Revenue to Cover Operations/Maintenance and Enforcement	Produce Enough Revenue to Cover Debt Service	Private Investment Profit	Provide Connectivity to Critical Regions of the Community
P	•			•		•	•	•					•				•	•	•	•	•
V	•	•		•	•	•	•	•	•	•		•	•	•	•	•					•
A	•					•		•					•								•
P + V	•	•		•		•				•			•	•	•	•	•	•	•	•	•
V + A	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•					•
P + V + A	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

SELECTED MANAGEMENT STRATEGIES FOR EVALUATION

After careful consideration of the possible goals and objectives associated with applying managed lanes strategies to ramps, the research team identified four operational scenarios that have the most potential to meet various needs of TxDOT districts across the state. The following sections describe these scenarios.

Flow Balance Scenario

This scenario assesses the implementation of managed ramps to balance flow on a facility so that the general-purpose lanes can absorb a smaller amount of flow. The goal of this scenario is to assess if TxDOT could replace the need for implementing ramp metering by 1) restricting access at a ramp to specific user classes; 2) restricting certain user classes from using a ramp; or 3) encouraging enough diversion of demand by employing managed strategies, such as HOT lanes. The research team first assessed how much traffic would need to be diverted from one or more ramps. The team then assessed how they could accomplish that diversion with different managed lanes strategies, both from an isolated ramp perspective and from a system perspective.

Incident/Special Management Scenario

This scenario assesses the implementation of managed ramps to support incident management on a freeway facility, an alternative to closing a ramp to all traffic. The goal of this scenario is to look at providing preferential treatment to user classes both upstream and downstream of an incident. Upstream of an incident, the objective may be to apply managed ramp strategies to keep an incident bottleneck from becoming oversaturated. Downstream of an incident, the objective may be to apply managed ramp strategies to provide preferential treatment to special user classes in returning to the freeway facility, particularly under an incident scenario where the entire facility is closed. This scenario may also be applied to special event management in which access to a freeway facility is managed via managed ramps in and around a special event facility.

Managed Lanes Facility Preference Scenario

This scenario assesses the application of managed ramps to support effective access to managed lanes facilities. The goal of this scenario is to provide priority access at general-purpose ramps to users destined for downstream access points to managed lanes facilities that operate within the corridor. The intent is to identify appropriate ramps within a corridor that provide optimum weaving distances for managed lanes users and manage their entry to optimize access to the managed lanes facilities.

Ramp Safety Scenario

This scenario assesses the implementation of managed ramps to address safety-related issues associated with a ramp. Because of poor geometrics, a ramp may experience a high number of accidents or conflicts. This scenario assesses whether the application of a managed lane strategy to a ramp can improve safety at that ramp. For example, one application may be the restriction of trucks during certain times of the day because of limited sight distance, short acceleration lanes, grades on ramps, and/or short weaving distances.

CHAPTER 5: MODELING MANAGED RAMPS

MODELING MANAGED RAMPS IN SUPPORT OF FLOW BALANCE

Ramp meters are one of the tools in the traffic engineer's toolbox for reducing congestion and improving safety on urban freeways. Past research and evaluations have shown the benefits of ramp meters to be as follows:

- improves system operation by increased vehicle throughput, increased vehicle speeds, and improved utilization of the existing capacity on the freeway;
- reduces the number of crashes and the crash rate in the merge area and on the freeway upstream of the ramp/freeway merge zone;
- reduces environmental effects caused by congestion through reduced vehicle emissions and reduced fuel consumption; and
- promotes multi-modal operation.

Table 6 shows some of the measured benefits from variation ramp meter deployment in the United States.

Table 6. Measured Benefits of Ramp Meter Deployments in the United States (from *27*).

Measure	Location	Benefits
Safety	Minneapolis, MN	26% reduction in peak period collisions and 38% decrease in peak period collision rate.
	Seattle, WA	34% decrease in collision rate.
	Denver, CO	50% reduction in rear-end and side swipe collisions.
	Detroit, MI	50% reduction in total collisions, 71% reduction in injury collisions.
	Portland, OR	43% reduction in peak period collisions.
	Long Island, NY	15% reduction in collision rate.
Travel Time and Speed	Long Island, NY	9% increase in average vehicle speed
	Portland, OR	26 to 66 km/h increase in vehicle speeds (16 to 41 mph).
	Denver, CO	69 to 80 km/h improvement in average vehicle speeds (43 to 50 mph).
	Seattle, WA	Decrease in average travel time from 22 to 11.5 minutes.
	Minneapolis, MN	64 to 69 km/h improvement in average peak-hour speeds (40 to 43 mph)
Throughput	Minneapolis, MN	25% increase in peak volume.
	Seattle, WA	74% increase in peak volume
	Denver, CO	18% increase in peak volume.
	Long Island, NY	2% increase in throughput.
Environmental	Minneapolis, MN	2% to 55% reduction in fuel consumption. Savings of 1160 tons of emissions.

While the ramp metering can generate significant benefits, potential negative impacts do exist with ramp meters. First, ramp meters have the potential to divert traffic away from the freeway as motorists, especially those making short trips, bypass queues that form at the ramp meter. If the potential adjacent street network cannot support the diverted traffic, operations on nearby arterials can be negatively affected. Second, a question concerning equity may also exist with ramp meters. Some individuals argue that ramp meters favor suburban motorists who make longer trip versus those that live in the immediate areas around the ramp meter. They argue that those who live in locations where the ramps are not metered are not delayed as much when they enter the freeway than those who have to access the freeway at the ramp meter. Finally, opponents of ramp meters often cite that ramp meters merely shift traffic congestion (and its associated impacts) from one location to another. Queues for improperly operated ramp meters have the potential to back up through an adjacent arterial intersection, thereby, causing specific approaches or movement to become congested. Because of these perceived disbenefits, some practitioners in Texas are hesitant to deploy ramp meters where needed.

TxDOT defines a managed lane facility as "one that increases freeway efficiency by packaging various operational and design actions"(*48*). This definition is purposely broad so as to allow practitioners the flexibility they need to determine what a "managed lane" means for their communications (*48*). Examples of different types of operational strategies that are commonly deployed in managed lane applications in Texas include the following:

- Restricting the use of a freeway lane to vehicles which contain a specified number of occupants. This strategy is commonly referred to as a high-occupancy vehicle lane.
- Requiring a vehicle to pay a toll for the use of a particular lane or facility. The rate of the toll may depend upon the time of day or the number of occupants in the vehicle. These types of managed lane facilities are called high-occupancy toll lanes or value-priced lanes.
- Providing an exclusive lane or facility for use by a designated vehicle class, such as a bus or large trunk.
- Providing a bypass or separate lane on a facility for a particular class of vehicle, such as a high-occupancy vehicle or a truck.
- Limiting or closing a facility to all vehicles entirely or some specific class of vehicle.

While traditionally these strategies have been deployed to the mainlanes of a freeway facility, an agency may elect to deploy one or more of the above listed strategies to a ramp (1) as an alternative to installing a ramp meter and/or (2) for the expressed purposes of improving operations on the mainlanes. For example, instead of installing a ramp meter, an agency may elect to restrict the use of a particular ramp to high-occupancy vehicles or convert a ramp into a value-priced lane. Likewise, an agency may want to consider charging a toll on a vehicle for using a particular ramp during certain periods of the day to reduce demand on the ramp to avoid the political hassle of installing a ramp metering system. Finally, an agency may be more willing to restrict or limit the use to a specified vehicle class instead of installing a ramp meter. Regardless of the type of managed lane strategy deployed at a ramp in place of a ramp meter, one question that applies equally for all strategies is as follows:

> *How much traffic must be diverted away from the ramp by a managed lane strategy to achieve the same level of operation on the freeway if a ramp meter was used at the same ramp?*

To address this question, we devised a series of simulation experiments that compared the performance of the section of freeway with and without a ramp meter active at an entrance ramp in the corridor. The experiments focused on specifically quantifying how much traffic needed to be diverted from the ramp at different freeway and ramp volume conditions and ramp geometries (specifically the length of the ramp acceleration lane) to achieve the same level of performance on the freeway if the ramp was controlled by a ramp meter. For the purposes of this project, we did not attempt to quantify how effective any one particular managed lane technique was at diverting traffic. For the purposes of this study, we assumed that a signal managed lane strategy (or combination of strategies) could be deployed at a ramp to achieve the required amount of diversion.

Simulation Scenarios

Freeway/Ramp Configurations

For the purpose of this simulation scenario, we used the hypothetical freeway/ramp configuration shown in Figure 4. We used a simulation network consisting of a two-lane section of frontage road connected to a two-lane section of freeway by a single-lane entrance ramp 1000 ft in length with a merge area of 1500 ft on the freeway. To ensure that we adequately captured the effects of queues that formed on the freeway approach lanes and to ensure adequate storage for entering demands, we used long approach links upstream of the entrance ramp on both the freeway (48,000 ft) and the frontage road (10,400 ft). Likewise, to ensure that the freeway traffic had adequate time to recover after clearing the merge area around the ramp, the link downstream of the merge area was 4500 ft. We examined only one direction of travel in each simulation scenario.

One of the factors that we varied in our experimental design was the length of the acceleration lane for the ramp. As shown in Figure 5, we examined the operations on the freeway, with and without ramp metering, using five different acceleration lane lengths.

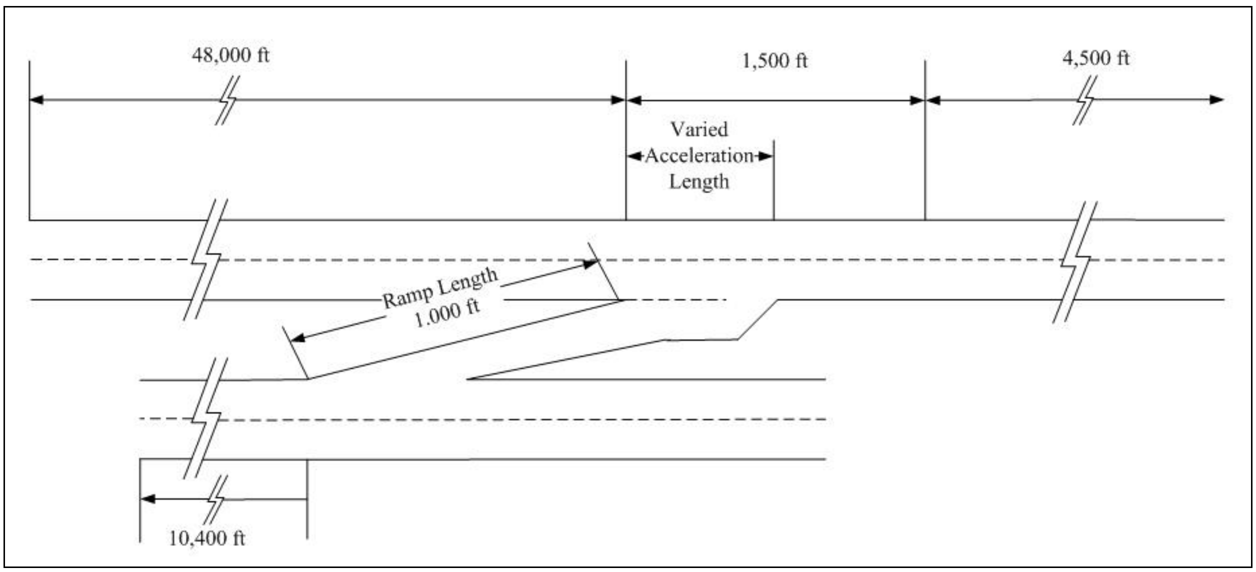


Figure 4. Basic Freeway/Ramp Configuration Used in VISSIM Simulation.

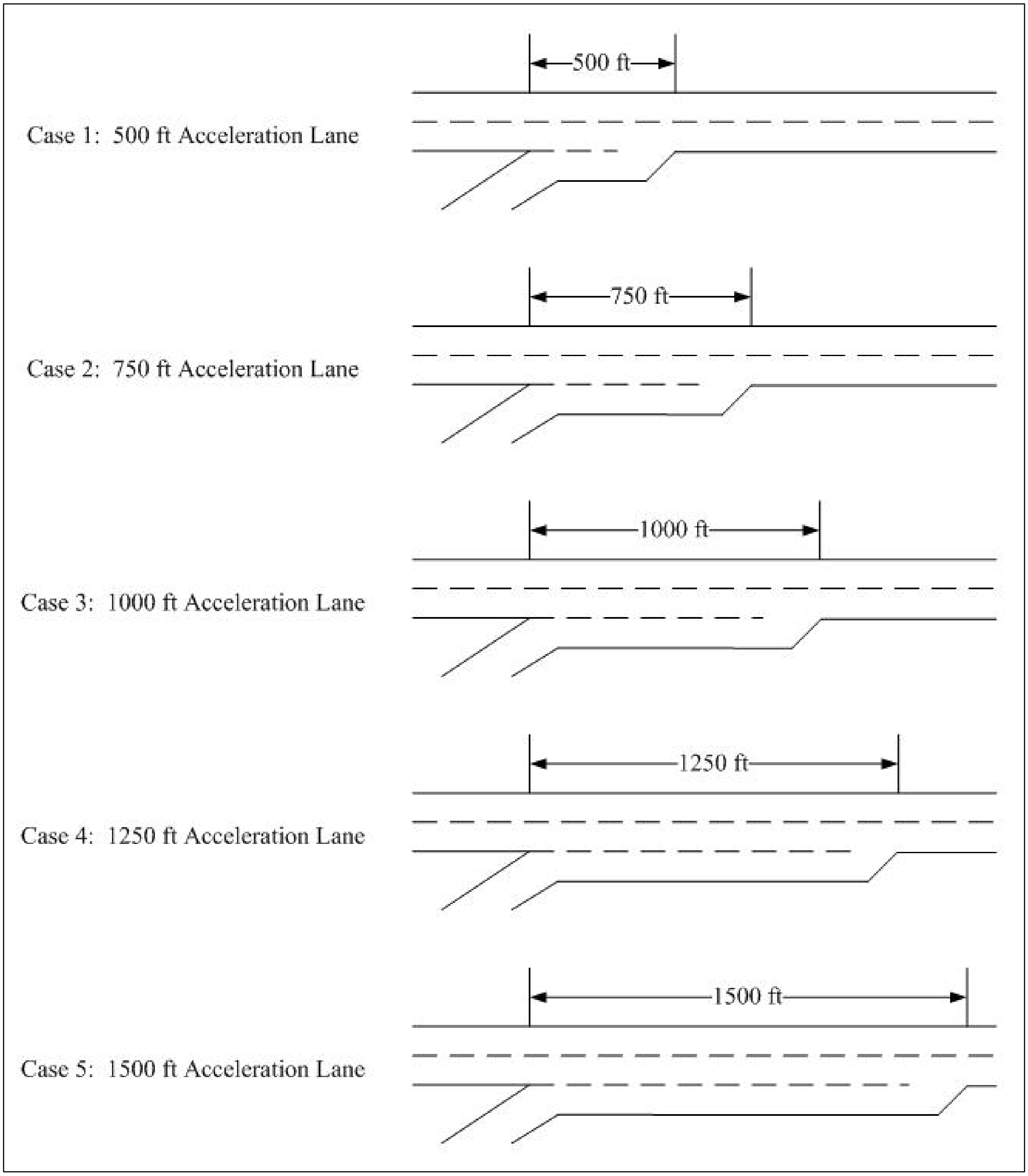


Figure 5. Different Acceleration Ramp Lengths Evaluated in Simulation Experiments.

Traffic Demands

Ramp metering is generally a strategy that is employed when traffic demands on the freeway are beginning to approach capacity. If ramp metering is employed when freeway volumes are relatively light, ramp delays will become excessive and drivers will become frustrated waiting at the ramp meter for no apparent purpose or benefit. Likewise, if too much demand exists on the freeway, not enough adequate gaps exist in the freeway traffic stream to “absorb” traffic that is entering from the ramp. When this occurs, traffic entering the ramp stops in the merge area to wait from a gap that is big enough to merge into the freeway lane or, if the driver is aggressive enough, will create their own gap in the freeway traffic stream by forcing their way onto the freeway. Therefore, the relative window where ramp metering provides the maximum benefit is relatively small and is when traffic demand on the freeway is approaching, but not exceeding, capacity.

As such, we designed our simulation experiments to consider traffic demands to be at or near capacity. For the purposes of our experiments, we assumed a theoretical capacity for a single freeway lane to be 2400 passenger cars per hour per lane (pcphpl), which we have used as the maximum demand level for our simulation experiments. For the purpose of our simulation experiments, we varied the freeway demand levels from 1500 pcphpl to 2400 pcphpl in 100 pcphpl increments. A total of 10 freeway demand levels were used in these experiments.

In addition to varying the freeway demand level, we also varied the ramp demand levels. For each freeway demand level, we conducted simulation runs using 10 different ramp demand levels, ranging from 0 pcphpl to 900 pcphpl (the maximum amount supported by a single-lane, single-vehicle ramp meter). Ramp demand levels of more than 900 pcphpl where NOT evaluated as part of these experiments, as 900 pcphpl represents the maximum number of vehicles that can be supported by a single-lane, single-vehicle ramp metering strategies. Generally, ramp demands greater than 900 pcphpl require either dual lane metering or bulk meter to accommodate the total demand without excessive queues building on the ramp. Table 7 shows the freeway demand levels that we examined at each ramp configuration, while Table 8 shows the ramp demand levels that were examined at each freeway volume level.

For the purposes of these experiments, we assumed a 90/10 vehicle mix: 90 percent passenger vehicles, 5 percent buses, and 5 percent heavy vehicles (i.e., trucks). The distribution of vehicle types that we used in the simulation is shown in Table 9, while Table 10 shows the operating characteristics of the vehicles used in the simulation.

Table 7. Freeway Demand Levels Evaluated in Simulation.

Freeway Demand Level	Desired Passenger Car Equivalent Per Lane Volume	Simulation Input Volume
1	**1500 pcphpl**	**2727 vph**
2	**1600 pcphpl**	**2909 vph**
3	**1700 pcphpl**	**3091 vph**
4	**1800 pcphpl**	**3272 vph**
5	**1900 pcphpl**	**3455 vph**
6	**2000 pcphpl**	**3636 vph**
7	**2100 pcphpl**	**3818 vph**
8	**2200 pcphpl**	**4000 vph**
9	**2300 pcphpl**	**4182 vph**
10	**2400 pcphpl**	**4364 vph**

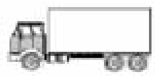
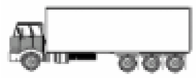
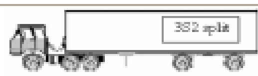
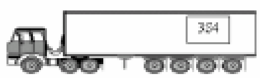
Table 8. Ramp Demand Levels Evaluated in Simulation.

Ramp Demand Level	Desired Passenger Car Equivalent Ramp Demand	Simulation Input Volume
1	**0 pcph**	**0 vph**
2	**100 pcph**	**91 vph**
3	**200 pcph**	**182 vph**
4	**300 pcph**	**273 vph**
5	**400 pcph**	**364 vph**
6	**500 pcph**	**455 vph**
7	**600 pcph**	**545 vph**
8	**700 pcph**	**636 vph**
9	**800 pcph**	**727 vph**
10	**900 pcph**	**818 vph**

Table 9. Distribution of Vehicle Types Used in Simulation.

Vehicle Type	Relative Flow (%)	Length (ft)	Width (ft)	Weight (lb)		Power (hp)	
				Min.	Max.	Min.	Max.
Truck Class 6	**0.41**	**23.58 to 37.58**	**8.5**	**15,000**	**46,000**	**220**	**300**
Truck Class 7	**0.045**	**21.17**	**8.5**	**25,000**	**52,000**	**250**	**300**
Truck Class 8	**0.10**	**41.50 to 65.50**	**8.5**	**28,000**	**66,000**	**315**	**380**
Truck Class 9	**4.175**	**62.42 to 67.42**	**8.5**	**30,000**	**80,000**	**380**	**480**
Truck Class 10	**0.03**	**68.25**	**8.5**	**32,000**	**87,000**	**415**	**490**
Truck Class 11	**0.195**	**72.33**	**8.5**	**35,000**	**92,000**	**440**	**500**
Truck Class 12	**0.045**	**76.58**	**8.5**	**35,000**	**106,000**	**505**	**525**
Car	**90.00**	**13.48 to 15.62**	**4.92**	**NA**	**NA**	**NA**	**NA**
Bus	**5.00**	**37.87**	**8.2**	**NA**	**NA**	**NA**	**NA**

Table 10. Operating Characteristics of Vehicles Used in Simulation.

Vehicle Type*	Typical Vehicle Type	Share	Length (ft)	Shaft Length (ft)	Front Clutch (ft)	Front Axle (ft)	Rear Axle (ft)	Rear Clutch (ft)
6		**0.33**	**23.58**	**0.00**	**0.00**	**3.08**	**17.87**	**23.58**
		0.33	**29.58**	**0.00**	**0.00**	**3.08**	**21.42**	**29.58**
		0.33	**37.58**	**0.00**	**0.00**	**3.08**	**26.42**	**37.58**
7		**1.0**	**21.17**	**0.00**	**0.00**	**4.04**	**17.50**	**17.50**
8		**0.33**	**17.83** **28.50**	**0.00** **0.00**	**0.00** **2.50**	**3.00** **25.50**	**15.50** **25.50**	**15.50** **28.50**
		**0.33**	**17.83** **53.00**	**0.00** **0.00**	**0.00** **3.00**	**3.00** **46.50**	**15.50** **46.50**	**15.50** **53.00**
		**0.33**	**21.17** **28.50**	**0.00** **0.00**	**0.00** **2.50**	**4.00** **25.50**	**17.42** **25.50**	**17.52** **28.50**
9		**0.80**	**21.17** **53.00**	**0.00** **0.00**	**0.00** **3.00**	**4.00** **46.50**	**17.42** **46.50**	**17.42** **53.00**
		**0.20**	**21.17** **48.00**	**0.00** **0.00**	**0.00** **3.00**	**4.00** **43.50**	**17.42** **43.50**	**17.42** **48.00**
10	 	**1.0**	**22.33** **53.00**	**0.00** **0.00**	**0.00** **3.00**	**2.50** **46.50**	**18.25** **46.50**	**18.25** **53.00**
11		**1.0**	**15.66** **28.50** **28.50**	**0.00** **0.00** **7.00**	**0.00** **2.50** **2.50**	**2.33** **25.5** **2.50**	**13.33** **25.50** **25.50**	**13.33** **28.50** **28.50**
12	 	**1.0**	**21.06** **28.50** **28.50**	**0.00** **0.00** **7.00**	**0.00** **2.50** **2.50**	**4.17** **25.50** **2.50**	**17.58** **25.50** **25.50**	**17.58** **28.50** **28.50**
Car	**NA**	**0.26**	**13.48**	**0.00**	**0.00**	**2.79**	**10.95**	**13.21**
		0.02	**14.24**	**0.00**	**0.00**	**2.86**	**10.54**	**14.24**
		0.18	**14.44**	**0.00**	**0.00**	**2.62**	**10.82**	**14.44**
		0.18	**14.93**	**0.00**	**0.00**	**2.65**	**11.46**	**14.93**
		0.18	**15.12**	**0.00**	**0.00**	**3.07**	**12.12**	**15.09**
		0.18	**15.62**	**0.00**	**0.00**	**2.99**	**12.12**	**15.46**
Bus	**NA**	**1.0**	**37.87**	**0.00**	**0.08**	**8.42**	**27.71**	**36.95**

*** Based on FWHA Truck Classification Scheme**

Ramp Operations

Each acceleration length/freeway demand/ramp demand level was evaluated both with and without a ramp meter in operation in the ramp. To simulate the operations of the ramp meter, we developed a VISSIM® Vehicle Actuated Programming (VAP) application that imitates the operations of a pre-timed ramp meter. The stop line to the ramp meter was located 600 ft from the mouth of the entrance ramp from the frontage road. For the purposes of this simulation experiment, the ramp meter was set to operate with a 2-second green indication followed by a 2-second red indication. This equates to a metering rate of 900 vehicles per hour (vph). The same metering rate was used at all traffic demand scenarios and ramp configurations. We used this metering rate because we believed that it represented the "worst case" scenario for operations on the freeway (i.e., allowing vehicles to enter the freeway at the fastest rate possible by a single-lane ramp meter). Only one vehicle per green indication was allowed to enter the freeway when the ramp meter was in operation.

To simulate ramp operations without the meter in operation, instead of removing the ramp meter, we simply turned the ramp meter to green (or "on") and did not allow it to cycle for the entire duration of the simulation. This allowed traffic entering the freeway to proceed immediately through the ramp meter without being delayed by the ramp meter. We deemed the performance of the ramp to be equivalent of no ramp meter.

Performance Measures

The primary measure of performance that we used in this study was average running speed. Running speed is the speed computed as the length of the highway section divided by the running time required for the vehicle to travel through a section. The American Association of State Transportation and Highway Officials (AASTHO) indicates that the average running speed is the most appropriate speed measure for evaluating a level of service and operations.

To compute the average running speed, we established a segment of the freeway over which to collect travel time measures. The total length of the travel time segment was 52,787.5 ft (or approximately 10 miles). We set a long length of the travel time segment because our initial investigation showed a queue extending approximately 9 miles upstream of the entrance ramp during some combination of ramp and freeway demand level. We set VISSIM to record the average travel time every 60 seconds during the data collection period. We averaged the 60-second travel time measures for the total duration of the data collection window, which was 5400 seconds (or 90 minutes).

In addition to average running speed, we also used throughput as a secondary measure of effectiveness. Throughput was defined as the total amount of traffic passing through the section of the freeway downstream of the merge area of the ramp. We determined the throughput by installing data collection points in each lane of the freeway on the link downstream of the ramp merge area. We configured the data collection points to count the number of vehicles traversing the point every 60 seconds. We computed the throughput by summing all the 60-second vehicle counts in each lane for the entire data collection window.

Data Collection

We performed a total of five replications of each simulation run at each freeway and ramp demand level under each ramp design configuration. We used different random seed values to start each freeway/ramp demand and ramp design configuration; however, we used the same random seed to evaluate the operations of the freeway with and without the ramp meter in operation. This allowed us to use a paired-T statistical test to compare the effects of the combination of freeway/ramp demand level for each ramp configuration, with and without the ramp meter in operation, on overall freeway performance.

We performed a total of 5000 simulation runs during this study (10 freeway demand levels × 10 ramp demand levels × 5 ramp acceleration lane lengths × 2 ramp meter conditions × 5 replications). Each simulation run lasted a total of 6800 seconds. The first 900 seconds (15 minutes) of the simulation was used as an initialization period to allow traffic demands where traffic was allowed to enter freeway and ramp area at its full rate. During the initialization period, we did not collect any performance measures. After the initialization period, we collected performance statistics for a total of 5400 seconds (or 90 minutes). During the last 500 seconds of the simulation, we altered to the freeway and ramp demands to very low levels (500 vph on the freeway and 100 vph on the ramp) to allow queues to flush through the system before beginning the next data collection run.

Results

Running Speed

Tables 11 through 15 show the average running speed of traffic on the mainlanes of the freeway for the travel time segment, both with and without the meter signal active on the ramp. The average running speed represents the average of all vehicles traversing the freeway link during the data collection window for all five replications. We also graphed the average running speeds as a function of the ramp and freeway demand levels, both with and without the ramp meter being active and for each acceleration lane length. These graphs are contained in Appendix A.

Tables 16 through 20 show the difference in the average running speed of the mainlane traffic with and without a meter controlling traffic entering the freeway from the ramp. A negative value implies that the average running speed was higher without the ramp meter than with the ramp meter. A positive value indicates that the ramp meter was able to produce average running speeds that were higher than the average running speed when no ramp metering was present for the same freeway and ramp demand levels and ramp acceleration lane length – indicating that metering the ramp demand had a positive impact on traffic operations on the freeway. A value of zero indicates that there was no difference in the average running speed with and without the ramp meter active. We used a standard paired t-test to determine, with a 90 percent and a 95 percent confidence level, that the difference was statistically different. Differences that are statistically significant at a 90 percent confidence level are highlighted in red on a white (or plain) background. Those differences that were statistically significant at a 95 percent confidence level are shown in bold red with gray shading in the table cell.

Table 11. Average Mainlane Running Speed (mph) with and without Ramp Metering Active – 500-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	59.6	59.3	59.1	59.0	58.9	58.5	58.2	57.9	57.3	56.0
	With	59.6	59.3	59.1	59.0	58.9	58.5	58.2	57.9	57.3	56.0
100	Without	59.5	59.2	59.0	58.9	58.8	58.4	58.1	57.7	57.1	55.6
	With	59.5	59.2	59.0	58.9	58.7	58.4	58.1	57.7	57.1	55.7
200	Without	59.5	59.2	59.0	58.9	58.6	58.3	58.0	57.6	56.8	55.2
	With	59.5	59.1	58.9	58.9	58.7	58.3	57.9	57.5	56.8	55.3
300	Without	59.4	59.1	58.9	58.8	58.6	58.2	57.8	57.3	56.3	52.6
	With	59.4	59.1	58.9	58.8	58.5	58.2	57.8	57.2	56.2	54.0
400	Without	59.4	59.0	58.8	58.7	58.4	58.0	57.6	56.8	54.5	48.7
	With	59.4	59.0	58.8	58.7	58.4	58.1	57.5	57.0	55.7	50.8
500	Without	59.3	58.9	58.7	58.5	58.1	57.7	56.9	55.7	49.8	43.2
	With	59.3	58.9	58.7	58.5	58.2	57.8	57.2	56.1	51.7	47.2
600	Without	59.3	58.7	58.6	58.4	57.5	56.8	54.9	51.5	44.2	38.8
	With	59.2	58.9	58.6	58.4	57.9	57.3	56.6	54.3	47.8	40.6
700	Without	59.2	58.8	58.1	58.1	56.2	55.6	50.7	46.3	39.1	34.1
	With	59.1	58.8	57.9	58.2	57.1	56.6	54.7	49.9	43.2	37.8
800	Without	59.1	58.5	58.0	57.6	55.6	52.3	45.9	40.1	35.8	33.0
	With	59.0	58.6	58.3	57.8	56.8	55.5	49.7	44.2	37.8	34.4
900	Without	58.8	58.4	57.4	55.8	51.4	46.1	41.5	34.2	33.2	28.3
	With	58.9	58.5	58.0	57.3	55.6	48.5	45.0	41.3	33.4	31.0

Table 12. Average Mainlane Running Speed (mph) with and without Ramp Metering Active – 750-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	59.5	59.2	59.0	58.9	58.7	58.4	58.3	57.8	57.2	56.1
	With	59.5	59.2	59.0	58.9	58.7	58.4	58.3	57.8	57.2	56.1
100	Without	59.5	59.2	59.0	58.9	58.6	58.4	58.2	57.7	57.2	55.9
	With	59.5	59.2	58.9	58.9	58.6	58.4	58.1	57.7	57.1	55.9
200	Without	59.4	59.1	58.9	58.9	58.6	58.3	58.1	57.6	57.0	55.6
	With	59.4	59.1	58.9	58.8	58.5	58.3	58.0	57.6	56.9	55.5
300	Without	59.4	59.1	58.8	58.7	58.5	58.2	57.9	57.5	56.7	54.3
	With	59.3	59.1	58.8	58.7	58.4	58.2	57.9	57.4	56.5	54.2
400	Without	59.3	59.1	58.8	58.7	58.4	58.1	57.8	57.0	55.8	50.2
	With	59.3	59.0	58.8	58.6	58.4	58.1	57.8	57.3	56.3	52.5
500	Without	59.3	59.0	58.7	58.6	58.2	57.9	57.4	56.8	51.3	45.5
	With	59.3	59.0	58.7	58.6	58.2	57.8	57.5	56.9	54.0	49.5
600	Without	59.2	58.9	58.6	58.4	58.1	57.4	57.0	54.6	47.2	40.8
	With	59.2	58.9	58.6	58.5	58.1	57.7	57.1	56.1	51.3	46.2
700	Without	59.1	58.8	58.5	58.2	57.9	56.8	53.2	46.4	41.8	37.0
	With	59.1	58.8	58.5	58.3	58.0	57.3	56.5	53.6	47.1	41.9
800	Without	59.1	58.7	58.2	58.1	56.9	53.3	45.5	43.1	35.5	32.3
	With	59.0	58.7	58.4	58.2	57.7	56.8	54.7	48.6	41.5	37.4
900	Without	59.0	58.5	58.1	57.4	54.7	48.1	41.8	36.4	32.9	30.0
	With	59.0	58.7	58.3	58.0	57.2	55.6	53.4	45.3	38.9	33.0

Table 13. Average Mainlane Running Speed (mph) with and without Ramp Metering Active – 1000-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**2400**
0	Without	59.6	59.3	59.2	59.0	58.8	58.5	58.2	57.9	57.3	56.4
	With	59.6	59.3	59.2	59.0	58.8	58.5	58.2	57.9	57.3	56.4
100	Without	59.6	59.3	59.1	59.0	58.8	58.5	58.2	57.9	57.2	56.1
	With	59.6	59.3	59.1	59.0	58.8	58.5	58.2	57.8	57.2	56.3
200	Without	59.7	59.3	59.1	58.9	58.7	58.4	58.1	57.8	57.1	56.1
	With	59.1	59.2	59.1	58.9	58.7	58.4	58.1	57.8	57.1	55.8
300	Without	59.7	59.2	59.1	58.9	58.6	58.4	58.0	57.6	56.8	55.1
	With	59.7	59.2	59.0	58.9	58.6	58.4	57.9	57.5	56.8	55.3
400	Without	59.7	59.2	59.0	58.9	58.6	58.3	57.8	57.4	56.5	53.2
	With	59.7	59.2	59.0	58.8	58.6	58.3	57.9	57.4	56.3	53.7
500	Without	59.6	59.1	58.9	58.8	58.5	58.1	57.5	57.1	54.4	49.5
	With	59.6	59.2	58.9	58.8	58.5	58.1	57.7	57.1	55.9	49.8
600	Without	59.6	59.1	58.9	58.7	58.4	58.0	57.1	55.6	50.8	44.9
	With	59.6	59.1	58.9	58.7	58.4	58.0	57.3	56.5	53.5	47.9
700	Without	59.4	59.0	58.8	58.6	58.2	57.7	56.2	52.5	45.9	40.4
	With	59.4	59.0	58.8	58.6	58.2	57.8	57.1	55.6	51.4	43.7
800	Without	59.3	59.0	58.7	58.5	58.1	57.0	55.0	46.8	40.0	36.0
	With	59.3	59.0	58.8	58.5	58.1	57.5	56.5	52.4	45.8	40.4
900	Without	59.2	58.9	58.6	58.2	57.2	55.4	49.3	42.8	37.9	32.7
	With	59.3	58.9	58.6	58.4	57.9	57.3	54.4	48.5	42.4	37.3

Table 14. Average Mainlane Running Speed (mph) with and without Ramp Metering Active – 1250-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	59.7	59.4	59.4	59.0	59.0	58.7	58.4	58.1	57.7	56.5
	With	59.7	59.4	59.4	59.0	59.0	58.7	58.4	58.1	57.7	56.5
100	Without	59.7	59.4	59.3	59.0	59.0	58.6	58.4	58.0	57.6	56.4
	With	59.7	59.4	59.3	59.0	58.9	58.6	58.4	58.0	57.5	56.3
200	Without	59.7	59.4	59.3	59.0	58.9	58.6	58.3	57.9	57.2	56.0
	With	59.7	59.4	59.3	59.0	58.9	58.6	58.3	57.8	57.3	56.2
300	Without	59.7	59.3	59.3	58.9	58.8	58.5	58.2	57.7	57.2	55.5
	With	59.6	59.3	59.3	58.9	58.8	58.5	58.2	57.7	56.9	55.5
400	Without	59.6	59.3	59.2	58.9	58.8	58.4	58.0	57.6	56.8	54.2
	With	59.6	59.3	59.2	58.8	58.8	58.4	58.0	57.5	56.7	54.6
500	Without	59.6	59.2	59.2	58.8	58.7	58.2	57.9	57.1	55.8	50.9
	With	59.6	59.3	59.1	58.8	58.7	58.2	57.9	56.9	55.9	51.1
600	Without	59.6	59.2	59.1	58.8	58.6	58.1	57.5	56.3	53.1	47.2
	With	59.5	59.2	59.1	58.7	58.6	58.0	57.7	56.8	54.1	47.2
700	Without	59.5	59.2	59.0	58.6	58.5	58.1	57.3	54.5	48.8	42.6
	With	59.5	59.1	59.0	58.6	58.4	58.0	57.4	54.8	51.3	43.8
800	Without	59.5	59.1	58.9	58.6	58.4	57.7	56.2	49.9	44.4	39.7
	With	59.4	59.1	58.9	58.6	58.3	57.8	57.0	52.4	47.2	41.5
900	Without	59.4	59.0	58.8	58.3	57.9	56.9	50.3	46.4	41.1	36.4
	With	59.4	59.0	58.9	58.5	58.2	57.5	56.0	48.6	43.0	38.5

Table 15. Average Mainlane Running Speed (mph) with and without Ramp Metering Active – 1500-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	59.3	59.1	58.9	58.7	58.5	58.4	58.1	57.7	57.1	55.8
	With	59.3	59.1	58.9	58.7	58.5	58.4	58.1	57.7	57.1	55.8
100	Without	59.3	59.1	58.9	58.6	58.5	58.3	58.0	57.6	57.0	55.6
	With	59.3	59.1	58.9	58.6	58.5	58.3	58.0	57.6	57.0	55.7
200	Without	59.3	59.1	58.9	58.6	58.5	58.3	57.9	57.6	56.8	55.5
	With	59.3	59.0	58.8	58.6	58.4	58.3	57.9	57.5	56.8	55.5
300	Without	59.3	59.0	58.8	58.6	58.4	58.2	57.8	57.4	56.8	55.0
	With	59.3	59.0	58.8	58.6	58.4	58.2	57.9	57.5	56.7	55.3
400	Without	59.2	59.0	58.8	58.5	58.3	58.1	57.8	57.2	56.3	53.4
	With	59.2	59.0	58.7	58.5	58.3	58.1	57.8	57.1	56.3	54.1
500	Without	59.2	58.9	58.7	58.5	58.2	58.0	57.6	57.0	55.9	52.3
	With	59.2	58.9	58.7	58.5	58.2	58.0	57.6	57.1	56.1	52.2
600	Without	59.1	58.9	58.7	58.4	58.2	57.9	57.5	56.4	53.8	47.9
	With	59.1	58.9	58.6	58.4	58.1	58.0	57.4	56.8	54.8	48.5
700	Without	59.1	58.9	58.6	58.3	58.1	57.8	56.9	55.3	49.7	44.3
	With	59.1	58.8	58.6	58.3	58.1	57.7	57.1	56.2	52.2	44.7
800	Without	59.0	58.8	58.5	58.2	57.9	57.5	56.7	53.0	46.9	40.7
	With	59.1	58.8	58.5	58.2	57.9	57.6	56.7	55.0	47.9	41.4
900	Without	59.0	58.7	58.4	58.0	57.7	57.0	55.9	48.9	42.3	38.8
	With	59.0	58.7	58.5	58.1	57.7	57.2	55.7	49.3	43.9	38.5

Table 16. Difference in Average Running Speed (mph) on the Mainlane of the Freeway with and without Ramp Metering Active – 500-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
200	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	0.0	1.4
400	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	**1.2**	**2.2**
500	0.0	0.0	0.0	0.0	0.1	0.1	0.4	0.4	1.9	**3.9**
600	-0.1	0.1	0.0	0.0	0.4	0.5	**1.8**	**2.8**	**3.6**	1.8
700	0.0	0.0	-0.1	0.1	0.9	1.0	**3.9**	**3.6**	4.2	3.7
800	-0.1	0.1	0.2	0.2	1.2	**3.2**	3.8	**4.1**	1.9	1.4
900	0.1	0.1	0.6	1.5	4.2	2.4	3.6	**7.1**	0.2	2.8
XX.XX	Represent differences that are significant at a 90 percent confidence level or higher.									
XX.XX	Represent differences that are significant at a 95 percent confidence level or higher.									

Table 17. Difference in Average Running Speed (mph) on the Mainlane of the Freeway with and without Ramp Metering Active – 750-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	-0.1	-0.1
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	0.0
400	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.3	0.5	2.3
500	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	**2.7**	**4.0**
600	0.0	0.0	0.0	0.0	0.0	0.3	0.1	**1.5**	**4.1**	**5.3**
700	0.0	0.0	0.0	0.1	0.1	0.5	**3.4**	**7.2**	**5.4**	**4.9**
800	0.0	0.0	0.2	0.1	0.8	3.5	**9.2**	**5.5**	**6.0**	**5.1**
900	0.0	0.2	0.2	**0.6**	2.5	**7.4**	**11.7**	**8.9**	**6.0**	3.0
XX.XX	Represent differences that are significant at a 90 percent confidence level or higher.									
XX.XX	Represent differences that are significant at a 95 percent confidence level or higher.									

Table 18. Difference in Average Running Speed (mph) on the Mainlane of the Freeway with and without Ramp Metering Active – 1000-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
200	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.1	0.3
400	0.0	0.0	0.0	-0.1	0.0	0.0	0.1	0.0	-0.2	0.5
500	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	**1.6**	0.4
600	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.9	**2.7**	**3.0**
700	0.0	0.0	0.0	0.0	0.0	0.1	0.9	**3.1**	**5.5**	**3.4**
800	0.0	0.0	0.1	0.0	0.0	0.5	1.5	**5.6**	**5.8**	**4.3**
900	0.0	0.0	0.0	**0.2**	**0.7**	**1.9**	**5.1**	**5.7**	**4.5**	**4.6**
XX.XX	Represent differences that are significant at a 90 percent confidence level or higher.									
XX.XX	Represent differences that are significant at a 95 percent confidence level or higher.									

Table 19. Difference in Average Running Speed (mph) on the Mainlane of the Freeway with and without Ramp Metering Active – 1250-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcph)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
200	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
300	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.3	0.0
400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.4
500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.1	0.2
600	0.0	0.0	0.0	-0.1	0.0	0.0	0.2	0.4	1.0	0.0
700	0.0	0.0	0.0	0.0	-0.1	0.0	0.1	0.4	2.5	1.2
800	0.0	0.0	0.0	0.0	-0.1	0.1	**0.8**	2.5	2.9	1.8
900	0.0	0.0	0.0	**0.2**	**0.3**	0.5	5.7	2.2	1.9	**2.1**
XX.XX	Represent differences that are significant at a 90 percent confidence level or higher.									
XX.XX	Represent differences that are significant at a 95 percent confidence level or higher.									

Table 20. Difference in Average Running Speed on the Mainlane of the Freeway with and without Ramp Metering Active – 1500-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
200	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	0.3
400	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	-0.1	0.0	0.7
500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	-0.1
600	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	0.4	1.0	0.5
700	0.0	0.0	0.0	0.0	0.0	-0.1	0.2	0.9	2.5	0.3
800	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.7
900	0.0	0.0	0.0	0.1	0.1	0.2	-0.2	0.3	1.6	-0.2
XX.XX	Represent differences that are significant at a 90 percent confidence level or higher.									
XX.XX	Represent differences that are significant at a 95 percent confidence level or higher.									

From these tables, we have made the following observations about the performance of the freeway mainlanes with and without ramp metering:

- Even if the ramp traffic remains constant, average running speeds decrease slightly as traffic demand on the freeway increases, regardless of whether or not the ramp meter is active. This is to be anticipated because as traffic on the freeway begins to approach capacity, travel speeds on the freeway generally reduce. This behavior is consistent with what is illustrated in the 2004 *Highway Capacity Manual*.
- At the same freeway volume level, the average running speed decreases as the amount of traffic entering on the freeway increases. Again, this was anticipated because as the number of vehicles entering the freeway increases, they are competing more with one another for space in the traffic stream. The turbulence that ramp traffic makes as it enters the freeway is also well documented in the 2004 *Highway Capacity Manual.*
- At the very high freeway and ramp demand levels, entering vehicles from the ramp would often go the end of the acceleration lane where they would stop and wait until

a gap of suitable size becomes available allowing them to change lanes into the mainlane. We observed this behavior more frequently when the length of the ramp acceleration lane was relatively short (i.e., less than 1250 ft). Based on our field observations, this behavior does not appear to happen as frequently in real life as it does in simulation, though. In real life, drivers on the freeway tend to adjust their speeds to create gaps in the traffic stream to allow ramp traffic to merge into the freeway. In other situations, some drivers of ramp vehicles tend to force themselves into gaps that generally would not be permitted in the simulation. We do not believe, however, that these differences in driver behavior are significant enough to invalidate the results of the simulation, especially at the light and moderate freeway and ramp demand levels.

- The presence of the ramp meter was able to produce a significant difference in the average running speed of the mainlane traffic. At relatively light freeway and ramp demand levels, ramp metering did not have any impact (positive or negative) on the average running speed of traffic on the mainlane. As long as ramp demands stayed below 400 to 500 pcph, regardless of the freeway demand level, the presence of a ramp meter had no impact on average running speed of traffic. Similarly, as long as the freeway demand level stayed below 1800 to 2000 pcphpl, the presence of a meter controlling traffic at the entrance ramp did have an impact of the average running speed. We did not observe any significant differences in average running speed until both the freeway and the ramp demands were relatively high.
- As the length of the acceleration lane increased, the amount of difference in the average running speed with and without the ramp meter active diminished. In fact, when the acceleration lane length was 1500 ft, the difference in the average running speed was minimal and not statistically different. This suggests that the effect of ramp metering on mainlane travel speed diminishes when long acceleration lanes are provided. We believe that longer acceleration lane lengths allow vehicles entering from the ramp to better match the prevailing speed of traffic on the freeway.

Throughput

In addition to average running speed, we also examined the effects that ramp metering had on throughput in the system. Because all traffic was made to enter the freeway in the simulation model, throughput was measured using a pair of data collection points (similar in concept to loop detectors) in the simulation model. The throughput values are expressed in the number of vehicles per hour that traversed through the simulation during the 90-minute data collection period. Tables 21 through 25 show the average observed throughput (in vph) on the freeway mainlanes with and without the ramp meter active during the simulation.

Tables 26 through 30 show the differences in vehicle throughput on the freeway mainlanes with and without the ramp meter. A negative value indicates that the observed throughput was higher when no ramp metering was used compared to when the metering controlled traffic entering via the ramp. A positive value indicates that the ramp meter provided more vehicle throughput than when the ramp meter was not used. A value of zero indicates that throughput was exactly the same regardless of whether or not the ramp meter was used.

As in the analysis of average running speed, we used a standard paired t-test to determine if the differences in throughput were statistically significant, with a 90 percent and a 95 percent confidence level. Differences that are statistically significant at a 90 percent confidence level are highlighted in red on a white (or plain) background. Those differences that were statistically significant at a 95 percent confidence level are shown in bold red with gray shading in the table cell.

Table 21. Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering– 500-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	2695.3	2874.4	3046.4	3225.7	3398.5	3573.9	3763.7	3958.8	4134.9	4310
	With	2695.3	2874.4	3046.4	3225.7	3398.5	3573.9	3763.7	3958.8	4134.9	4310.1
100	Without	2786.9	2965.6	3137.3	3318.7	3491.5	3661.9	3856.7	4049.1	4226.8	4400.8
	With	2786.7	2965.5	3137.7	3317.6	3491.9	3665.1	3854.1	4048.7	4223.9	4400.7
200	Without	2876.5	3054.8	3227.9	3409.7	3585.5	3752.8	3945.5	4136.9	4315.7	4481.9
	With	2877.1	3053.3	3228.4	3406.9	3582.1	3754.3	3943.7	4137.3	4313.5	4485.5
300	Without	2969.2	3148.3	3302.1	3500.1	3675.1	3844.9	4034.8	4223.9	4408.9	4532.5
	With	2965.3	3145.5	3317.5	3498.4	3667.3	3846	4033.3	4223.3	4397.5	4559.5
400	Without	3062.8	3240.9	3407.7	3590.8	3763.1	3956	4122	4318.9	4469.5	4523.2
	With	3062	3241.7	3412.9	3590.9	3765.7	3950.4	4128.8	4319.3	4488.5	4580.7
500	Without	3149.5	3331.6	3500.8	3683.7	3968.5	4030.8	4212.9	4396.9	4468.1	4475.9
	With	3148.7	3330.4	3501.1	3687.5	3970.4	4036.4	4222.3	4408.5	4514.7	4592.9
600	Without	3244.8	3424.1	3592.7	3776	3968.5	4124.3	4296.9	4406	4401.2	4406.8
	With	3244.8	3420.9	3592.4	3777.7	3970.4	4127.1	4324.3	4482	4517.6	4491.2
700	Without	3334	3516.3	3671.7	3859.7	4003.3	4188.1	4312.1	4352.8	4340.7	4318
	With	3333.5	3513.2	3673.6	3861.1	4016.8	4214.8	4380	4423.5	4484	4482.3
800	Without	3423.3	3606.9	3769.7	3954.1	4117.3	4225.3	4255.3	4258.8	4259.2	4268.9
	With	3428.5	3602	3772.1	3954.4	4127.2	4272.8	4348.5	4360.9	4355.5	4335.2
900	Without	3512.4	3691.1	3858.4	4034.4	4112.5	4104.7	4221.7	4120.1	4184.4	4167.6
	With	3510	3690.3	3858.3	4033.1	4170	4196.1	4266.9	4310	4251.2	4346

Table 22. Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering– 750-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	2695.6	2885.2	3050.4	3226.9	3405.9	3584.3	3769.2	3954.7	4135.6	4311.1
	With	2695.9	2885.2	3050.4	3226.9	3405.9	3594.3	3769.2	3954.7	4135.6	4311.1
100	Without	2787.5	2977.1	3141.1	3317.7	3496.7	3675.5	3861.9	4045.6	4227.1	4401.6
	With	2787.1	2976.5	3142.9	3318.1	3496.5	3675.6	3809.9	4046.5	4227.6	4403.3
200	Without	2877.3	3067.5	3232	3408.5	3587.7	3765.5	3950.3	4138.7	4314	4488.9
	With	2878.3	3066.9	3233.5	3407.3	3589.6	3766	3952.7	4137.3	4314.5	4487.6
300	Without	2970.3	3158.3	3322.7	3498.4	3678.5	3857.2	4046.9	4226.5	4408.3	4567.6
	With	2968.3	3158.4	3323.1	3498.5	3676.9	3855.7	4044.1	4226.4	4411.1	4571.2
400	Without	3062.9	3251.1	3416.9	3592.4	3770.4	3949.6	4132.9	4317.2	4487.1	4563.7
	With	3062.8	3250.7	3414	3592.7	3770.4	3948.1	4134.8	4318.4	4503.2	4633.5
500	Without	3151.5	3341.5	3505.1	3678.5	3864.7	4040.1	4219.2	4402.8	4520.4	4536.3
	With	3152	3338.9	3504.7	3683.1	3866.4	4043.5	4224.4	4403.2	4578	4644.9
600	Without	3243.2	3431.9	3598.1	3773.5	3952.3	4130.3	4316.7	4466.4	4466.7	4478.5
	With	3244.9	3430.7	3598.8	3774.4	3955.7	4133.6	4325.3	4498.9	4597.2	4639.1
700	Without	3334.7	3523.1	3684.7	3859.1	4042.1	4206.1	4357.3	4389.9	4427.9	4425.7
	With	3332.4	3517.9	3690.7	3860.3	4049.5	4203.7	4412.7	4548.3	4593.9	4610.9
800	Without	3429.2	3617.7	3778.7	3957.6	4133.7	4274.4	4288.5	4257.5	4351.9	4319.1
	With	3424.8	3614.8	3783.3	3952.5	4136.5	4316.5	4473.5	4541.1	4585.2	4558.9
900	Without	3517.9	3708.1	3875.6	4046.1	4167.2	4244.9	4248.8	4251.3	4289.5	4313.5
	With	3517.5	3698.5	3865.3	4041.9	4219.2	4385.6	4522.1	4537.5	4546.3	4506

Table 23. Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering– 1000-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	2695.9	2880.8	3056.1	3228.4	3405.1	3583.2	3773.2	3953.2	4076.9	4316.7
	With	2695.9	2880.8	3056.1	3228.4	3405.1	3583.2	3773.2	3953.2	4076.9	4316.7
100	Without	2787.2	2972.4	3147.7	3285.3	3496.5	3674.3	3864.4	4044.7	4229.7	4408.1
	With	2787.9	2971.6	3147.2	3319.9	3495.9	3675.9	3865.6	4043.9	4230	4407.7
200	Without	2877.6	3062.9	3238.3	3408.8	3587.1	3765.2	3954.8	4134.7	4320.3	4496.4
	With	2877.7	3061.3	3237.3	3409.3	3586.8	3764.5	3953.1	4134.1	4318.5	4496.5
300	Without	2968.7	3154.9	3330.3	3501.3	3677.9	3858.6	4044.8	4226.4	4392.3	4578.7
	With	2968	3152.8	3328.3	3499.3	3677.1	3854.9	4044.1	4224.9	4407.5	4572.1
400	Without	3061.6	3246.1	3421.5	3591.9	3770	3949.9	4136.4	4320.3	4494.7	4629.1
	With	3060.9	3246.8	3421.1	3592.9	3770.4	3942.2	4136.8	4315.5	4497.3	4636.4
500	Without	3150.8	3335.5	3511.6	3684.5	3862.3	4040.3	4223.5	4406.9	4558.3	4619.7
	With	3151.5	3336	3509.7	3684.3	3860.7	4041.2	4224.7	4411.6	4578.5	4654.9
600	Without	3244	3428.9	3603.7	3774.5	3952.3	4128.9	4306.3	4487.7	4563.3	4591.7
	With	3244.7	3428.4	3604.9	3773.9	3952.4	4130.8	4317.2	4498.3	4631.5	4673.2
700	Without	3332.9	3517.3	3688.1	3860.7	4047.1	4217.5	4399.2	4511.5	4549.1	4541.5
	With	3333.9	3517.2	3696.9	3860.8	4043.5	4220.8	4406	4570.7	4674.9	4660.3
800	Without	3424.9	3611.6	3780.5	3955.1	4128.8	4309.6	4461.5	4480.7	4472.1	4496.7
	With	3426.8	3610.1	3783.7	3955.6	4135.3	4307.2	4491.6	4613.5	4634.9	4657.7
900	Without	3510	3703.1	3876.4	4044.3	4207.9	4366.7	4433.2	4455.2	4446.1	4440.8
	With	3513.1	3697.5	3870.3	4040.7	4218.9	4400	4539.7	4614.8	4648.9	4613.7

Table 24. Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering– 1250-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	2698.8	2883.5	3052	3232	3407.1	3581.1	3775.2	3958	4143.2	4318.1
	With	2698.8	2883.5	3052	3232	3407.1	3581.1	3775.2	3958	4143.2	4318.1
100	Without	2790.5	2975.1	3142.4	3324.1	3351.5	3672.1	3867.1	4049.5	4234.7	4409.6
	With	2790.8	2974.5	3144	3324	3499.1	3673.3	3866	4049.2	4234.3	4410.7
200	Without	2880.9	3065.5	3233.9	3414.8	3590.9	3763.6	3957.2	4140.3	4320.9	4492.1
	With	2880.7	3064.8	3233.7	3410.9	3589.9	3762.5	3956.3	4141.9	4324.4	4499.5
300	Without	2972.8	3156.4	3325.6	3502.9	3682.1	3853.7	4048.9	4231.9	4415.1	4577.9
	With	2972	3155.9	3324.3	3501.2	3681.5	3851.9	4048	4229.6	4411.6	4573.2
400	Without	3064.8	3249.7	3416.3	3593.5	3772.9	3947.7	4139.3	4326.3	4503.9	4630.5
	With	3064.5	3249.7	3416	3596.8	3774	3946.4	4141.3	4321.3	4507.5	4655.5
500	Without	3154.8	3338.8	3508	3684.5	3865.5	4037.6	4233.9	4415.9	4589.6	4660.1
	With	3156.4	3338.7	3505.7	3685.9	3866.8	4036	4228.8	4418.4	4582.8	4675.9
600	Without	3247.3	3432.4	3597.5	3776.9	3956.5	4126.5	4320.1	4503.9	4604.9	4658.1
	With	3247.6	3430.9	3599.5	3776.4	3960	4131.6	4318.7	4504.8	4644.4	4672.5
700	Without	3318.4	3519.9	3686.7	3864.4	4046.5	4219.1	4408.5	4556	4613.5	4626
	With	3336.3	3520.7	3688.3	3865.9	4048	4220.8	4409.5	4581.5	4667.5	4666.9
800	Without	3432.1	3610.4	3779.3	3953.1	4142.5	4316.1	4495.9	4572.8	4603.3	4623.3
	With	3430.7	3611.5	3780.9	3956.3	4140.1	4312.9	4494.3	4612.7	4673.9	4681.7
900	Without	3520.5	3702.9	3871.5	4045.9	4231.7	4402.5	4433.2	4562.9	4572.4	4580.5
	With	3517.3	3700.8	3864.9	4044.1	4228.3	4398.1	4562.3	4629.3	4647.2	4669.7

Table 25. Average Throughput (in vph) on the Freeway Mainlanes with and without Ramp Metering– 1500-ft Ramp Acceleration Lane Length.

Ramp Demand (pcph)	Ramp Meter Active	Freeway Demand (pcphpl)									
		1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	Without	2699.6	2880.7	3051.9	3226.3	3397.5	3585.1	3771.2	3952.1	4137.9	4306.8
	With	2699.6	2880.7	3051.9	3226.3	3397.5	3585.1	3771.2	3952.1	4137.9	4306.8
100	Without	2791.6	2972.5	3143.5	3318.1	3488.5	3676.8	3862.5	4043.1	4229.2	4398.8
	With	2790.9	2972	3143.6	3318.4	3488.7	3677.7	3862.8	4043.5	4228.8	4392.9
200	Without	2881.6	3062.4	3233.7	3408.5	3579.6	3766.5	3953.1	4132.8	4318.3	4487.1
	With	2881.3	3061.2	3234	3408.7	3579.2	3766	3953.2	4132.7	4316	4487.2
300	Without	2972.7	3153.7	3324.5	3499.6	3670.5	3857.5	4043.6	4223.6	4410.4	4578.1
	With	2972	3153.1	3324.4	3499.9	3669.3	3855.5	4044	4225.1	4406.5	4572.5
400	Without	3065.5	3246.5	3417.1	3591.7	3762.4	3949.1	4134.8	4315.9	4497.1	4637.1
	With	3065.6	3247.6	3419.5	3593.3	3762.4	3947.7	4137.1	4315.5	4501.3	4649.9
500	Without	3154.8	3336.3	3508.7	3680.7	3852.1	4037.3	4223.9	4401.7	4586	4686.4
	With	3156.7	3334.5	3507.2	3682.5	3855.2	4038.5	4225.9	4402.4	4586	4695.1
600	Without	3247.6	3430	3599.1	3774.5	3943.6	4131.2	4317.7	4492.9	4631.6	4684.7
	With	3248.5	3427.2	3599.2	3775.6	3944.4	4130	4316	4497.6	4659.5	4682.1
700	Without	3337.3	3515.2	3689.1	3862.7	4033.6	4219.5	4401.1	4569.2	4648.3	4680.9
	With	3336.1	3516.5	3686.4	3860	4035.2	4220.5	4404.1	4578.8	4693.7	4687.3
800	Without	3429.1	3610.7	3779.6	3956.4	4128.5	4315.1	4495.7	4624.4	4667.5	4668.7
	With	3429.7	3608.4	3781.7	3954.1	4130.3	4312.9	4497.7	4662.1	4674.8	4685.2
900	Without	3520.5	3700.9	3871.7	4049.2	4219.3	4401.3	4573.5	4629.9	4610	4679.9
	With	3517.1	3697.6	3867.5	4042.1	4211.5	4396.1	4561.3	4645.2	4611.8	4667.5

Table 26. Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering – 500-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0	0	0	0	0	0	0	0	0	0
100	-0.2	-0.1	0.4	-1.1	0.4	3.2	-2.6	-0.4	-2.9	-0.1
200	0.6	-1.5	0.5	-2.8	-3.4	1.5	-1.8	0.4	-2.2	3.6
300	-3.9	-2.8	15.4	-1.7	-7.8	1.1	-1.5	-0.6	-11.4	27
400	-0.8	0.8	5.2	0.1	2.6	-5.6	6.8	0.4	19	**57.5**
500	-0.8	-1.2	0.3	3.8	1.9	5.6	9.4	11.6	**46.6**	**117**
600	0	-3.2	-0.3	1.7	1.9	2.8	27.4	**76**	**116.4**	**84.4**
700	-0.5	-3.1	1.9	1.4	13.5	26.7	67.9	70.7	**143.3**	**164.3**
800	5.2	-4.9	2.4	0.3	9.9	47.5	**93.2**	102.1	**96.3**	66.3
900	-2.4	-0.8	-0.1	-1.3	57.5	91.4	45.2	**189.9**	66.8	**178.4**

Table 27. Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering – 750-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0.3	0	0	0	0	0	0	0	0	0
100	-0.4	-0.6	1.8	0.4	-0.2	0.1	-52	0.9	0.5	1.7
200	1	-0.6	1.5	-1.2	1.9	0.5	2.4	-1.4	0.5	-1.3
300	-2	0.1	0.4	0.1	-1.6	-1.5	-2.8	-0.1	2.8	3.6
400	-0.1	-0.4	-2.9	0.3	0	-1.5	1.9	1.2	16.1	**69.8**
500	0.5	-2.6	-0.4	4.6	1.7	3.4	5.2	0.4	**57.6**	**108.6**
600	1.7	-1.2	0.7	0.9	3.4	3.3	8.6	32.5	**130.5**	**160.6**
700	-2.3	-5.2	6	1.2	7.4	-2.4	55.4	**158.4**	**166**	**185.2**
800	-4.4	-2.9	4.6	-5.1	2.8	42.1	**185**	**283.6**	**233.3**	**239.8**
900	-0.4	-9.6	-10.3	-4.2	52	**140.7**	**273.3**	**286.2**	**256.8**	**192.5**

Table 28. Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering – 1000-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**2400**
0	0	0	0	0	0	0	0	0	0	0
100	0.7	-0.8	-0.5	34.6	-0.6	1.6	1.2	-0.8	0.3	-0.4
200	0.1	-1.6	-1	0.5	-0.3	-0.7	-1.7	-0.6	-1.8	0.1
300	-0.7	-2.1	-2	-2	-0.8	-3.7	-0.7	-1.5	15.2	-6.6
400	-0.7	0.7	-0.4	1	0.4	-7.7	0.4	-4.8	2.6	7.3
500	0.7	0.5	-1.9	-0.2	-1.6	0.9	1.2	4.7	20.2	35.2
600	0.7	-0.5	1.2	-0.6	0.1	1.9	10.9	10.6	**68.2**	**81.5**
700	1	-0.1	8.8	0.1	-3.6	3.3	6.8	**59.2**	**125.8**	**118.8**
800	1.9	-1.5	3.2	0.5	6.5	-2.4	30.1	**132.8**	**162.8**	**161**
900	3.1	-5.6	-6.1	-3.6	11	33.3	**106.5**	**159.6**	**202.8**	**172.9**

Table 29. Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering – 1250-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**2400**
0	0	0	0	0	0	0	0	0	0	0
100	0.3	-0.6	1.6	-0.1	147.6	1.2	-1.1	-0.3	-0.4	1.1
200	-0.2	-0.7	-0.2	-3.9	-1	-1.1	-0.9	1.6	3.5	7.4
300	-0.8	-0.5	-1.3	-1.7	-0.6	-1.8	-0.9	-2.3	-3.5	-4.7
400	-0.3	0	-0.3	3.3	1.1	-1.3	2	-5	3.6	25
500	1.6	-0.1	-2.3	1.4	1.3	-1.6	-5.1	2.5	-6.8	15.8
600	0.3	-1.5	2	-0.5	3.5	5.1	-1.4	0.9	39.5	14.4
700	17.9	0.8	1.6	1.5	1.5	1.7	1	25.5	**54**	**40.9**
800	-1.4	1.1	1.6	3.2	-2.4	-3.2	-1.6	39.9	**70.6**	**58.4**
900	-3.2	-2.1	-6.6	-1.8	-3.4	-4.4	129.1	**66.4**	**74.8**	**89.2**

Table 30. Difference in Throughput (in vph) with Ramp Metering Than without Ramp Metering – 1500-ft Ramp Acceleration Lane.

Ramp Demand (pcph)	Freeway Demand (pcphpl)									
	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	0	0	0	0	0	0	0	0	0	0
100	-0.7	-0.5	0.1	0.3	0.2	0.9	0.3	0.4	-0.4	-5.9
200	-0.3	-1.2	0.3	0.2	-0.4	-0.5	0.1	-0.1	-2.3	0.1
300	-0.7	-0.6	-0.1	0.3	-1.2	-2	0.4	1.5	-3.9	-5.6
400	0.1	1.1	2.4	1.6	0	-1.4	2.3	-0.4	4.2	12.8
500	1.9	-1.8	-1.5	1.8	3.1	1.2	2	0.7	0	8.7
600	0.9	-2.8	0.1	1.1	0.8	-1.2	-1.7	4.7	27.9	-2.6
700	-1.2	1.3	-2.7	-2.7	1.6	1	3	9.6	45.4	6.4
800	0.6	-2.3	2.1	-2.3	1.8	-2.2	2	37.7	7.3	16.5
900	-3.4	-3.3	-4.2	-7.1	-7.8	-5.2	-12.2	15.3	1.8	-12.4

Based on these tables, we have made the following observations about the impacts of ramp metering on throughput:

- Ramp metering clearly has a positive impact on the throughput of the freeway mainlanes, especially when the combined ramp and mainlane volumes approach 2800 pcphpl. This is especially true at low to moderate ramp acceleration lane lengths.
- When ramp and freeway demands are relatively light (i.e., less than 300 to 400 pcphpl), ramp metering had no impact on throughput. Similarly when freeway demands are less than 2000 pcphpl, ramp metering had no impact on throughput of the freeway.
- The effects of ramp metering on throughput lessened as the length of the ramp acceleration lane increased. Ramp metering had no impact on system throughput at all freeway and ramp demand levels at the 1500-ft ramp acceleration lane length level.

Application of Managed Lanes Strategies as an Alternative to Ramp Metering

The results of the simulation analysis clearly show that metering the demand on higher volume ramps allows operators to maintain a higher level of operating speed and throughput on freeways; however, the purpose of this study was to assess how much traffic needs to be diverted away from a ramp through the application of a managed lane strategy to achieve the same level of operation on a freeway if ramp metering was deployed. To do this, we utilized the graphs contained in Appendices A through E to determine what level of ramp demand when no ramp meter was present produced the same level of operation on the freeway (i.e., average running speed) that occurred when ramp metering was used on the ramp. The process we used to determine the amount of ramp demand that could be accommodated at a non-metered ramp to achieve an equivalent level of operations in a freeway section where ramp metering was utilized is illustrated Figure 6. We started out by first determining the level of operation of the freeway at a particular ramp demand level with the ramp meter active (see ① in Figure 6). Then working parallel to the x-axis (see ② in Figure 6), we found the point on the performance line of the freeway when no ramp metering was used. Finally, we determined the amount of ramp traffic that could be accommodated on the ramp that achieved that same level of operation when ramp metering was not used (see ③ in Figure 6). This ramp demand level represents that maximum amount of ramp demand that can be accommodated on a ramp that utilizes some type of managed lane strategy to limit the demand on the ramp. The difference between the two ramp demand levels (with and without ramp metering) represents the amount of traffic that needs to be diverted away from the ramp by the managed lane strategy to achieve the equivalent level of operation on the freeway that utilizes ramp metering. This process was repeated everywhere the performance of the freeway with ramp metering was statistically significant.

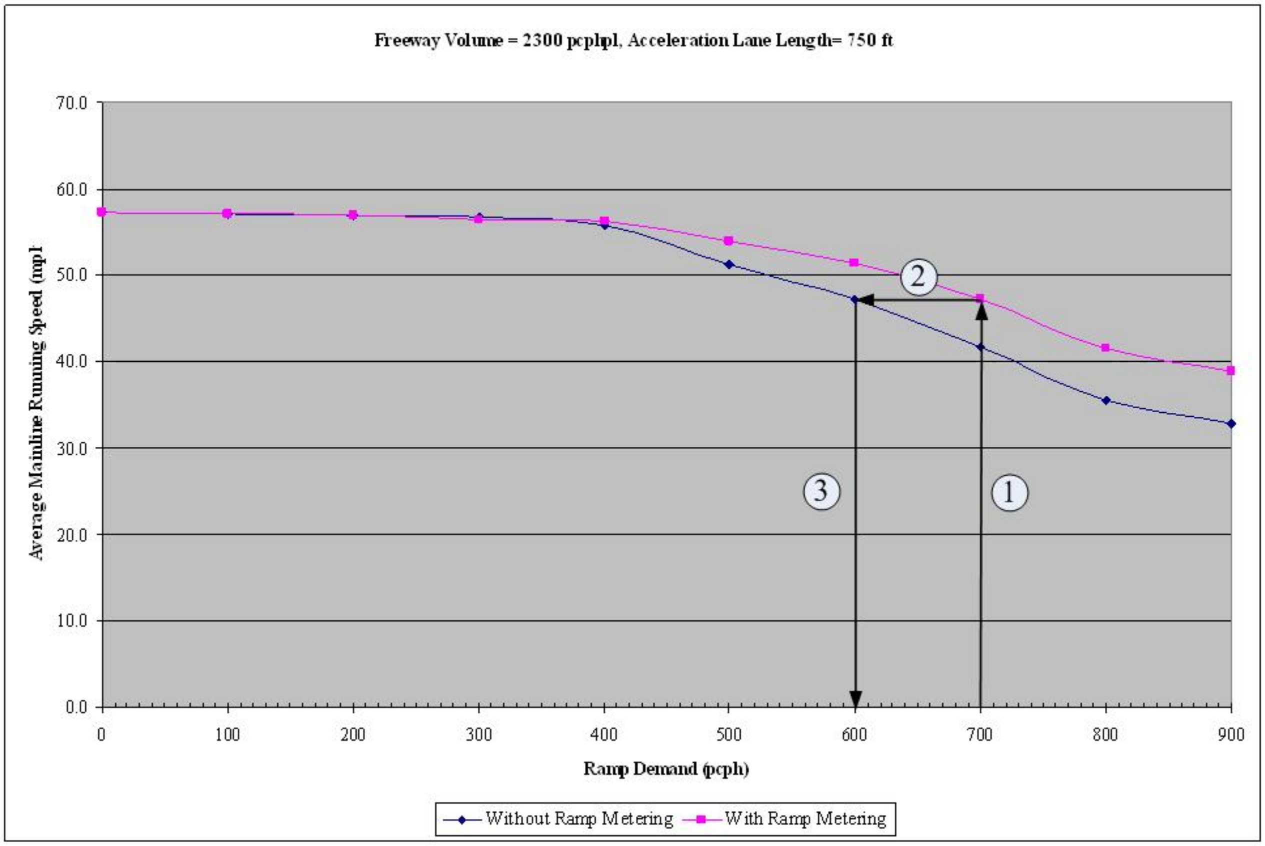


Figure 6. Illustration of Process Used to Determine Ramp Demand at a Non-Metered Ramp to Achieve an Equivalent Level of Operations on the Freeway Where Ramp Metering Was Utilized.

Figure 7 through Figure 13 are graphs depicting the results of this process. The graphs show the maximum amount of ramp demand that can be supported without ramp metering to achieve the same level of performance on a freeway section where ramp metering was used. We have provided graphs for freeway volumes ranging from 1800 pcphpl to 2400 pcphpl. Each volume level contains lines depicting the ramp demand levels that can be supported without ramp metering for the different ramp acceleration lane lengths.

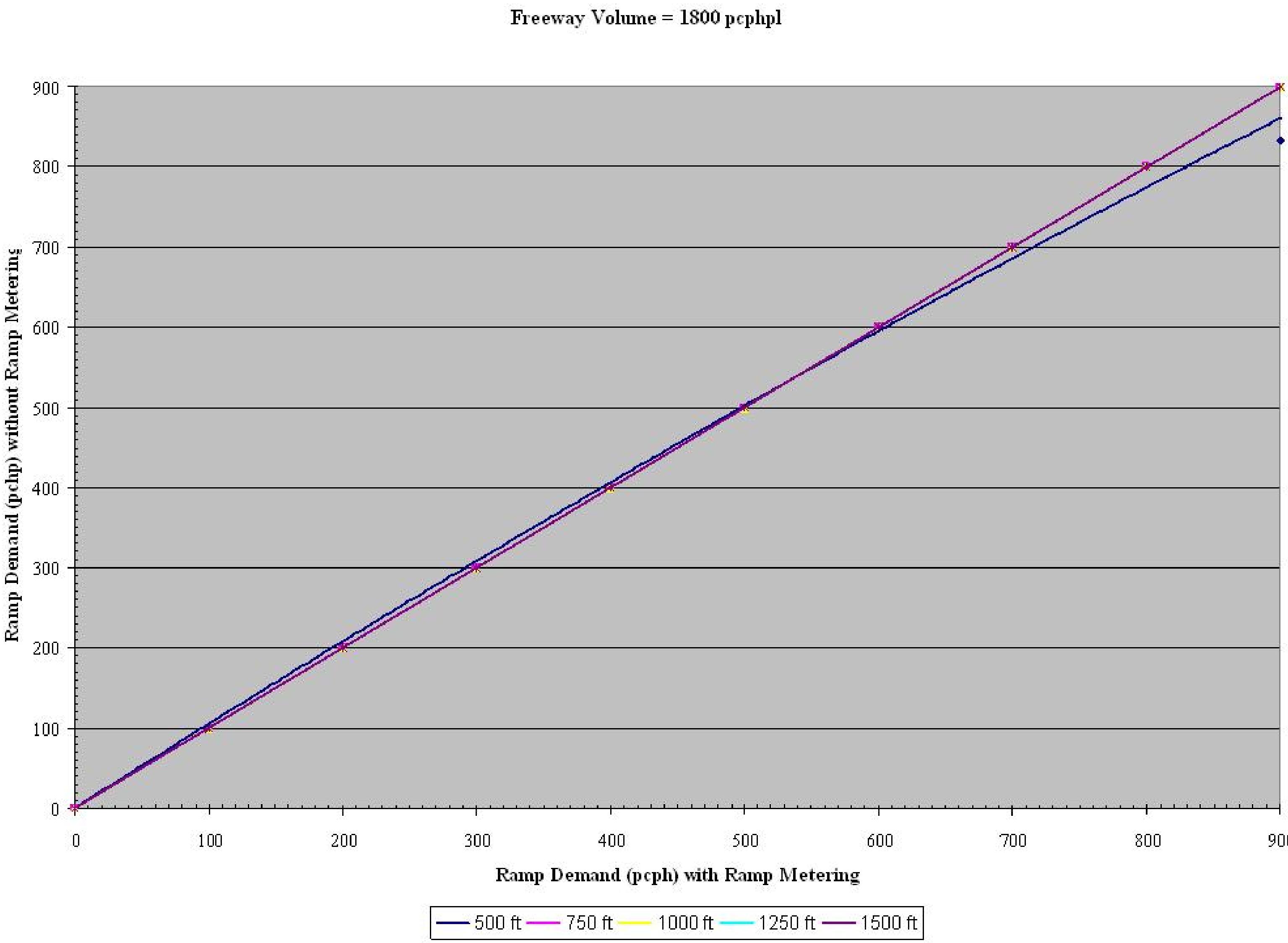


Figure 7. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1800 pcphpl

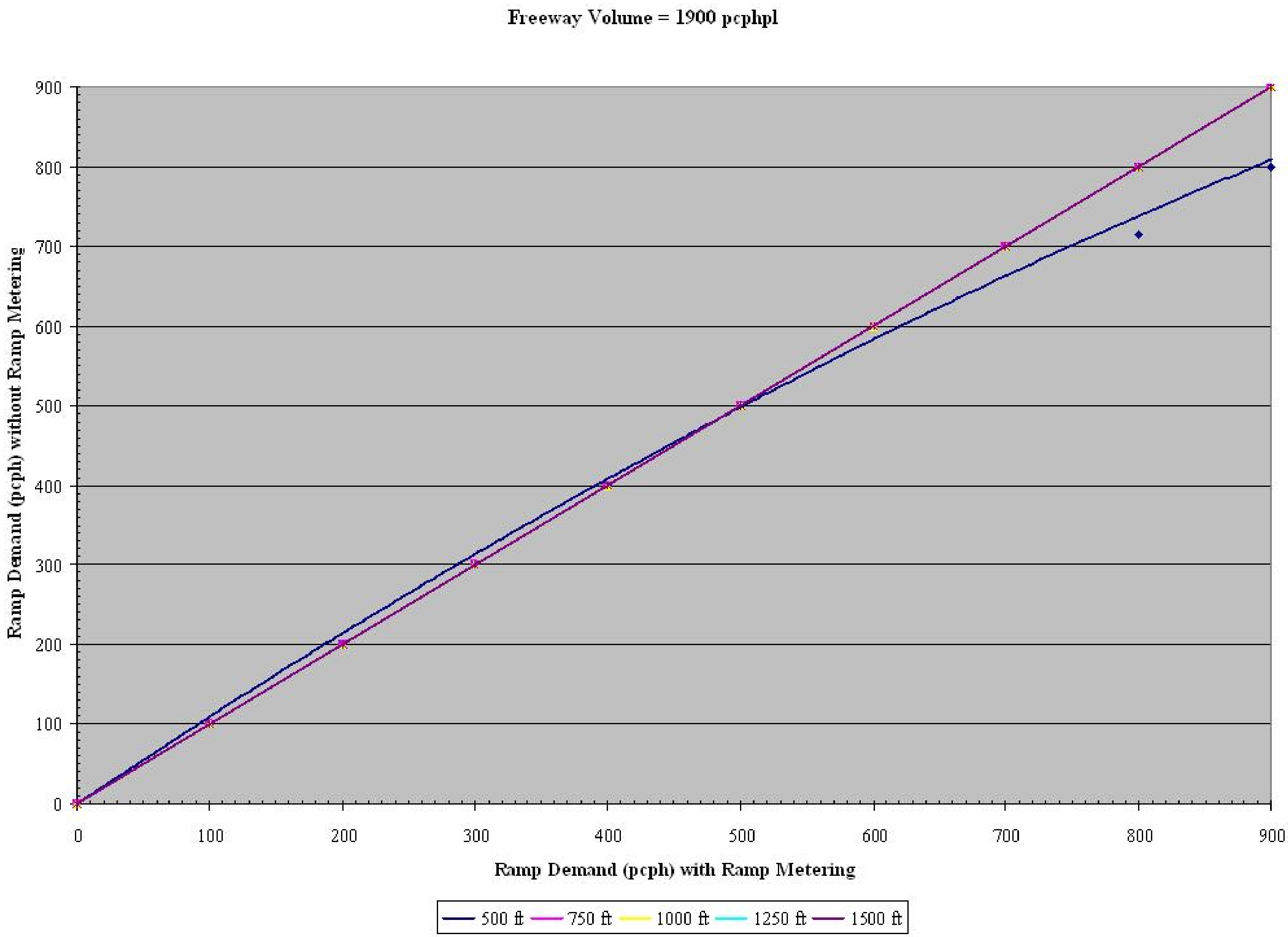


Figure 8. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1900 pcphpl

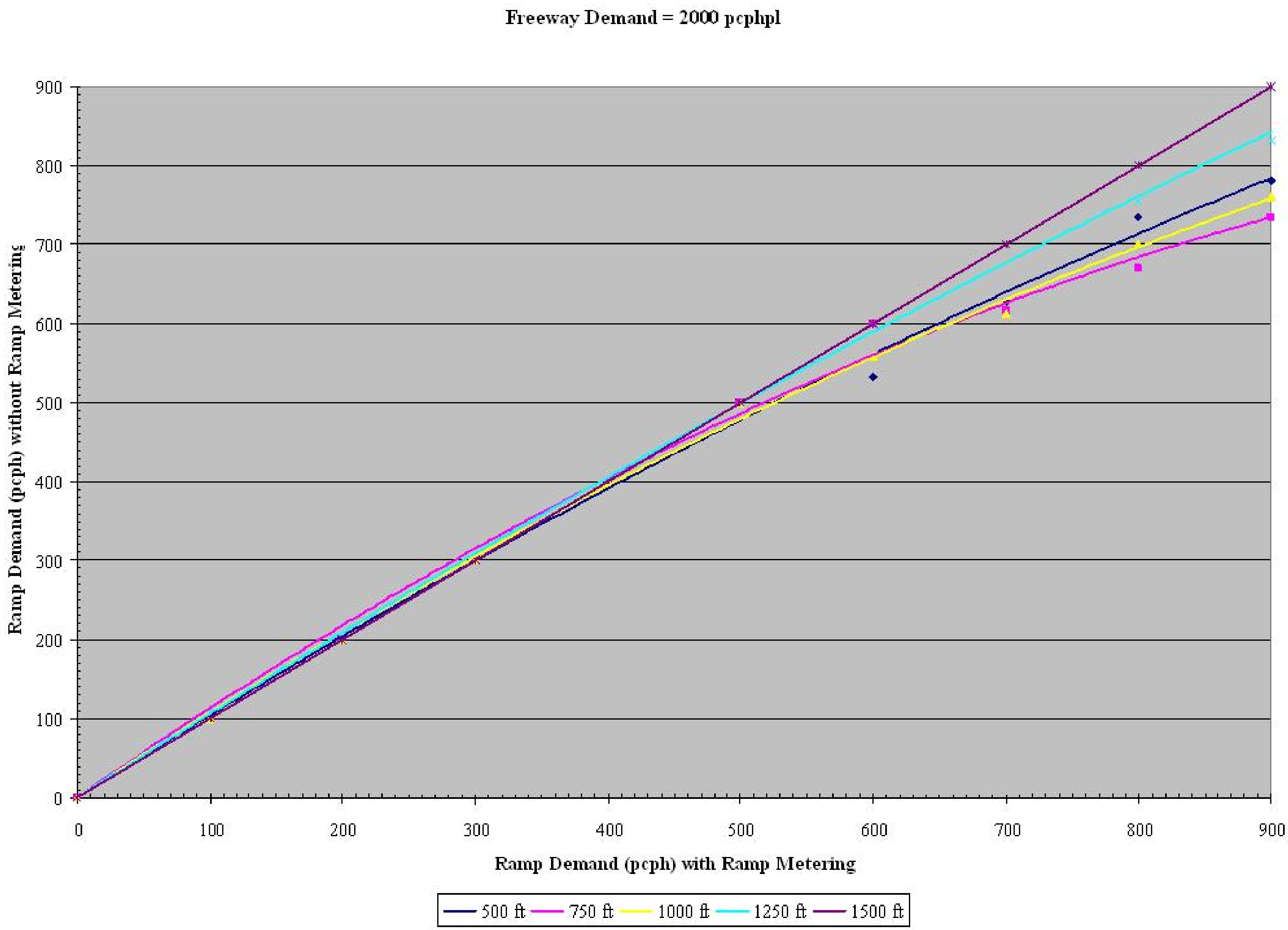


Figure 9. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2000 pcphpl

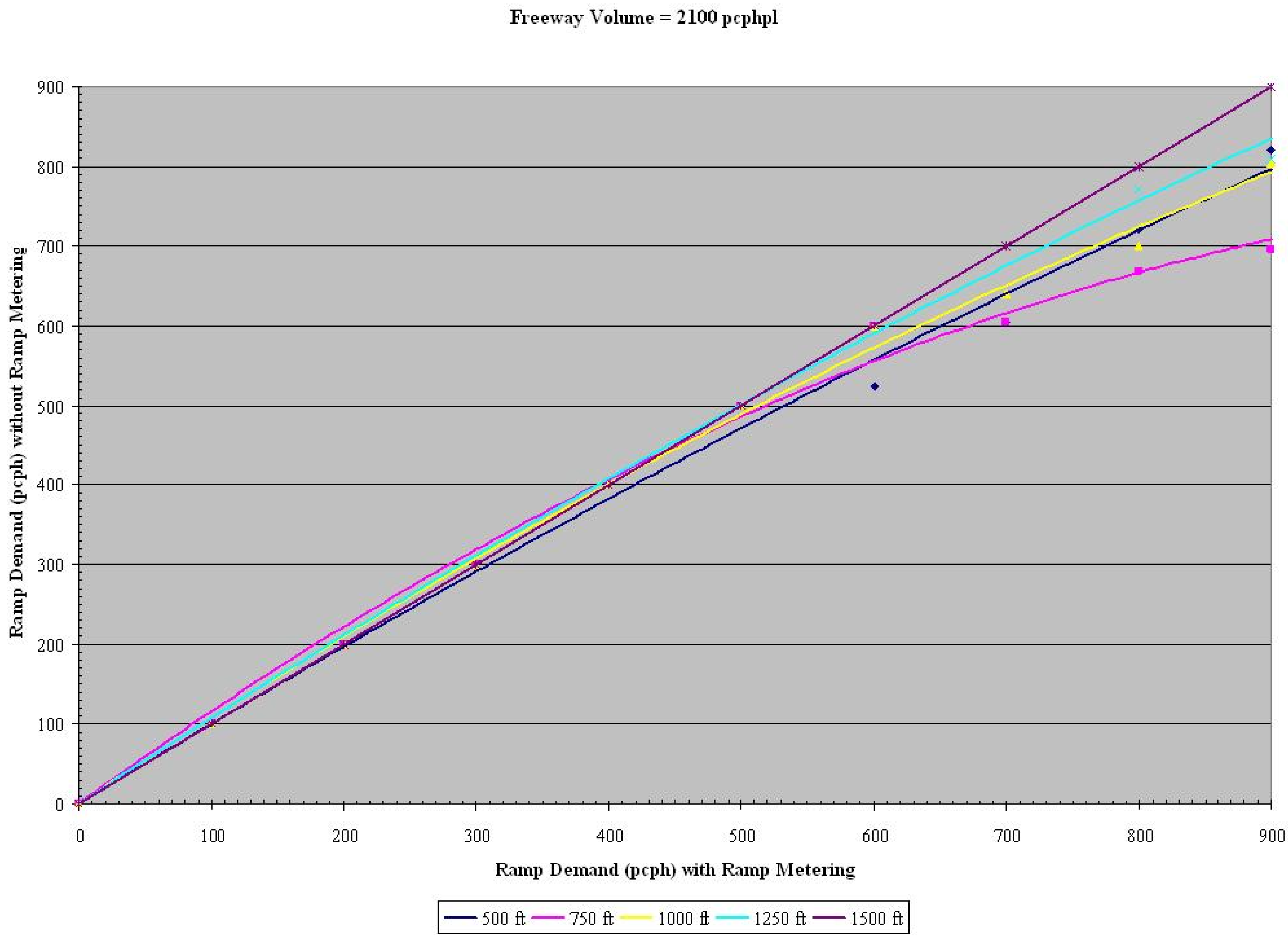


Figure 10. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2100 pcphpl

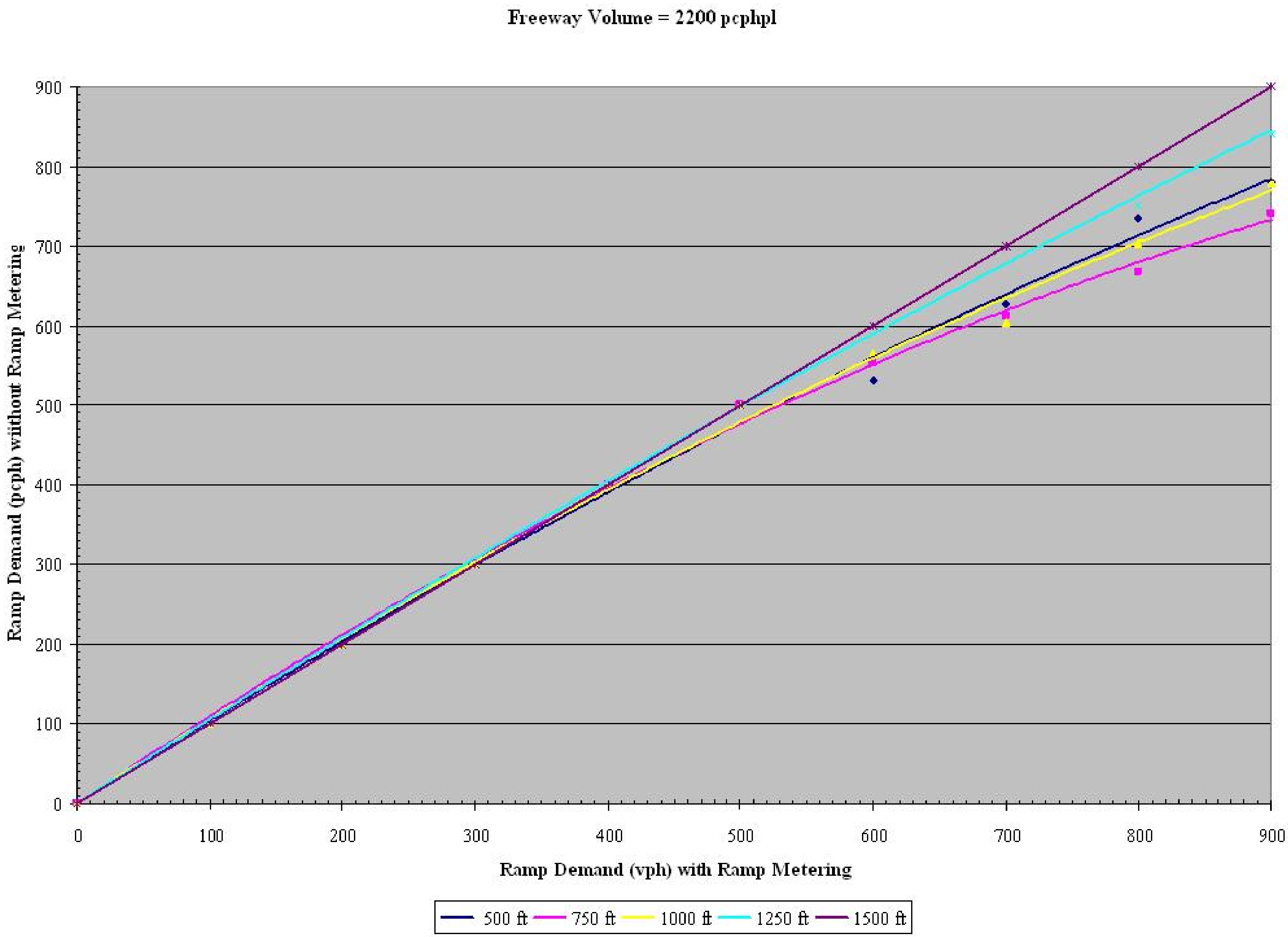


Figure 11. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2200 pcphpl

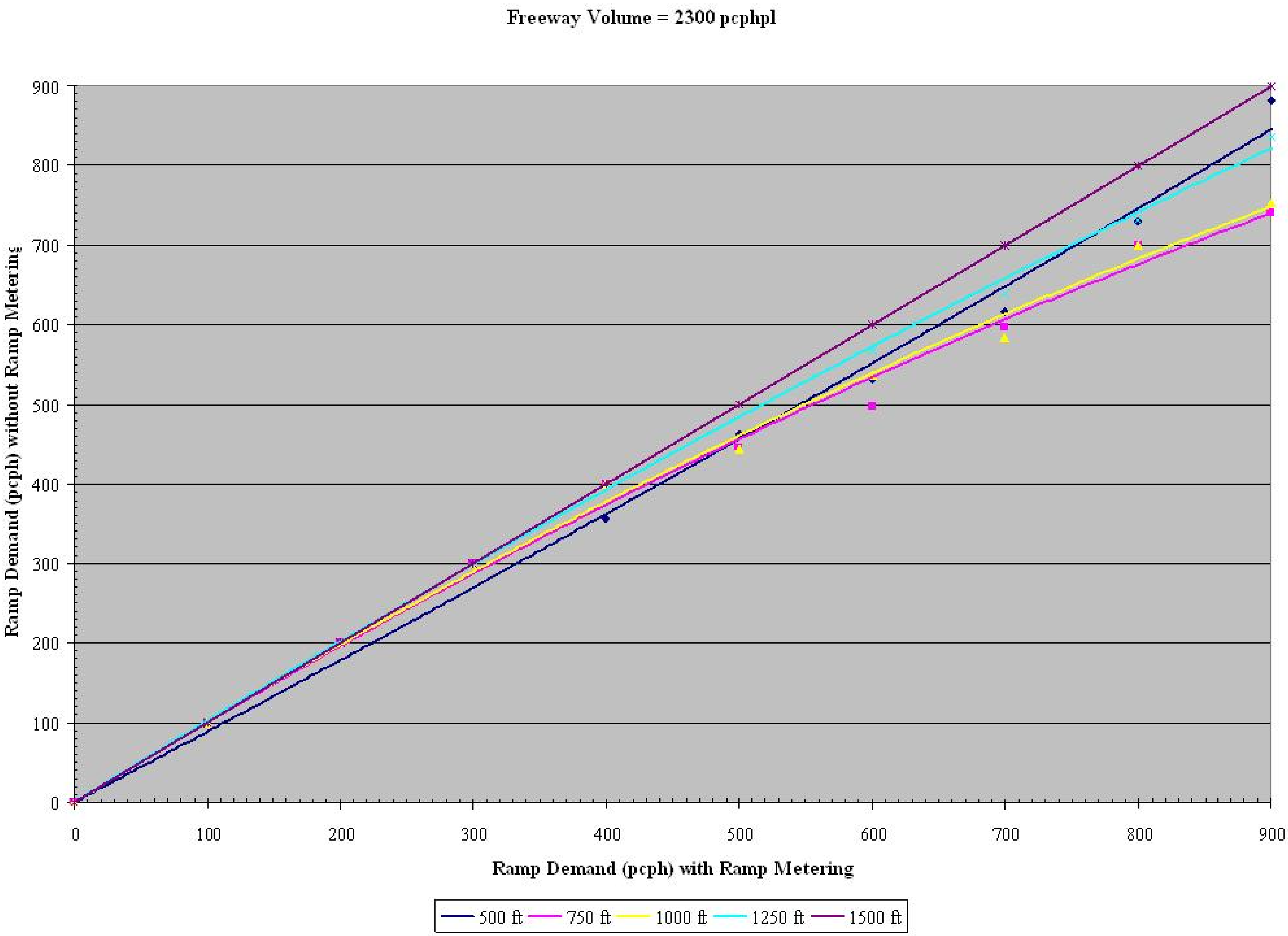


Figure 12. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2300 pcphpl

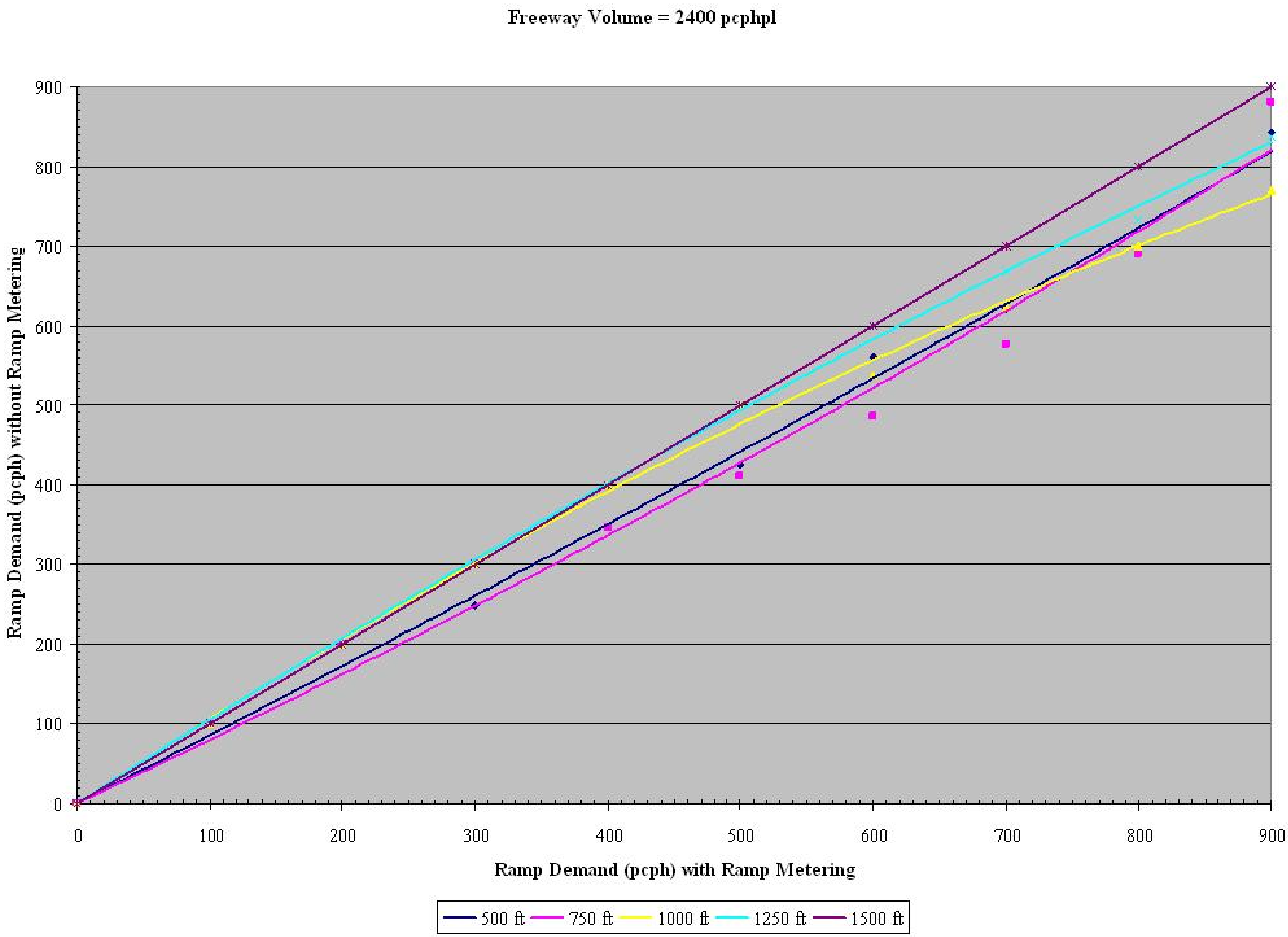


Figure 13. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2400 pcphpl

To use the graphs, a practitioner would first find the series of graphs which correspond to the prevailing freeway volume conditions. For purposes of illustration, let us say that the demand on the freeway is equal to 2200 passenger cars per hour per lane. After determining which series of graphs to use (Figure 11), the practitioner would then locate on the x-axis the amount of traffic that currently exists on the ramp (in our example, let us say that it is 680 pcph). To determine the equivalent amount of ramp traffic to achieve the same level of performance on the freeway section if a ramp meter was installed, the practitioner would then travel up from the x-axis to the line corresponding to the length of the ramp acceleration lane (in this case, 750 ft). Then moving to the left parallel to the x-axis, the practitioner would find the amount to ramp traffic that could be supported on the ramp without installing a ramp meter (in our example 615 pcph). With this number, the practitioner could then determine the amount of traffic that needs to be diverted from the ramp by the managed lane strategy in order to achieve the same level of performance on the freeway if a ramp meter was installed at the ramp – in our example, the amount of traffic that would need to be diverted away from the ramp by a managed lane strategy equals 65 pcph.

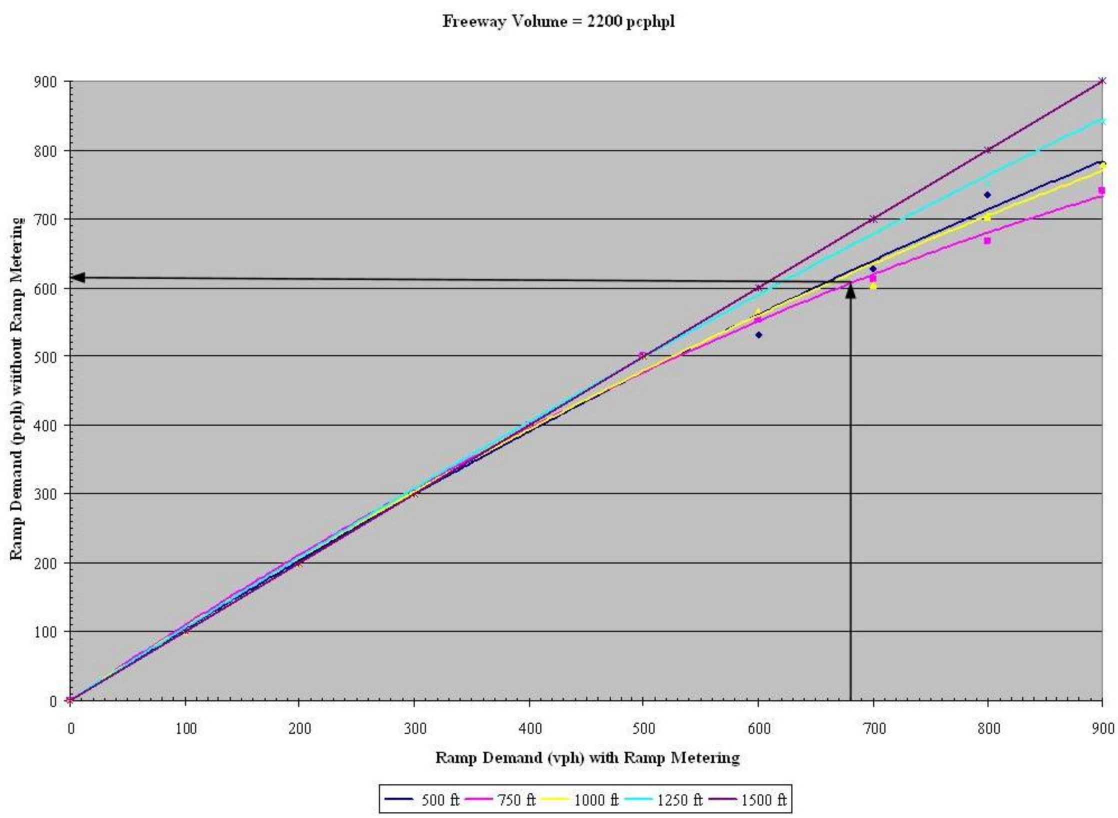


Figure 14. Illustration of Use of Ramp Demand Curves to Determine Amount of Traffic to Be Diverted by Managed Ramp Strategy.

Table 31. Summary of "Best Fit" Regression Equation for Estimate Non-Meter Ramp Demand to Obtain Equivalent Operations with Ramp Metering.

Freeway Demand Level (pcphpl)	Ramp Acceleration Lane Length (ft)	"Best-Fit" Regression Equation	R-Squared Value
1800	500	$y = -0.000119117647058832x^2 + 1.06379411764706x$	0.9977
1900	500	$y = -0.000244875222816403x^2 + 1.11855169340464x$	0.9959
2000	500	$y = -0.000213179590017834x^2 + 1.10635398841354x$	0.9969
	750	$y = -0.000390485739750451x^2 + 1.16794162210339x$	0.9951
	1000	$y = -0.000290987076648850x^2 + 1.10454344919786x$	0.9984
	1250	$y = -0.000156818181818900x^2 + 1.07731818181819x$	0.9986
2100	500	$y = -0.000143538324420683x^2 + 1.01472459893048x$	0.9936
	750	$y = -0.000462577985739756x^2 + 1.20355102495544x$	0.9934
	1000	$y = -0.000242535650623890x^2 + 1.09952094474154x$	0.9970
	1250	$y = -0.000185160427807494x^2 + 1.09471925133690x$	0.9974
2200	500	$y = -0.000212455436720150x^2 + 1.06207798573976x$	0.9967
	750	$y = -0.000348919340463463x^2 + 1.12882865418895x$	0.9981
	1000	$y = -0.000260594919786101x^2 + 1.08922972370767x$	0.9974
	1250	$y = -0.000146167557932272x^2 + 1.07087344028521x$	0.9987
2300	500	$y = 0.0000681595365418855x^2 + 0.878904188948312x$	0.9936
	750	$y = -000224821746880575x^2 + 1.02514527629234x$	0.9948
	1000	$y = -0.000224721479500894x^2 + 1.03409157754011x$	0.9964
	1250	$y = -0.0001373217468805770x^2 + 1.03739527629234x$	0.9986
2400	500	$y = 0.0000656417112299412x^2 + 0.850622994652412x$	0.9946
	750	$y = 0.000140318627450974x^2 + 0.785703431372553x$	0.9814
	1000	$y = -0.000260238413547245x^2 + 1.08385360962567x$	0.9981
	1250	$y = -0.00016468360071302x^2 + 1.0703453654189x$	0.9988

Table 31 shows the "best fit" regression equations and the regression correlation coefficient (R-squared value) for each line shown in Figures 4 through 10. Individuals can use these equations to estimate the non-metered ramp demand that would produce an equivalent level of operations on a freeway segment, if the ramp were metered. Using these equations, we produced Table 32, which shows the amount of demand that must be diverted away from a ramp by a managed lane strategy to achieve an equivalent level of operation on the freeway segment if ramp meters were to be deployed at the ramp. This table provides estimates of demand only where the performance of the freeway was measured to be statistically significant when ramp metering was used compared to when it was not used. This table shows that a managed lane strategy needs to be able to divert approximately 10 to 20 percent of the initial demand from the ramp in order to produce the same effect on freeway performance as installing a ramp meter.

Table 32. Percentage of Demand That Must Be Diverted from Ramp by Managed Lanes Strategies.

Freeway Demand Level (unit?)	Ramp Acceleration Lane Length (ft)	Ramp Demand (pcph) with Metering	Equivalent Ramp Demand (pch) without Metering	Diverted Demand (pchp)	Percent Diverted Demand
1800	500	900	861	39	4.34%
1900	500	900	808	92	10.18%
2000	500	800	714	86	10.70%
		900	785	115	12.83%
	750	900	735	165	18.35%
	1000	900	758	115	15.73%
	1250	900	843	57	6.38%
2100	500	600	557	43	7.14%
		700	640	60	8.57%
		800	720	80	10.01%
		900	797	103	11.45%
	750	700	616	84	12.03%
		800	667	133	16.65%
		900	709	191	21.28%
	1000	900	793	107	11.88%
	1250	800	757	43	5.34%
2200	500	600	561	39	6.54%
		700	639	61	8.66%
		800	714	86	10.79%
		900	784	116	12.91%
	750	600	552	48	8.05%
		700	619	81	11.54%
		800	680	120	15.03%
		900	733	167	18.52%
	1000	700	635	65	9.32%
		800	705	95	11.92%
		900	769	131	14.53%
	1250	900	845	55	6.07%
2300	500	400	362	38	9.38%
		500	456	44	8.70%
		600	552	48	8.02%
		700	649	51	7.34%
	750	500	456	44	8.73%
		600	534	66	10.97%
		700	607	93	13.22%
		800	676	124	15.47%
		900	741	159	17.72%
	1000	500	461	39	7.83%
		600	540	60	10.07%
		700	614	86	13.22%
		800	683	117	15.47%
		900	749	151	17.72%
	1250	700	659	41	5.87%

Table 33. Percentage of Demand That Must be Diverted from Ramp by Managed Lanes Strategies (Cont.)

Freeway Demand Level (unit?)	Ramp Acceleration Lane Length (ft)	Ramp Demand (pcph) with Metering	Equivalent Ramp Demand (pch) without Metering	Diverted Demand (pchp)	Percent Diverted Demand
2400	500	400	351	49	12.31%
		500	442	58	11.66%
		600	534	66	11.00%
		700	628	72	10.34%
	750	500	428	72	14.41%
		600	522	81	13.01%
		700	619	82	11.61%
		800	718	79	10.20%
		900	821	43	8.80%
	1000	600	557	43	7.23%
		700	631	69	9.83%
		800	701	99	12.43%
		900	765	135	15.04%
	1250	900	830	70	7.79%

Summary and Conclusions

Although ramp meters have been shown to be an effective tool at helping to maintain efficient traffic flow on a segment of freeway, many agencies are hesitant to install ramp meters because of potential negative public opinion. Managed lane strategies offer the potential to manage traffic demand on a facility. The purpose of this study was to assess the feasibility of using managed lanes strategies applied to a ramp as an alternative to installing a ramp meter. Specifically, we wanted to determine the amount of traffic that needed to be diverted away from an entrance ramp, presumably by a managed lane strategy, to achieve an equivalent level of operation on a freeway segment that used ramp metering.

Using simulation, we compared the performance of a freeway segment with and without ramp metering. We used two measures to assess the performance of the freeway: average running speed and throughput. Our simulation studies showed that ramp metering was able to maintain higher average running speeds and allow more throughput in a section of freeway than if ramp metering was not used in the segment. We then used the results of this analysis to determine what level of demand on a non-metered ramp would produce the same performance on the freeway that used ramp metering. We found that, on average, a managed lane strategy needs to be able to produce a 10 to 20 percent reduction in ramp demand to achieve the same level of operation on a freeway segment than if ramp metering was used on the same segment. Additional research is needed to determine which managed lane strategies would be most effective at achieving this level of demand reduction.

MODELING MANAGED RAMPS IN SUPPORT OF INCIDENT MANAGEMENT

In recent years, transportation engineers have been using innovative approaches and technologies to address traffic congestion on highways. Over the past few decades, managed lane strategies have become more prevalent in addressing congestion issues. Most of the research focused on these managed lane strategies has been based on pricing, accessibility, and user classifications. In addition, these strategies have all focused on freeway mainlane traffic with great success. However, there has been little research on applying these strategies to ramps. In general, the most well sought out approach to analyzing traffic patterns of managed lane facilities was to use state-of-the-art simulation models. Engineers today rely more and more on these simulation models to forecast and predict travel patterns of the traveling public based on network configuration, peak congestion, and viable operational strategies. The research component of this scenario is to apply managed lane strategies to various scenarios in response to incident and special event management. For incident management, the research team used several different types of incident severity in conjunction with the ramp management scenarios including tier 1 and tier 3 accidents. The first component of this scenario focuses on microscopic simulation in response to incident management. The second component of scenario 2 is to analyze incident management from a more system-wide level. The final component of scenario 2 focuses on a microscopic simulation to analyze ramp management scenarios in response to special events.

Since this portion of the managed lane study is committed to freeway ramps that support ramp management within a specified section of corridor, the managed lane strategies implemented at each access point are associated with vehicle class restrictions, accessibility, and pricing. The most widely used form of vehicle class restriction includes truck-restricted lanes. This specified research scenario looks at restricting trucks, cars, and buses independently as well as in various combinations to see how these restrictions relate to travel time and freeway queuing in response to incident and special event management. The research team also used a mesoscopic simulation tool capable of analyzing various pricing schemes as well as vehicle eligibility restrictions. The mesoscopic model analyzes traffic on a link-by-link basis as well as on a system-wide level. Researchers compared output from both models to validate performance measure results.

Purpose

The incentive for analyzing various vehicle class restrictions in support of incident/special event management is to provide insight on freeway dynamics and the relationship between single versus multiple vehicle restrictions in concurrence with ramp management. The research team also wanted to ensure that the use of any procedure developed from this analysis indicates whether or not ramp management restrictions is a viable option in support of congestion management as it relates to accidents and special events. They also wanted to verify whether pricing had any significant impact on ramp management.

Currently, operational strategies that support incident management include total ramp closure and Intelligent Transportation Systems (ITS) where travelers are informed of lane closures either pre-trip or en route. Although the basis of this research does not include advanced warning of congestion, it may give insight to Traffic Management Centers (TMCs) on how a facility currently operates in support of an accident and how pre-trip and/or en route information may or may not improve travel time for motorists. Modeling each ramp management scenario gives facility owners insight on how various combinations of strategies operate and which is the most viable option given the mix and percentage of vehicles currently using the facility. Operational strategies that support special events also include ITS technologies that give en route information pertaining to specific congestion locations. Regulating the amount of flow through a specific off-ramp could benefit not only freeway mainlanes but also overall network performance.

Ramp Management Scenarios Supporting Managed Lanes

The research team encountered several obstacles when trying to analyze ramp management strategies in support of incident management. The first issue that came to the forefront was the location of the simulated incident. Accidents are random occurrences and their location cannot be predicted with any degree of accuracy. The research team had to keep the range of possible modeled scenarios for accident locations within a practical limit and therefore used one location for all scenarios modeled. They replicated a section of freeway and used it as the foundation of all model runs. The second issue that arose was the amount of volume to use when modeling various vehicle eligibility restrictions. The research team used weekend traffic volumes, as this provided a greater degree of variability when analyzing one managed ramp versus several simultaneous ramps. The final issue that arose was whether or not to use dynamic traffic assignment for each simulation scenario. While VISSIM is capable of differentiating various vehicle classes while concurrently running dynamic traffic assignment, the model did have a limitation of closing a specific link in the middle of the simulation. This link closure was necessary in the analysis of incident management. In other words, the model could not close a specific ramp to certain vehicle classes in the middle of simulation (when an accident occurs) while using dynamic traffic assignment. Therefore, the research team used static assignment with a special script that would dynamically reroute traffic when congestion levels reached certain thresholds (i.e., freeway density increase upstream of accident). The fact of the matter remained as to whether it was necessary to use a model capable of performing dynamic traffic assignment (DTA) to validate traffic diversion caused by freeway congestion. Ultimately, the team decided to use both types of models and compare results based upon a predefined set of scenarios. The various factors that the research team eventually chose were based upon hypothetical freeway incident situations.

The research team also encountered difficulties when trying to analyze ramp management strategies in support of special events. Again, the microscopic simulation software was not capable of closing specific ramps during the simulation while utilizing DTA. Therefore it was also necessary to use static assignment with dynamic routing in support of special event scenarios. The research team used a mesoscopic model of Fort Worth, Texas, to validate microscopic simulation results.

A separate section of El Paso freeway adjacent to the University of Texas at El Paso (UTEP) was replicated and used as the basis for special event management. Special event scenarios used the first week of fall semester traffic data as the basis of this research component. The first week of school during the fall semester has major traffic congestion in and around the UTEP campus. The majority of all students, faculty, and staff tend to use the main campus entrance that is fed from IH-10 westbound at exit 18A (Schuster Avenue). Traffic volumes and turning percentages for exit ramp 18A (Schuster Avenue) and IH-10 were collected from the

University Master Plan *Campus Entrance Realignment Study* performed by the UTEP transportation laboratory and input into the VISSIM model *(49)*. The research team modeled two scenarios including restricting student vehicles and total ramp closure, both of which refer to dynamic ramp closure. In essence, the length of queue spillback dictates (activates) the ramp management strategies.

Incident Management (VISSIM)

Freeway Mainlanes

A section of IH-10 in El Paso, Texas, was replicated from entry ramp 32 (Zaragoza Boulevard) to entry ramp 26 (Hawkins Boulevard). Freeway mainlanes increase from three to four lanes at entry ramp 28A (McRae Boulevard). There are currently seven on-ramps on IH-10 westbound between Zaragoza and Hawkins, each of which is a single-lane entry point. The corridor speed limit is 60 mph and all lanes are general-purpose lanes. Grades for all entry ramps are less than 4 percent and have no significant impact on entry flow rate. Figure 15 shows corridor limits from ramp 32 (Zaragoza) to ramp 26 (Hawkins). Incident location for all scenarios is approximately 1200 ft downstream of Hawkins on ramp 26 as shown in Figure 16.

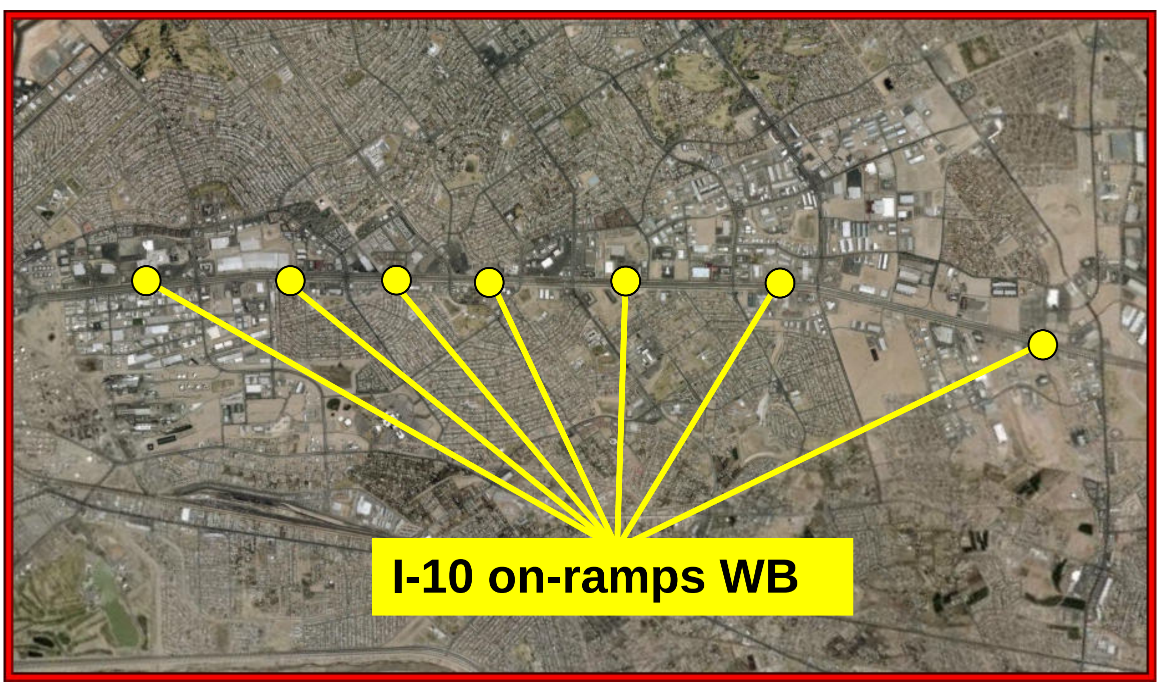


Figure 15. Managed On-Ramps – El Paso, Texas.

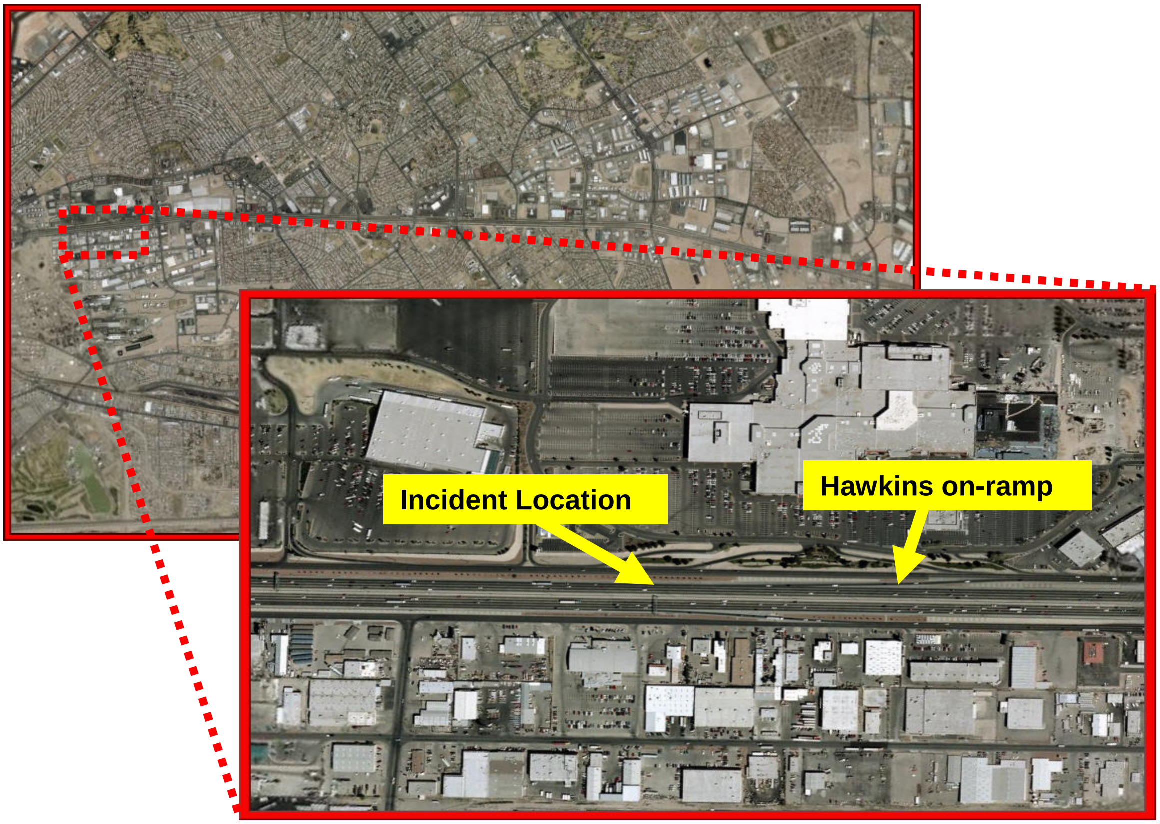


Figure 16. Simulated Incident Location – IH-10, El Paso, Texas.

Freeway Vehicle Mix

Since IH-10 in El Paso, Texas, is currently a non-tolled facility, all private vehicle classes are classified as one vehicle type. The vehicle class composition in El Paso has a high volume of truck traffic, usually ranging somewhere around 9 to 10 percent. Transit vehicles also have several routes that traverse through this corridor section of freeway. Therefore, a "normal mix" was chosen to include 90 percent cars, 9 percent trucks, and 1 percent buses.

Freeway Volume

Traffic volumes for every freeway facility vary by time of day and by day of week. Due to the various combinations of volumes that can be analyzed at any given time period, the research team chose one specific traffic volume for all modeled scenarios. A freeway volume of 1250 vehicles per lane, which is the approximate equivalent performance LOS "C" according to the *Highway Capacity Manual* (50), was chosen for model input.

Ramp Merge Condition

Two basic geometric design configurations exist on the IH-10 study area including a direct (forced) merge and the creation of an additional lane (free-flow ramp). In the direct merge areas, vehicles entering the facility on-ramp simply merge directly with the rightmost freeway lane. Vehicles entering the freeway must find an acceptable gap to merge with mainlane traffic and adjust their speed to do so. In the case of a free-flow ramp, vehicles entering the facility are not subjected to merge conditions and therefore create smoother transition of traffic flow.

Vehicle Mix/User Group

The freeway vehicle mix used for the selected freeway mainlanes and on-ramps consisted of one defined traffic composition. A traffic composition defines the vehicle mix of each input flow to be defined for the model network *(51)*. The traffic composition consisted of a mix of 90 percent automobiles, 9 percent trucks, and 1 percent buses. Since El Paso currently has no active managed lanes, HOVs were not used in the analyses.

Ramp Volume

Entry volumes on each of the defined on-ramps are dynamic and change constantly. Due to the various combinations of traffic volumes that can be analyzed at any given time period, the research team also used one specific set of entry volumes for all defined scenarios. Table 34 shows entry volumes for all seven freeway on-ramps.

Table 34. On-Ramp Entry Volume.

Name	Ramp Number	Entry Volume (vph)
Zaragoza Dr.	32	700
Lee Trevino Dr.	30	700
Lomaland Dr.	29	250
Yarbrough Dr.	28B	500
McRae Blvd.	28A	450
Viscount Blvd.	27	300
Hawkins Blvd.	26	400

Severity of Simulated Accident

All accidents occur randomly with various degrees of severity. In accordance with these random events, the research team modeled four different types of accidents ranging from tier 1 to tier 3. Tier 1 accidents refer to incidents that block only one lane of traffic whereas tier 3 incidents block all lanes. For simplicity purposes, the researchers simulated the accident locations in the same corridor section. The difference between scenarios was the amount of flow reduction caused by lane closures. A total of four separate scenarios were modeled using different degrees of incident severity.

Per Lane Spacing of Entrance Ramps

Spacing between successive on-ramps plays a crucial role in the amount of merging/weaving. Greater distances between successive on-ramps give way to greater gap distances between vehicles entering the facility and mainlane traffic flow. Larger gap distances between vehicles create less turbulence on mainlanes and ultimately smoother transition of traffic flow. The spacing between each on-ramp was measured from gore to gore and the distance was recorded below as shown in Table 35.

Table 35. Spacing between Entrance Ramps.

Location	Distance (ft)
Viscount Blvd. to Hawkins Blvd.	4910
McRae Blvd. to Viscount Blvd.	3050
Yarbrough Dr. to McRae Blvd.	4825
Lomaland Dr. to Yarbrough Dr.	5140
Lee Trevino Dr. to Lomaland Dr.	2460
Zaragoza Blvd. to Lee Trevino Dr.	9299

Performance Measures for Incident Management (VISSIM)

In the context of managed ramps in support of incident management, the ultimate effectiveness of ramp management is gauged not only by the balance of traffic flow around the accident area, but also the flow of traffic upstream of the incident. The most scrutinized performance measure during an accident is queue length and, more importantly, travel time. The research team used these two measures-of-effectiveness to gauge the performance of various vehicle class restrictions and accessibility during each of the defined accident scenarios.

Queue Length

As with any freeway incident, queuing lengths propagate with time. Depending on the severity and amount of flow restricted through the accident area, queue lengths can grow to several miles within a short period of time. For this reason, the research team chose queue length as one of their performance measures. The ability to gauge the propagation of vehicle spillback by managing the upstream ramps can give stakeholders better insight on which type of vehicles to restrict or give access to during incidents.

Travel Time

One of the most analyzed and scrutinized performance measures is travel time. Travel time prediction can vary by time of day, hours of congestion, and even weather conditions. Travel time prediction during an incident becomes even more challenging. Most cities that post travel times on freeway dynamic message signs (DMS) usually remove them when accidents occur because of the uncertainty. For this reason, the research team chose to use travel time as one of its key measures-of-effectiveness.

Incident Model Preparation (VISSIM)

The first task for researchers was to create a VISSIM model to test the various scenarios defined. The research team chose a section of IH-10 in El Paso, Texas, and replicated a 6-mile portion of the freeway in the westbound direction between exit 32 (Zaragoza) and exit 25 (Airway). The research team included all on- and off-ramps and the adjacent frontage road in the model as well as all interchanges and perpendicular intersections. The second step was to simulate an accident on the freeway mainlanes. VISSIM does not include accidents as identified input parameters, so the research team had to use a little ingenuity in creating a simulated accident. This accident simulation was done by inserting a traffic signal on the freeway mainlanes and setting the parameters so mainlane traffic would come to a complete stop at a predefined time interval. For this study, the research team used a total simulation time period of one hour (3600 seconds) and set the parameters to simulate the accident start time at 900 seconds and continue for the duration of the simulation. In essence, the accident time was 45 minutes

(2700 seconds) long. Loop detectors were placed immediately upstream of the accident location. Loop detectors were used to dynamically restrict various vehicles' classes on upstream ramps when speed dropped to zero on freeway mainlanes.

The next step was to calibrate the model so it would replicate real-world traffic conditions on a typical day on IH-10. The city provided signal timings, and the research team used green time allocations for frontage road traffic. Speed distribution for freeway ranged from 65 to 74.6 mph as shown in Figure 17. The majority of all vehicles traveling on the freeway had speeds below 70 mph with only a small percentage traveling between 70 and 74.6 mph. Speed reduction areas were needed as part of the calibration process. Vehicles traveling on roadways perpendicular to the freeway must decelerate when making right turns onto the frontage road. A speed reduction range of 2.5 to 15.5 mph was used. For vehicles exiting the freeway via off-ramps, a speed reduction range of 36 to 42.3 mph was used. A deceleration rate of -6.562 ft/s^2 was used in all speed reduction areas. Driver behavior parameters were kept at default settings.

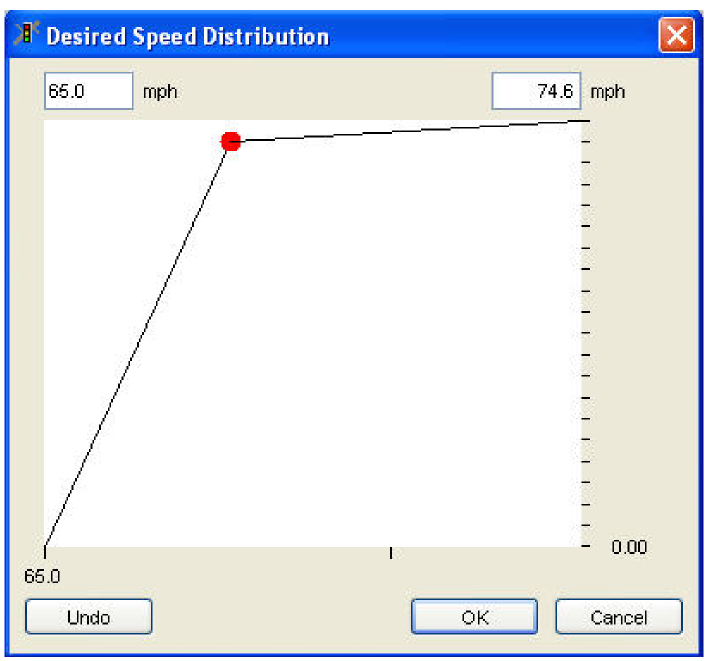


Figure 17. VISSIM Speed Distribution.

The next challenge to modelers was the development of vehicle mixes and features in the VISSIM model that represent vehicles operating on Texas roadways. This task is relatively simple in terms of automobiles and buses, since automobile performance is common across many countries and bus performance also does not vary widely. The size and configuration of trucks, however, is much different in European countries than in the United States in general. Since VISSIM was developed in Germany, many of its truck and trailer size, axle configuration, and weight characteristics are not well mated to heavy vehicles in the United States.

Several classification systems are used to stratify trucks. Both the "Texas 6" and FHWA systems are shown in Table 36. Previous research *(52)* was the guide in determining what types of trucks were typically found in Texas and what percentages of the truck traffic stream each comprised. The source of these data were TxDOT Automatic Traffic Recorder (ATR) stations (see Table 37), which record traffic volumes and classification on a year-round basis and provide permanent historical records of traffic conditions. Again, the research team used previous research on truck roadways in Texas *(52)* to identify heavy vehicles' properties and develop simulated counterparts in VISSIM. Table 38 is the result of combining the Texas truck type percentages in its fleet with characteristics of these trucks. Adapting each of these truck types into VISSIM, employing its default truck and trailer features is shown in Table 39. Information contained in Tables 38 and 39 was ultimately coded into VISSIM to create a representative Texas truck fleet. In any simulation where trucks were a part of the vehicle stream, those trucks were distributed according to the percentages shown and have the characteristics noted. The research team ultimately created a vehicle composition to complete the coding necessary in VISSIM. The distribution of vehicles for the traffic composition included 90 percent cars, 9 percent trucks, and 1 percent buses.

Table 36. Truck Classification Schemes.

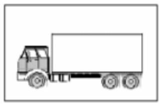
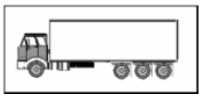
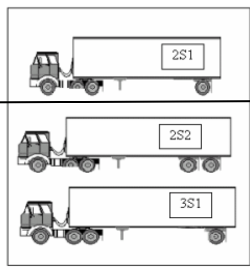
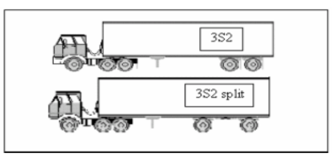
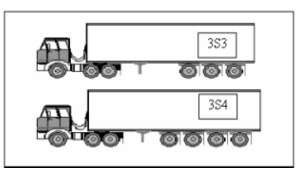
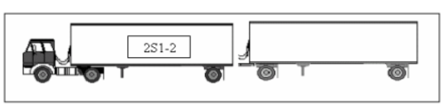
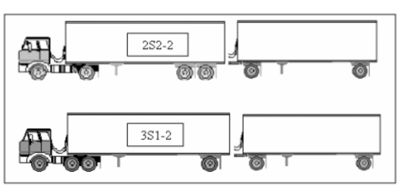
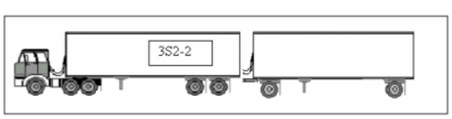
Typical Vehicle Type	Texas 6 Classification	FHWA Classification
	**Class 5**: 3 axles, single unit	**Class 6**: 3 axles, single unit
	**Class 6**: 4 or more axles, single unit	**Class 7**: 4 or more axles, single unit
	**Class 7**: 3 axles, single trailer	**Class 8**: 3 to 4 axles, single trailer
	Class 8: 4 axles, single trailer	
	**Class 9**: 5 axles, single trailer	**Class 9**: 5 axles, single trailer
	**Class 10**: 6 or more axles, single trailer	**Class 10**: 6 or more axles, single trailer
	**Class 11**: 5 or less axles, multi-trailers	**Class 11**: 5 or less axles, multi-trailers
	**Class 12**: 7 or more axles multi-trailers	**Class 12**: 6 axles, multi-trailers
	**Class 13**: 6 axles, multi-trailers	**Class 13**: 7 or more axles, multi-trailers

Table 37. Truck Type Distribution for Texas Conditions (52).

Texas 6 Truck Class	ATR Station 13D (40 Percent Weight) (Daily Volume - veh)	ATR Station 198 (60 Percent Weight) (Daily Volume - veh)	Final Distribution (Percent)
5	345	546	8.2
6	48	53	0.9
7	6	6	0.1
8	180	62	1.9
9	3169	5817	83.5
10	49	20	0.6
11	135	285	3.9
12	36	60	0.9
13	0	1	0.0

Table 38. Truck Characteristics Applied to Texas Truck Fleet – Incident Management Scenario.

Truck Class	Relative Flow	Length (ft)	Width (ft)	Weight (lb)		Power (hp)	
				Min.	Max.	Min.	Max.
5	0.004	27.89	8	15,000	46,000	220	260
6	0.001	27.89	8	20,000	53,000	220	300
7	0.000	30.94	8	25,000	52,000	250	300
8	0.001	36.13	8	28,000	66,000	315	380
9	0.042	60.22	8	30,000	80,000	380	480
10	0.000	55.39	8	32,000	87,000	415	490
11	0.002	70.69	8	35,000	92,000	440	500
12	0.040	67.24	8	35,000	106,000	505	525
13	0.000	92.35	8	35,000	120,000	570	580

Table 39. Texas Truck Fleet Translated into VISSIM Truck Types.

Truck Class	VISSIM Truck/Trailer	Truck Composition	Length (ft)	Shaft Length (ft)	Front Clutch (ft)	Front Axle (ft)	Rear Axle (ft)	Rear Clutch (ft)
5	truckUS_1.v3d	0.5	27.89	1.21	1.21	2.91	23.58	26.07
	truckUS_5.v3d	0.5	27.89	0.56	0.56	2.15	21.28	23.08
6	truckUS_1.v3d	0.5	27.89	1.21	1.21	2.91	23.58	26.07
	truckUS_5.v3d	0.5	27.89	0.56	0.56	2.15	21.28	23.08
7	truck1.v3b	1	18.25	0.00	0.00	5.18	15.39	13.60
	trail3b.v3b		21.66	0.00	4.32	4.33	17.90	21.47
8	truckUS2.v3d	1	16.40	0.85	0.85	2.25	14.06	12.32
	trail4.v3d		28.23	0.00	4.43	4.43	24.51	27.97
9	truckUS.v3d	1	20.67	0.00	0.00	2.27	18.23	16.61
	trailerUS3.v3d		47.57	0.00	3.96	40.85	43.97	46.14
10	truckUS_3.v3d	1	20.67	0.00	0.00	2.27	18.23	16.61
	trailerEuro1.v3d		42.65	0.00	3.87	3.87	32.05	41.41
11	truck1.v3b	1	18.25	0.00	0.00	5.18	15.39	13.60
	trail4.v3d		28.23	0.00	4.43	4.43	24.51	27.97
	trail3a.v3d		12.24	0.33	0.33	9.70	9.73	9.76
	trail4.v3d		28.23	0.00	4.43	4.43	24.51	27.97
12	truckUS3.v3d	1	20.67	0.00	0.00	2.27	18.23	16.61
	trail4.v3d		28.23	0.00	4.43	4.43	24.51	27.97
	trail3a.v3d		12.24	0.33	0.33	9.70	9.73	9.76
	trail3b.v3b		21.66	0.00	4.32	4.33	17.90	21.47
13	truckUS3.v3d	1	20.67	0.00	0.00	2.27	18.23	16.61
	trailerUS_3.v3d		47.57	0.00	3.96	40.85	43.97	46.14
	trail3a.v3d		12.24	0.33	0.33	9.70	9.73	9.76
	trail4.v3d		28.23	0.00	4.43	4.43	24.51	27.97

The final step in model setup was to place various travel time detection areas and queue length counters on freeway mainlanes. Travel time detectors were placed 5 miles upstream of the incident area. Queue length counters were placed immediately upstream of the incident area. VISSIM output files were converted to Excel spreadsheets and graphed.

Scenario Set Description for Incident Management (VISSIM)

The scenario sets included managing single and multiple ramps simultaneously with varying degrees of freeway lane closures due to a simulated accident. Figure 18 shows all the defined scenario sets that were modeled and analyzed. It must be noted that each individual scenario included 10 different random seed runs. Output data from all 10 random seeds were then averaged into tabular and graphical formats.

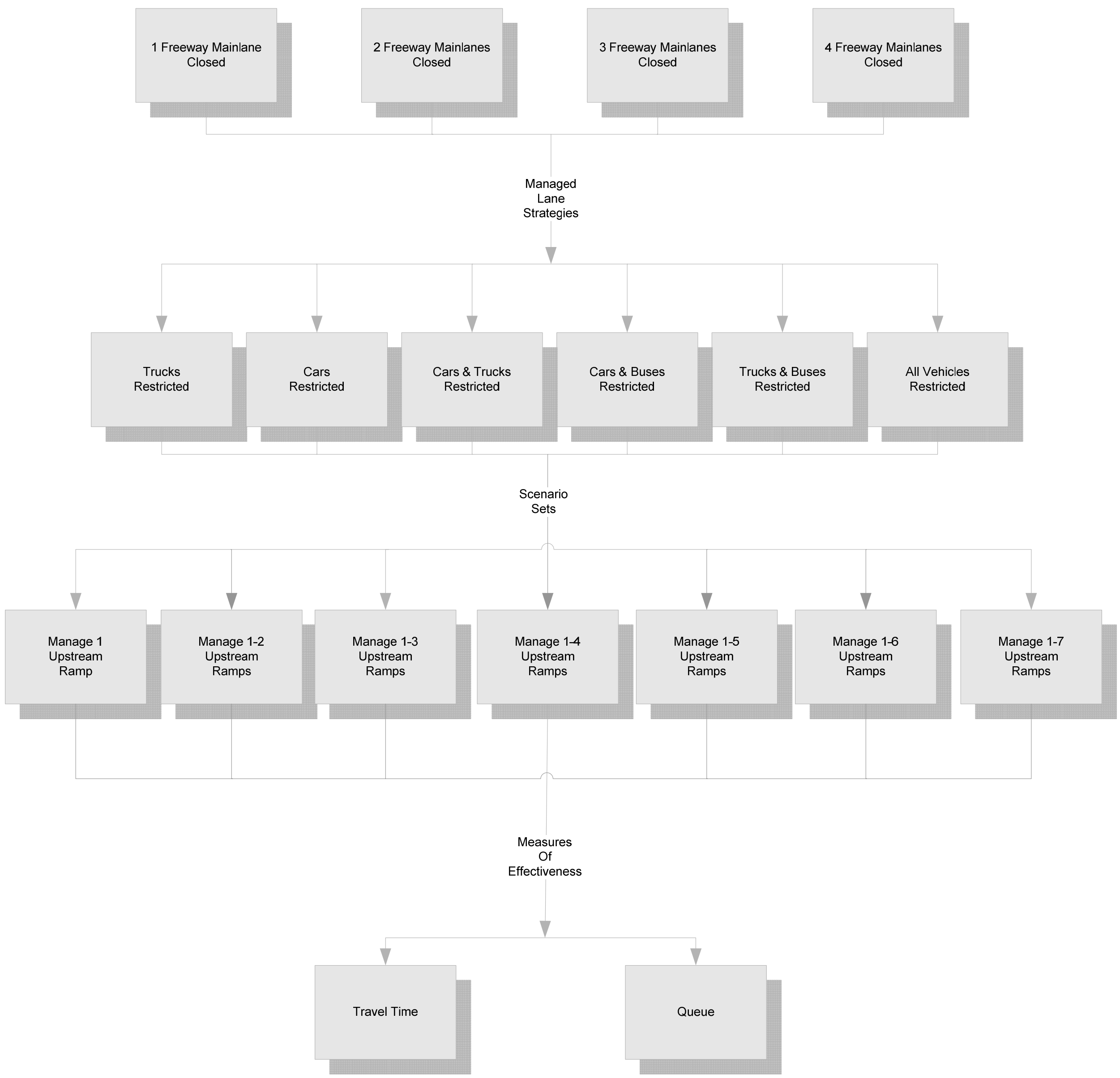


Figure 18. Flow Chart of Incident Management Scenarios.

Results

Researchers created various combinations of vehicle restriction scenarios to coincide with lane closures on freeway mainlanes resulting from simulated incidents of varying severity. Each of these scenarios was applied to single as well as multiple ramps upstream of the simulated incident area. It was necessary to run multiple random seed simulations of each scenario as recommended by the software developers. The research team ran 10 different random seeds for each defined scenario and each defined vehicle class restriction. In total, the research team coded and completed 1680 simulation runs. Various mixes of vehicle class restrictions were coded using a VAP logic that allowed researcher to run dynamic routing in static assignment mode. Researchers wrote a separate C++ program to run multiple random seeds within each defined scenario. The C++ program was able to output the designated measures-of-effectiveness into an offline program without overwriting data on each random seed run. Data were collected and graphs were generated in Excel for each scenario set.

After analyzing all graphical information from all the defined simulation models, the researchers determined that individual graphs for every defined scenario might confuse the intended audience. Data were consolidated and aggregated into compressed time intervals. This effort allowed the research team to easily interpret graphical results.

One Freeway Lane Closed

Researchers defined this scenario by simulating an incident on the freeway with one lane closed from time period 900 seconds to 3600 seconds. A speed reduction area in and around the incident area was included in the simulation model to represent "rubbernecking" of vehicles that slow down in the incident area. Figure 19 shows the distance of the reduced speed area and speed range reductions per lane**.**

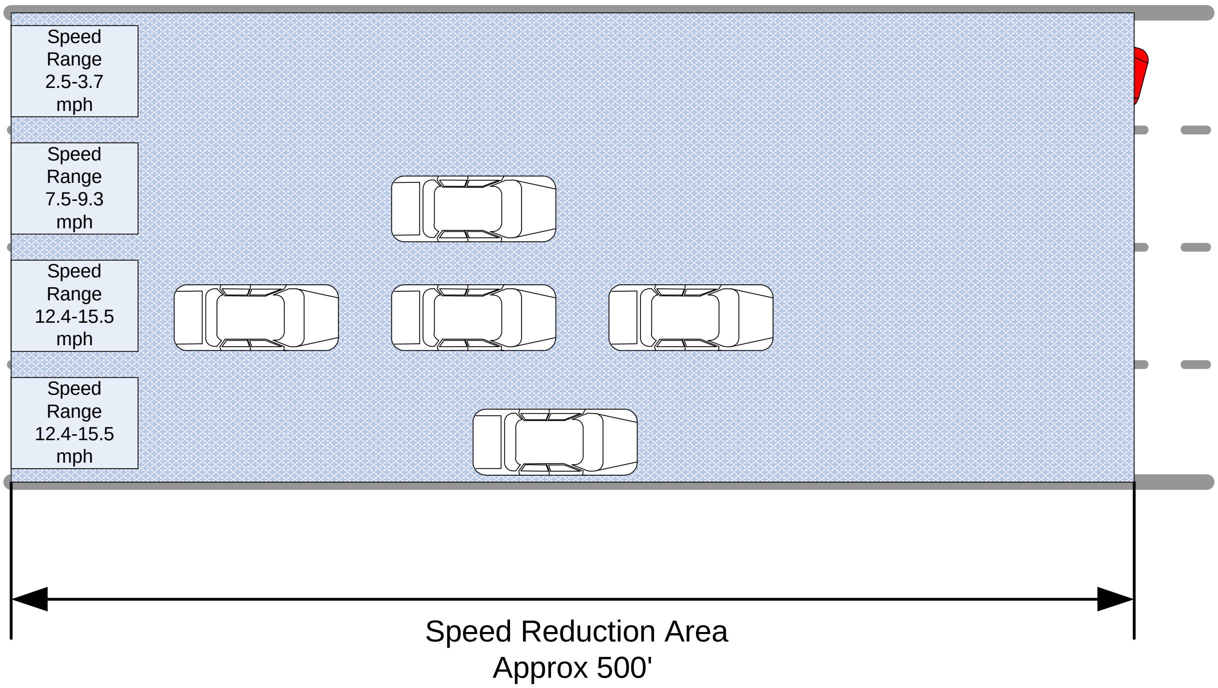


Figure 19. Speed Range Reduction for One Lane Closure.

Trucks Restricted

As specified in the scenario sets description figure, truck-restricted ramps were the first defined ramp management scenario. Trucks were not permitted to enter the freeway facility at the defined managed ramps for the duration of the simulated incident. When incrementally managing upstream ramps, performance measures on freeway mainlanes improved. The travel time for one to four ramps managed showed to have the highest travel time at 20.5 minutes, as shown in Figure 20, when comparing one ramp managed versus all seven ramps managed. Queue length reduced by 18 percent between only managing the first ramp versus restricting trucks from all seven upstream ramps, as shown in Figure 21.

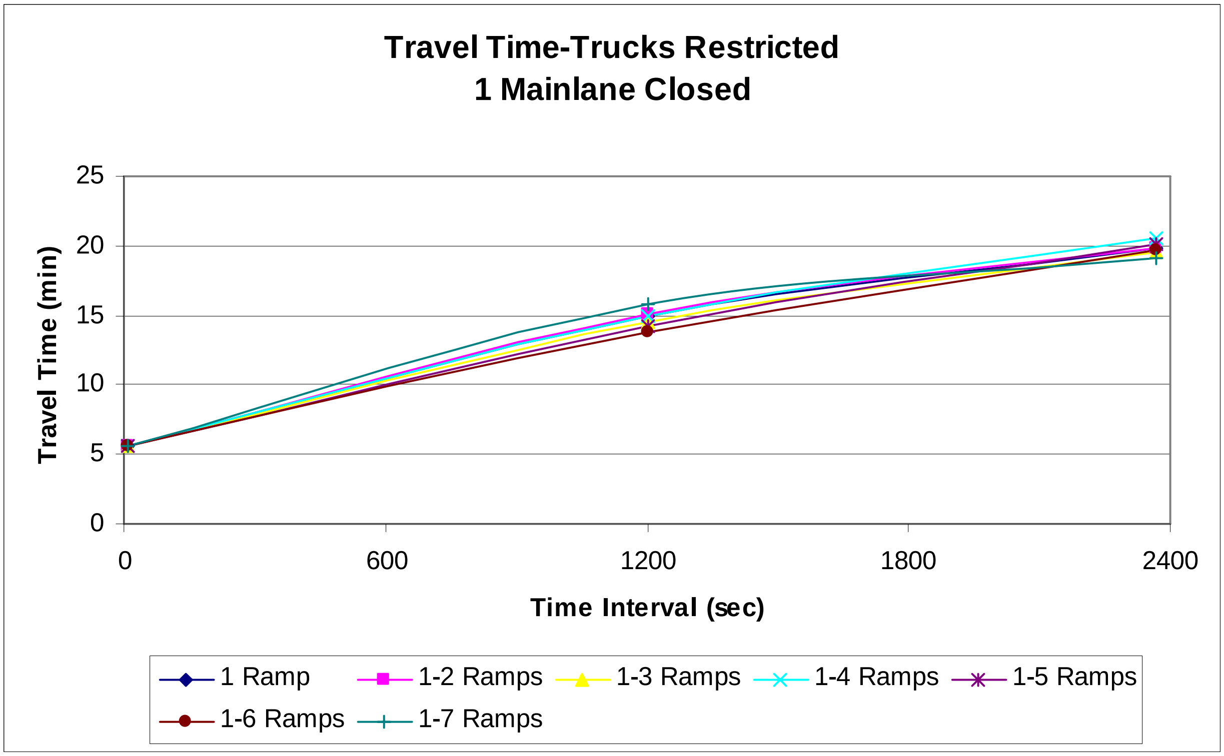


Figure 20. Travel Time Comparison – Trucks Restricted.

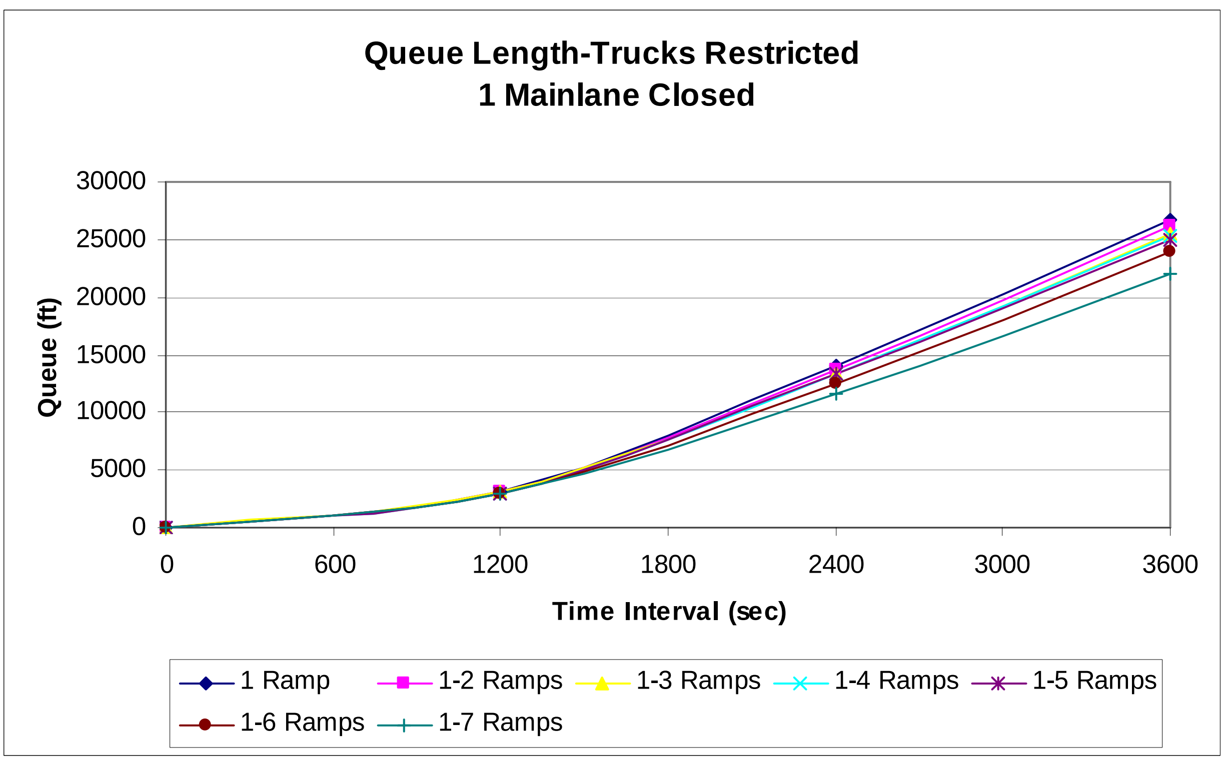


Figure 21. Queue Length Comparison – Trucks Restricted.

Cars Restricted

The cars-restricted scenario consisted of allowing only trucks and buses to enter the freeway facility during the accident time interval. Cars had the highest traffic composition percentage of 90 percent. Travel time decreased by 54 percent when comparing car restrictions for one ramp versus all seven ramps. Figure 22 depicts the trend of travel time for car-restricted ramps. Figure 23 is a representation of queue length propagation over time based on restricting cars from entering the freeway on one through seven ramps.

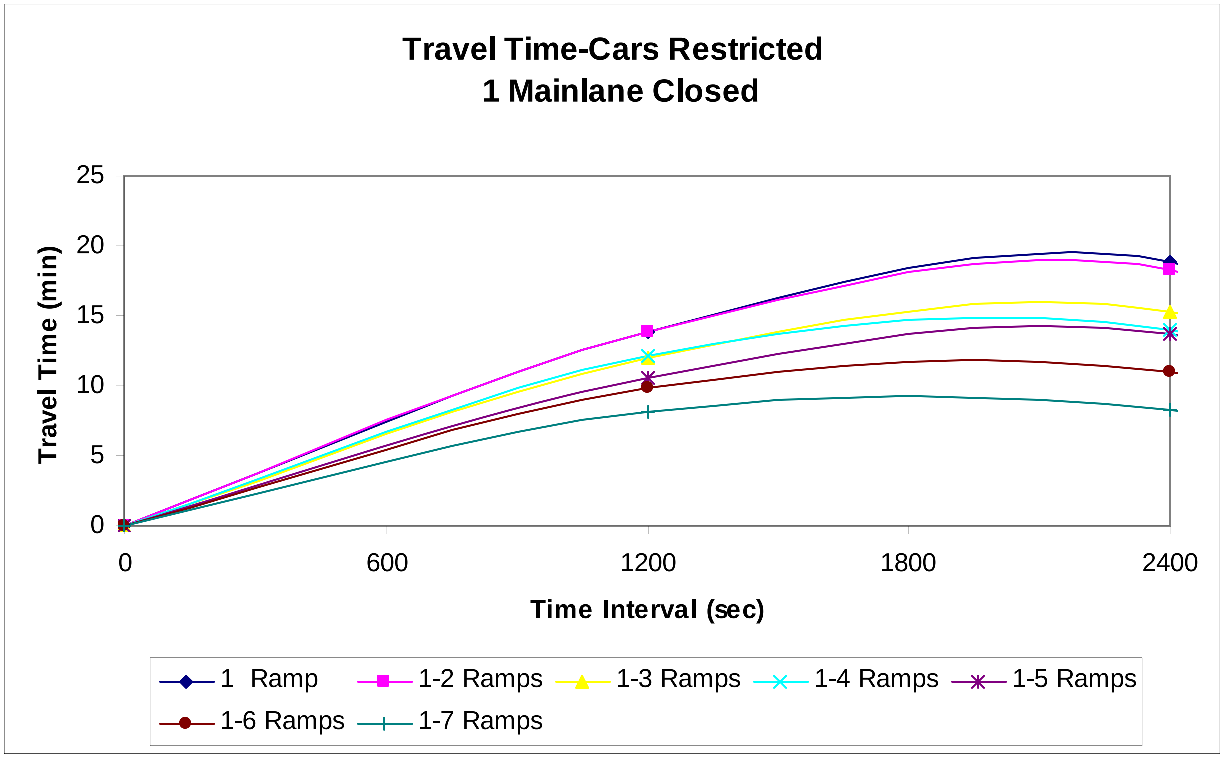


Figure 22. Travel Time Comparison – Cars Restricted.

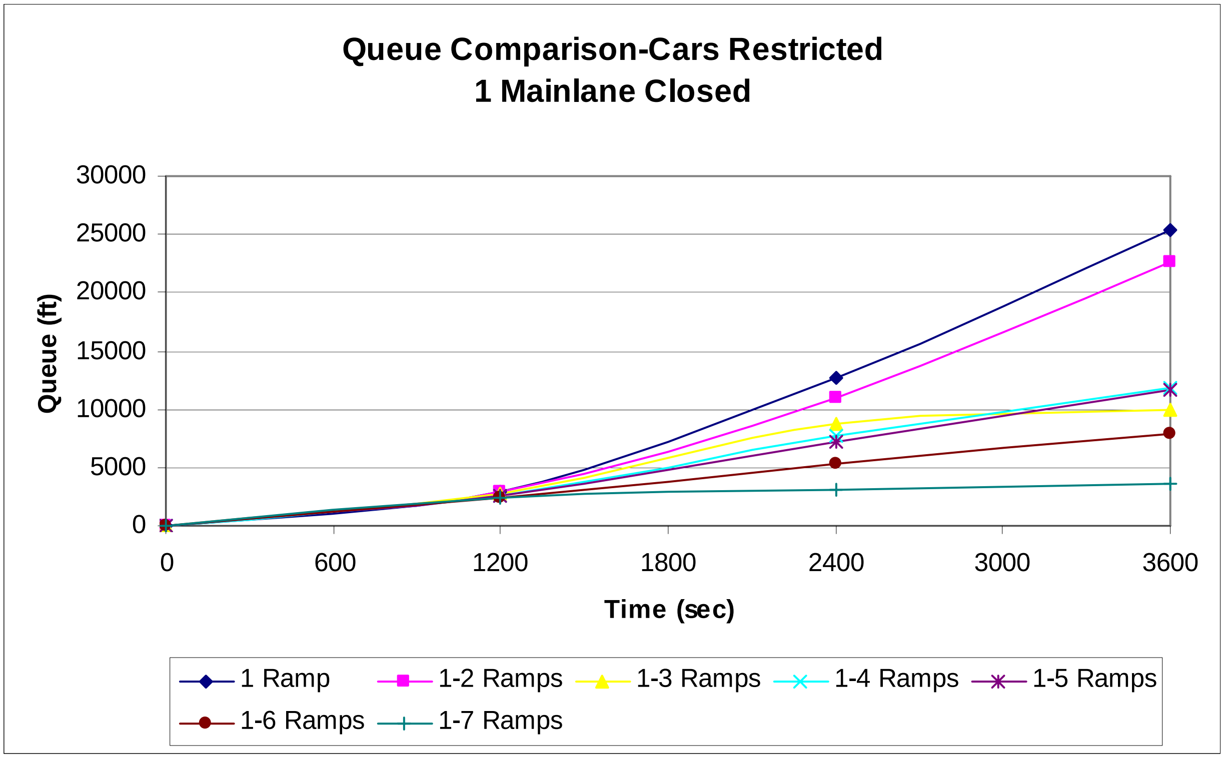


Figure 23. Queue Length Comparison – Cars Restricted.

Cars and Trucks Restricted

The third scenario set for one mainlane closure was restricting both cars and trucks and only allowing buses to enter the freeway facility. Buses account for only 1 percent of all vehicles defined in the simulation model. Buses also have lower speeds ranging from 52 to 59 mph. Figure 24 is a graphical depiction of freeway travel time when restricting cars and trucks from entering the freeway during the duration of the accident. Travel time improved by 67 percent when comparing the restriction of cars and trucks from one ramp to all seven ramps. Allowing access to buses only had a significant impact on queue length as more ramps were managed. Queue length was reduced by 96 percent when managing all seven ramps compared to just a single managed ramp. Figure 25 shows the comparison of queue length when managing various numbers of on-ramps.

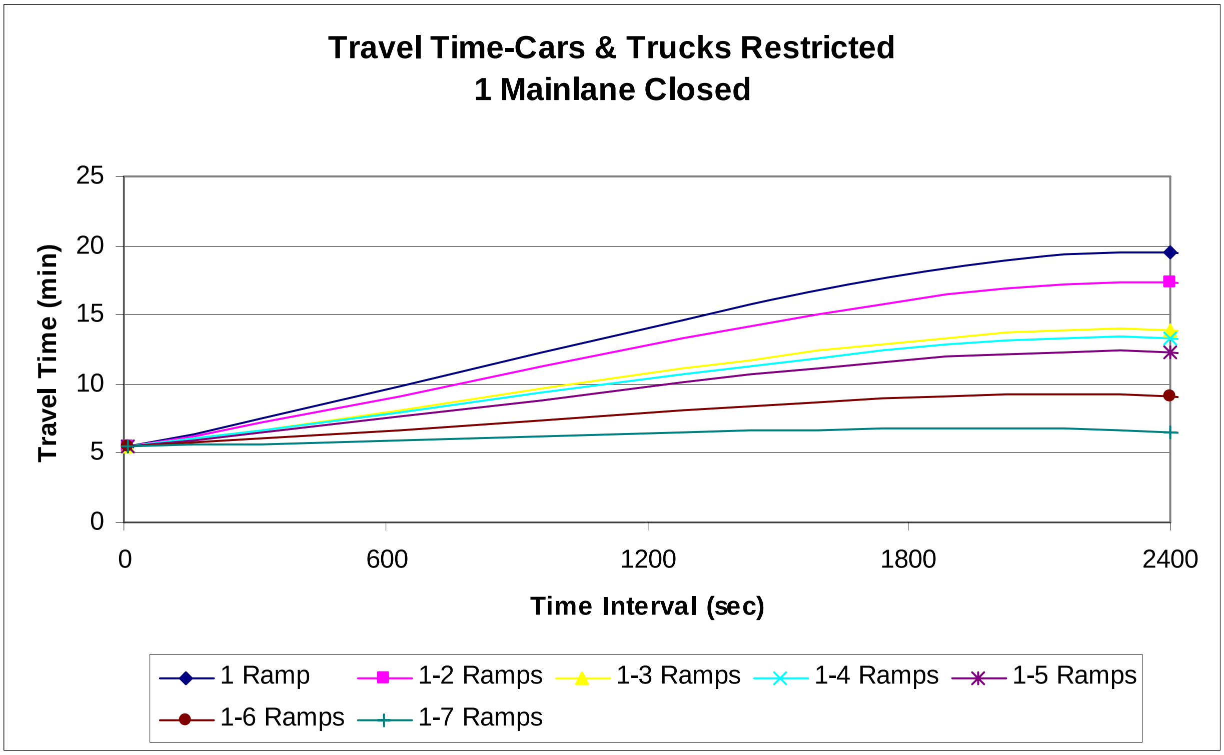


Figure 24. Travel Time Comparison – Cars and Trucks Restricted.

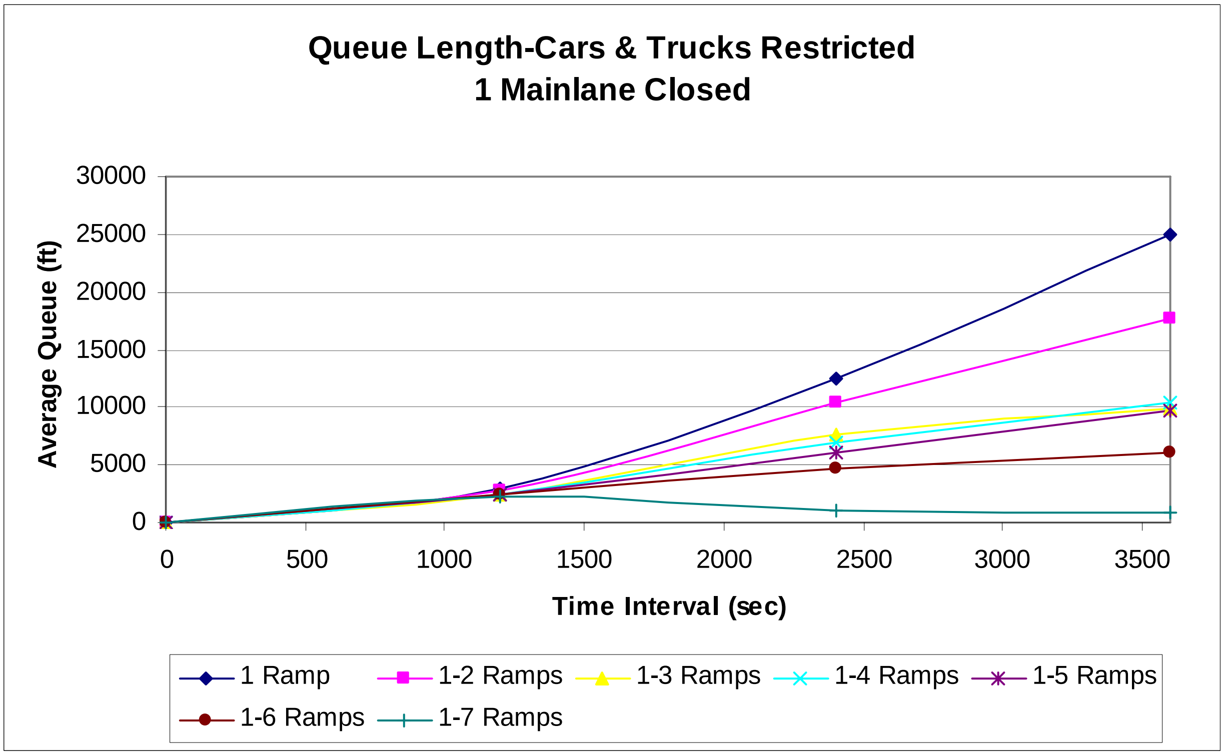


Figure 25. Queue Length Comparison – Cars and Trucks Restricted.

Cars and Buses Restricted

This scenario included the restrictions of both cars and buses on the freeway at the designated on-ramps and only allowed access to heavy vehicles. Trucks account for 9 percent of all vehicles in the network. Travel time improved by 63 percent when closing all seven ramps to cars and buses when evaluating against the restrictions applied to only the first ramp, as shown in Figure 26. Figure 27 shows the queue length propagation on the freeway as the result of the incident. Both of the graphs for this scenario depict the first ramp managed as having a shorter travel time and queue length, respectively, when compared to managing both the first and second ramps.

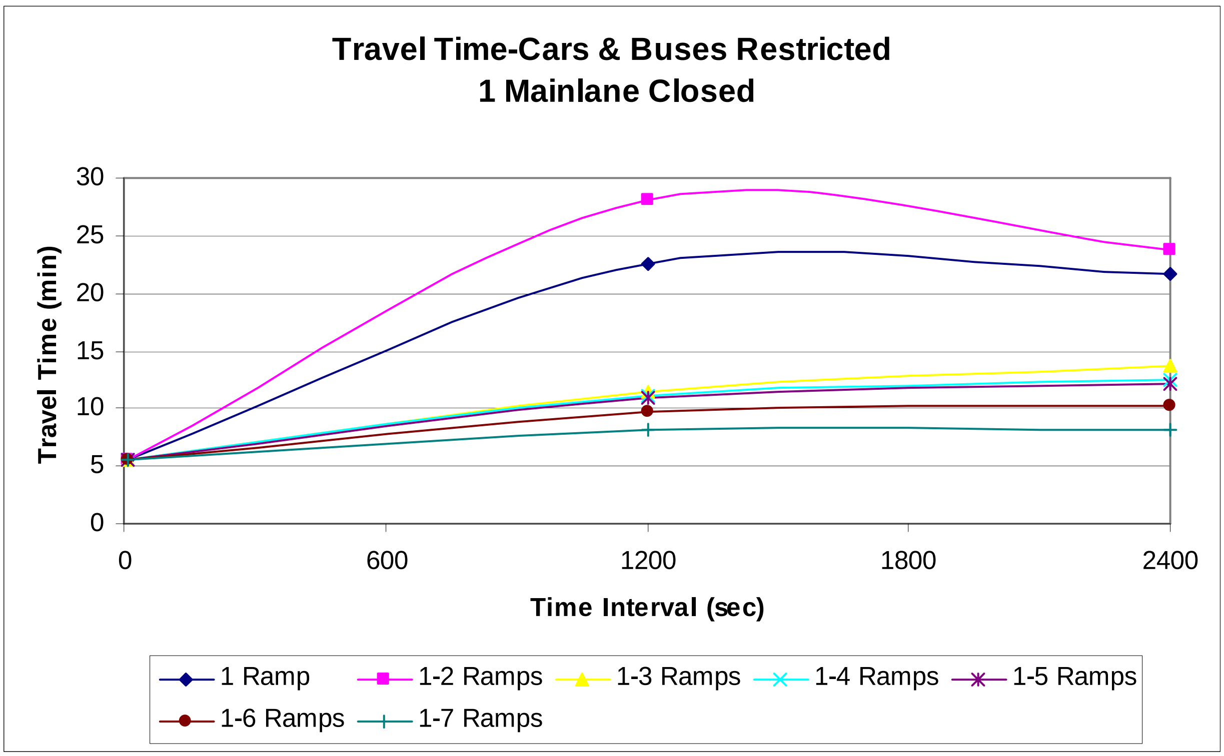


Figure 26. Travel Time Comparison – Cars and Buses Restricted.

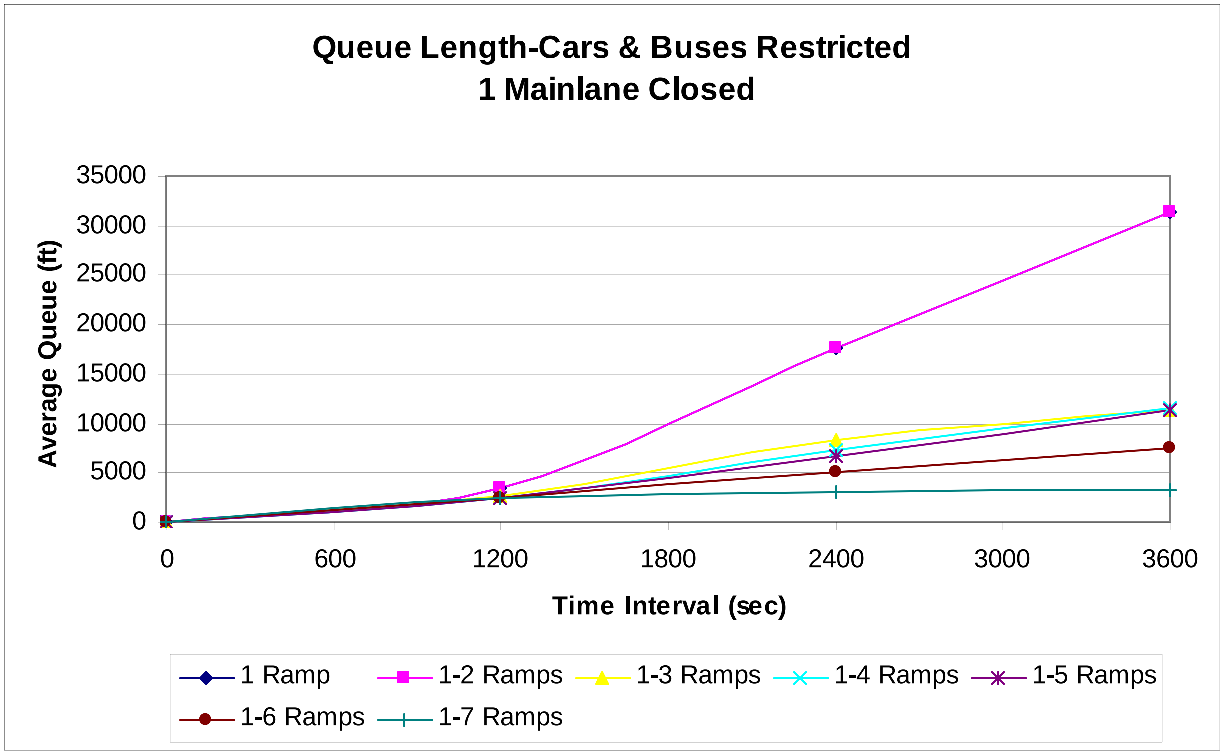


Figure 27. Queue Length Comparison – Cars and Buses Restricted.

Buses and Trucks Restricted

The fifth scenario set included restricting both trucks and buses from entering the freeway facility during the incident. Since cars comprise the majority of vehicles in the network, the variability of travel times when managing the first on-ramp compared to all seven ramps is smaller than other scenarios. Figure 28 shows that when one to three ramps are managed upstream of an incident, travel time is lower when compared to managing one to seven ramps. Queue length shows significant reduction, as shown in Figure 29. Queue length was reduced by approximately 3.5 miles when all seven ramps restrict both buses and trucks from the freeway facility upstream of an accident location.

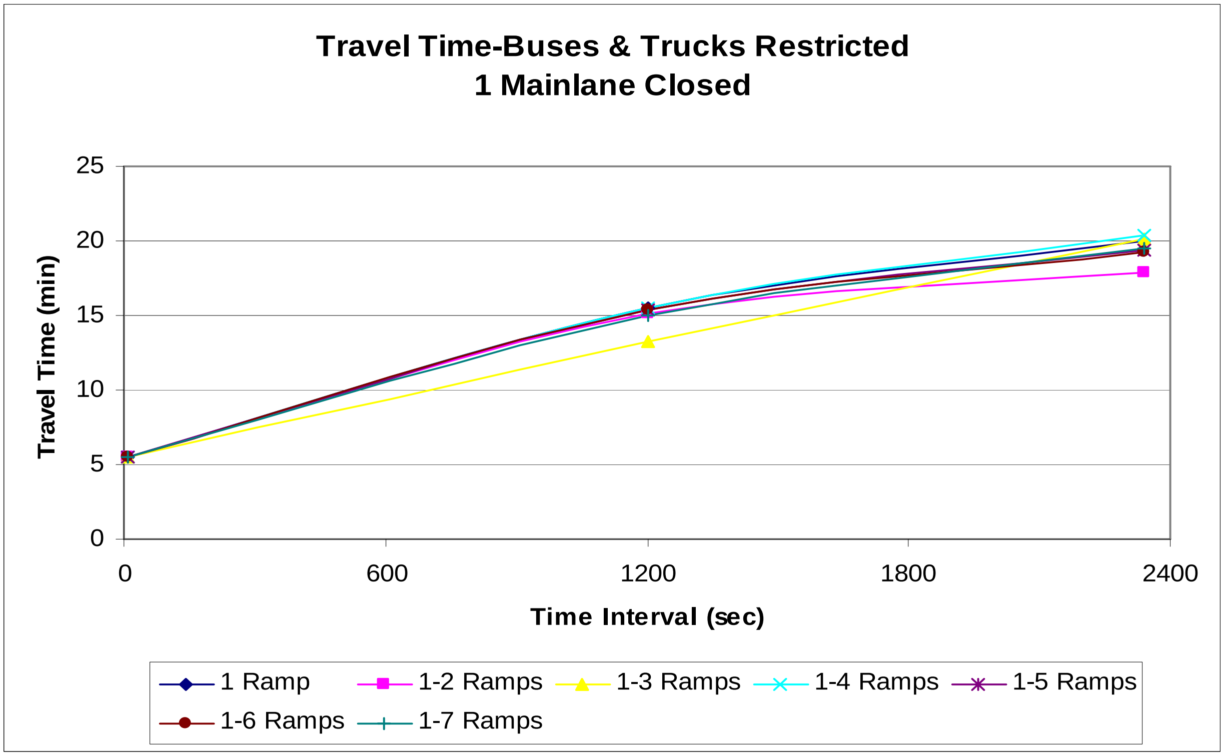


Figure 28. Travel Time Comparison – Buses and Trucks Restricted.

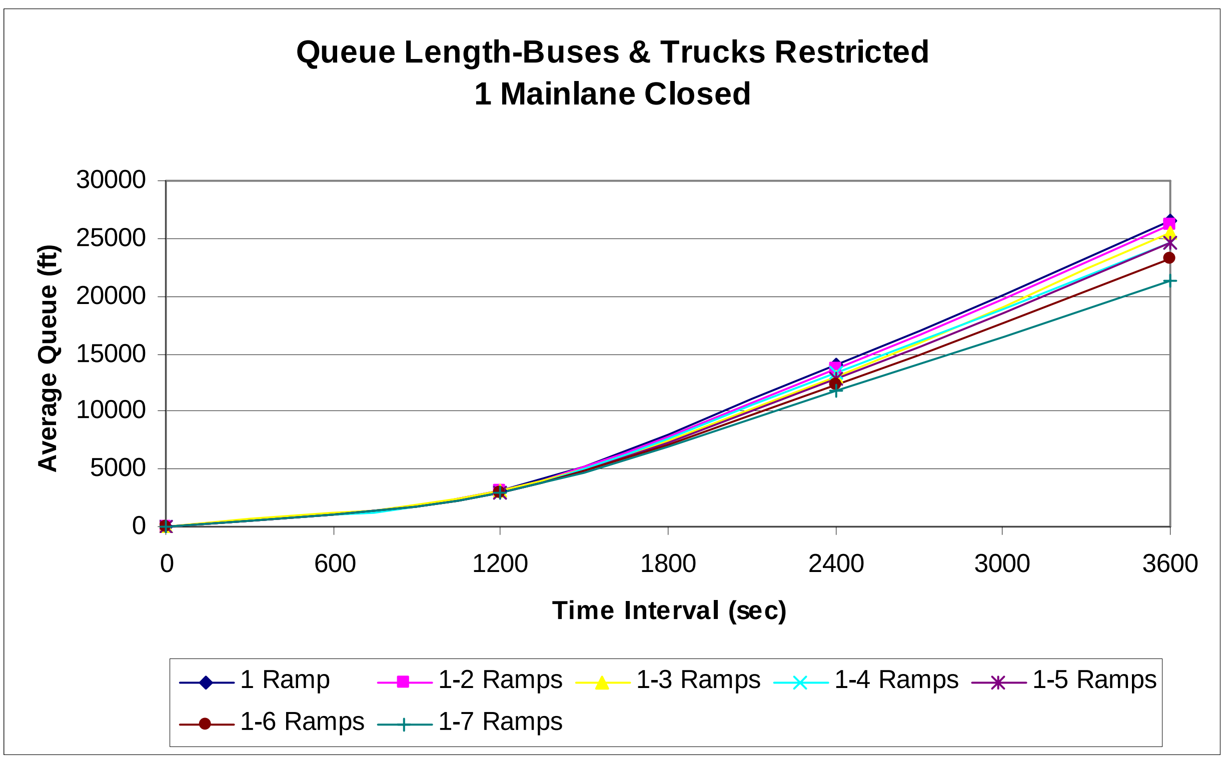


Figure 29. Queue Length Comparison – Buses and Trucks Restricted.

All Vehicle Classes Restricted

The final scenario modeled when one lane was closed due to an incident was restricting all vehicles from entering the freeway. Another term for all vehicle classes restricted is simply ramp closure. Once the incident has occurred on the freeway mainlanes, the model closes successive on-ramps upstream of the accident location. Restricting all vehicles at all seven defined on-ramps improved travel time by 65 percent when compared to only managing the first on-ramp. The travel time at time period 2400 seconds with one ramp managed was 18.8 minutes and the travel time for all seven managed on-ramps was 6.5 minutes. Figure 30 shows the correlation between the management of single versus multiple ramps. Queue length significantly improved when multiple ramps were managed, as shown in Figure 31. When all seven on-ramps are managed in this scenario, the queue length levels off at approximately 885 ft and stays constant for the duration of the simulation. This condition indicates that the freeway facility functioning at 75 percent flow capacity in the incident area is enough to handle the amount of traffic already on the mainlanes. When fewer ramps are managed, flow through incident area bottlenecks and queue lengths increase.

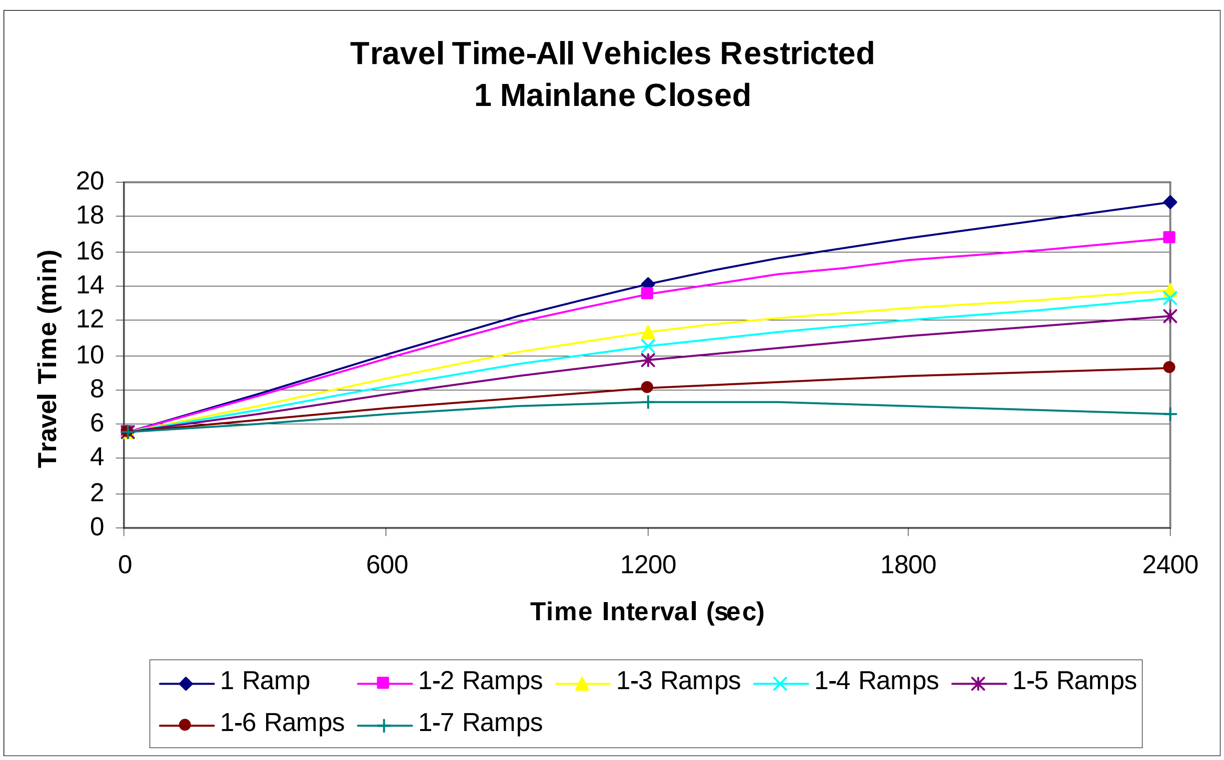


Figure 30. Travel Time Comparison – All Vehicles Restricted.

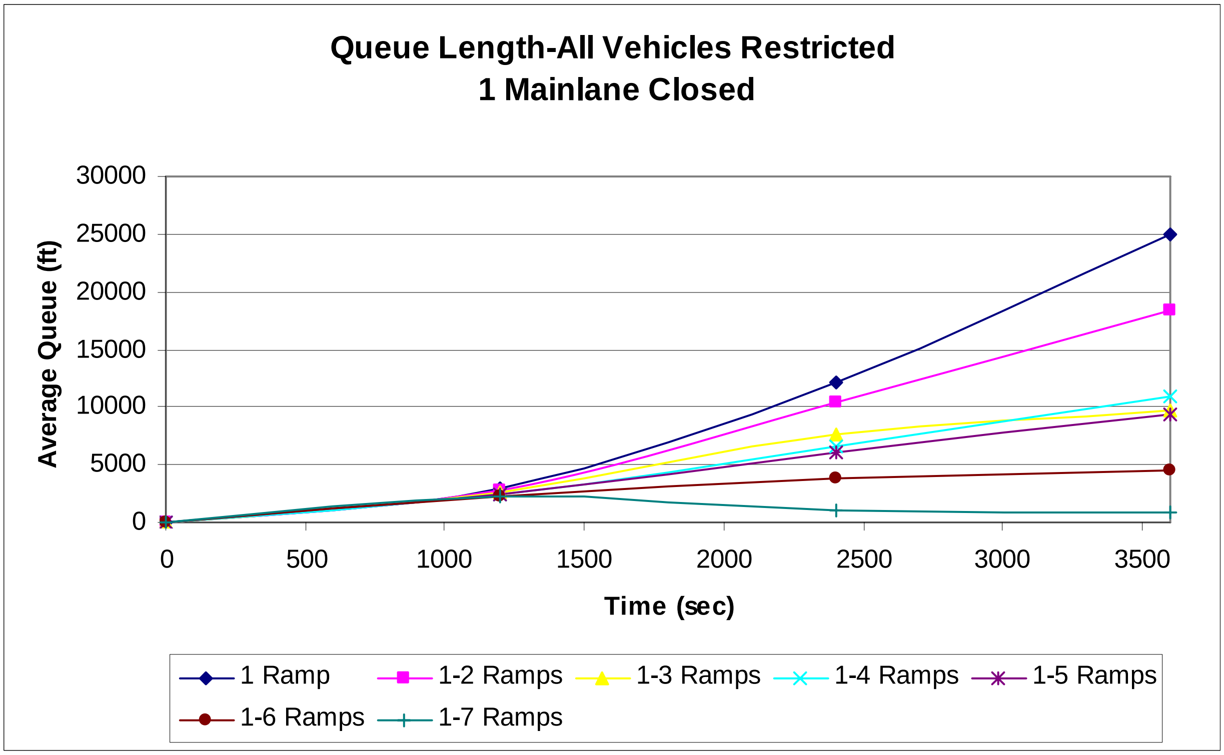


Figure 31. Queue Length Comparison – All Vehicles Restricted.

Multiple Lane Closure

The next sets of scenarios mimic the previous ones already analyzed with the exception of the number of freeway mainlanes open during the simulated accident. This process was repeated for two, three, and four (total) mainlanes closed. These scenarios were used to analyze travel time and queue length when the severity of incidents on freeways increased. Simulation results showed that truck lane restrictions had the greatest impact on travel time when compared to the other ramp management scenarios. As the severity of the accident increases from one lane closure to three lanes closed, the average travel time increased from 13.27 minutes to 16.74 minutes when applying truck-restricted ramps. The total ramp closure and car- and truck-restricted scenarios had the lowest travel times when compared to the other scenario sets, as shown in Figure 32. Travel time for total freeway closure was not compared to the less severe accidents because the simulated vehicles would not reach the second data collection point during the simulation and therefore returned a travel time value of zero.

All scenarios that included restricting trucks individually or in combination with other vehicle classes had much longer queue lengths when compared to other vehicle class restrictions.

Queue length for truck-restricted ramps ranged from 8165 ft for one mainlane closure to 11,162 ft (over 2 miles) when all lanes are closed due to a severe accident. Figure 33 shows the comparison of one to four lane freeway closures for all defined scenarios.

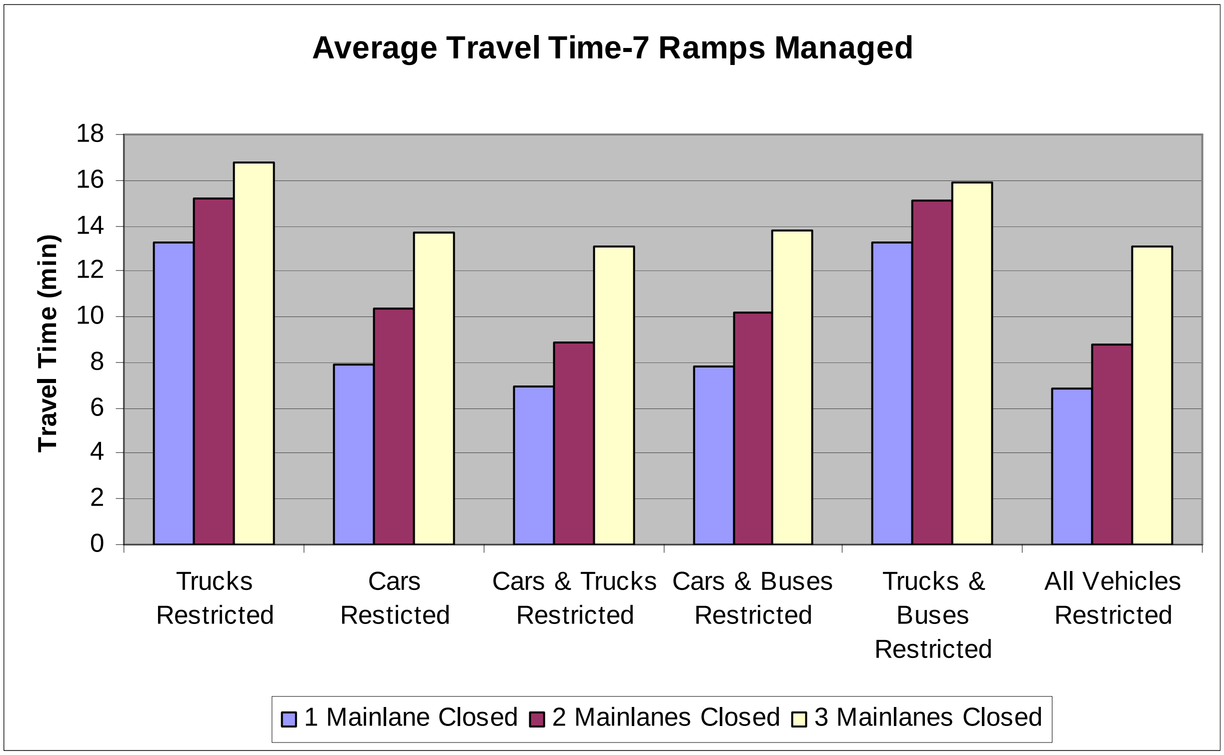


Figure 32. Average Travel Time Comparison for Single and Multiple Lane Closure.

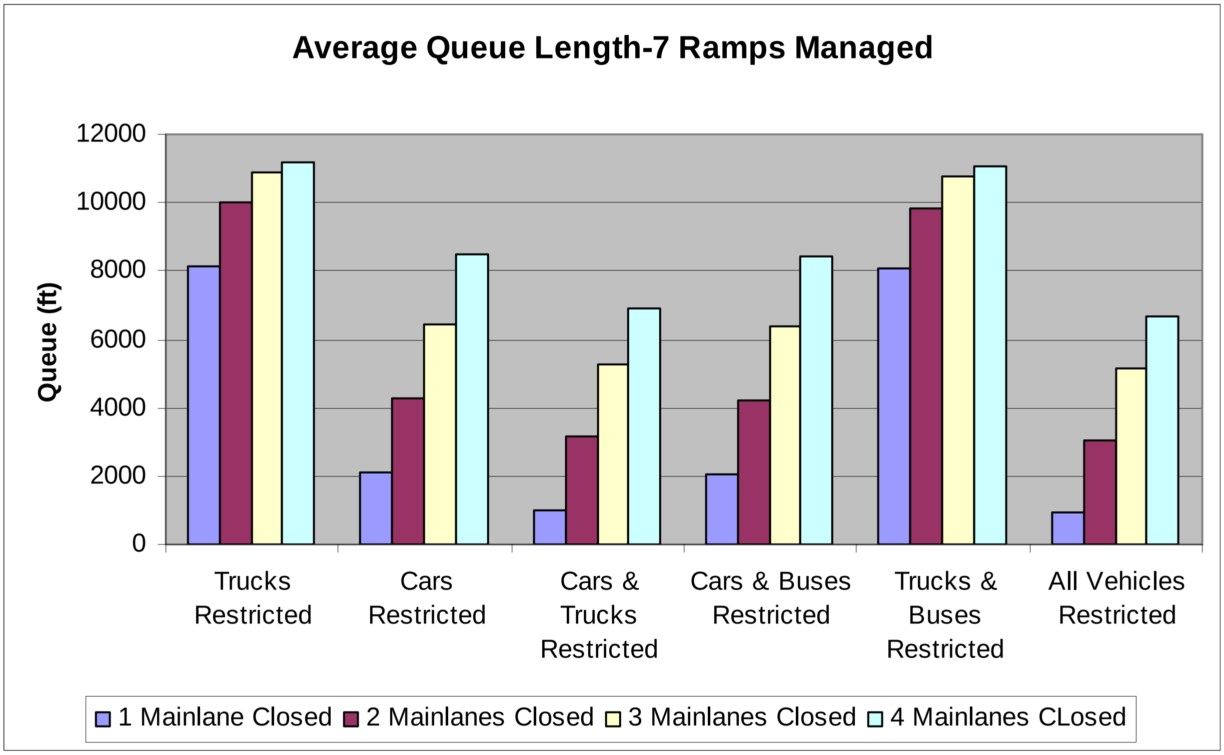


Figure 33. Average Queue Length Comparison for Single and Multiple Lane Closure.

Model Output Interpretations

While the results of all defined scenarios help researchers in analyzing and documenting the general impacts of various vehicle class restrictions in support of incident management, they could be misleading when various traffic compositions, traffic volumes, and vehicle paths are altered. The intent of this research was to prove whether restricting various combinations from entering a freeway facility upstream of an incident had significant impacts on queue lengths and travel time.

It must be noted that an offline analysis of total ramp closure was performed with inflated traffic volumes that mimic heavy congestion. Exit ramp traffic was excessive enough to induce queue spillback onto freeway mainlanes. Dynamic ramp closure to all vehicle classes and ramp metering was simulated on the first and second immediate upstream ramps and freeway conditions were free flow. Researchers compared both these scenarios to a base (do nothing) model. Results showed that total ramp closure upstream of a heavily utilized off-ramp had adverse results when compared to ramp closure scenarios performed for incident management.

Figure 34 shows the dramatic increase in travel time when ramps are closed upstream of a heavily congested off-ramp. Therefore, researchers must take care when interpreting data results.

It must be further noted that the VISSIM model did not take into account the amount of traffic diverting off the freeway upstream from the incident location. In reality, motorists have an option to take alternate paths to their destinations. This type of modeling must be done with software capable of assigning traffic dynamically based on shortest path. Therefore, a new model capable of performing DTA was used to analyze ramp management strategies in support of incident management.

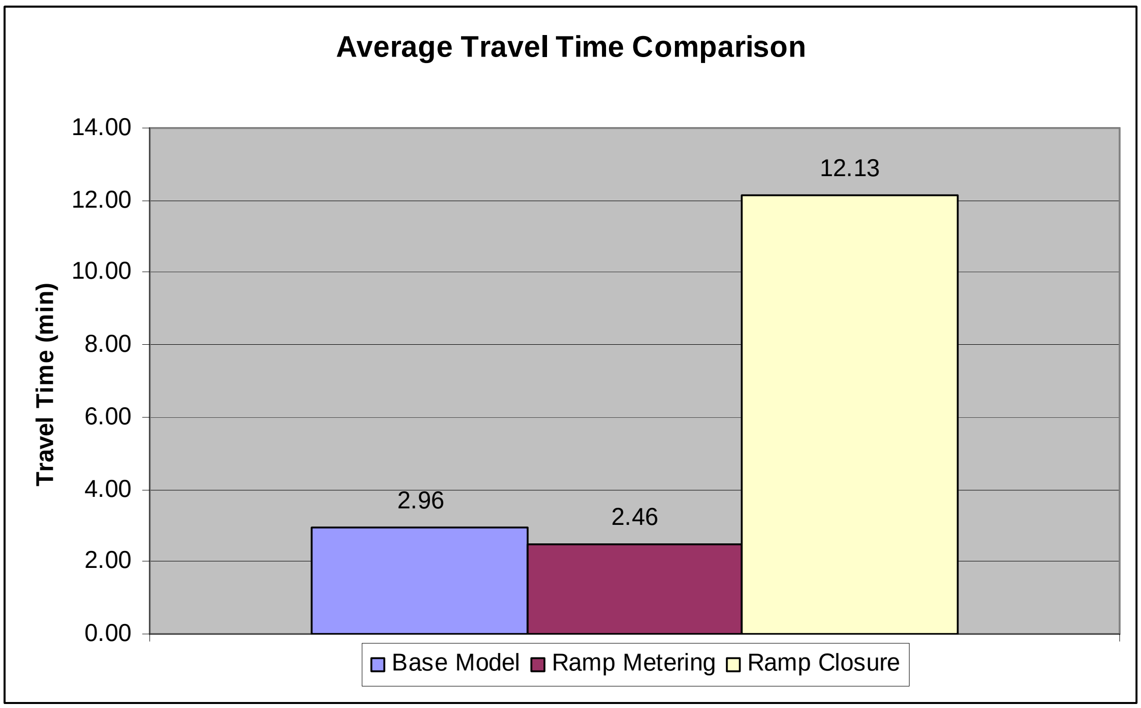


Figure 34. Travel Time Comparison for Heavily Congested Off-Ramp.

Incident Management (DYNASMART-P)

A new version of DYNASMART-P (DSP), developed by researchers from the University of Arizona, was used to analyze similar ramp management strategies in support of incident management. Previous versions of DSP did not allow time-dependent alternate multi-mode choice assignment for analyzing traffic flow. The new version of DSP allowed the simulation model to perform vehicle eligibility restrictions, access control, and time-dependent variable pricing while utilizing its DTA capabilities. The following section describes the analyses performed and the results obtained.

Freeway Mainlanes

A 5-mile section of IH-35W, in Fort Worth, Texas, was replicated on DYNASMART-P and used as the foundation for the mesoscopic analysis of incident management. The freeway had four lanes and five entrance ramps between East Seminary Drive and East Vickery Boulevard. The defined corridor speed limit was set at 65 mph and grades for all entrance ramps were negligible. A baseline model was created for comparison of all incident management scenarios. Figure 35 shows the incident area and managed ramp in the DSP model.

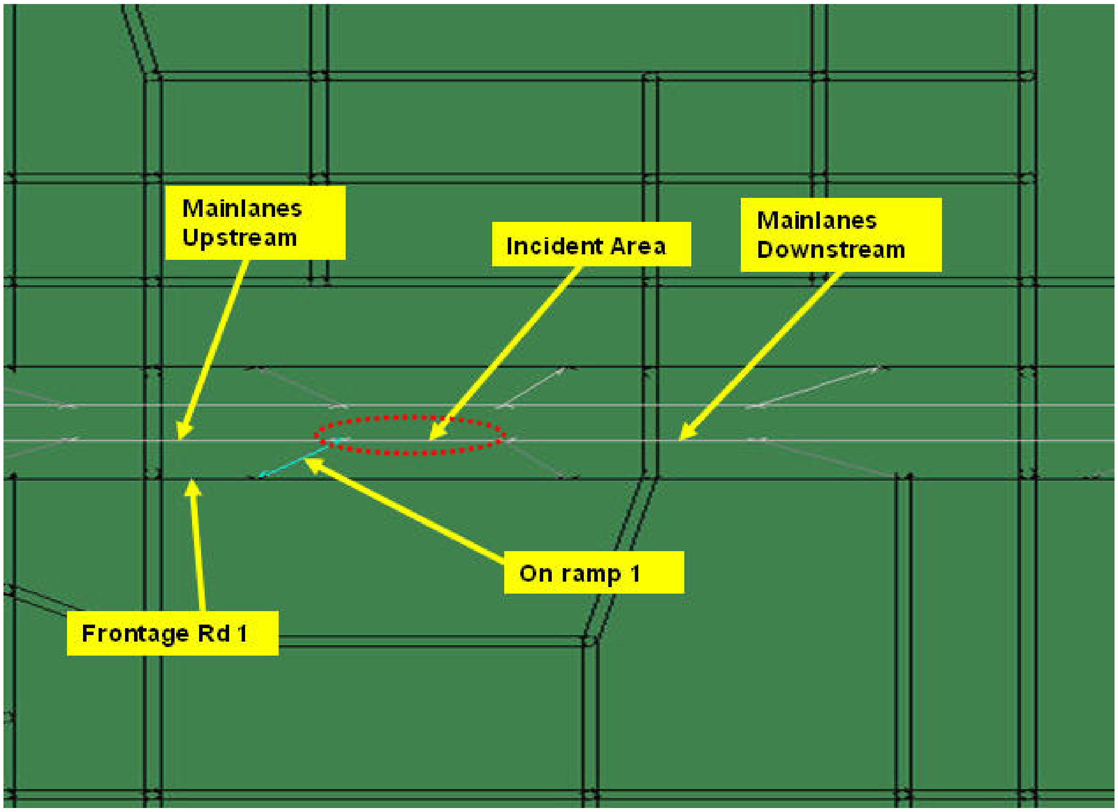


Figure 35. Data Collection Location – DYNASMART-P.

Freeway Vehicle Mix

IH-35W in Fort Worth, Texas, is currently a non-tolled facility, all private vehicle classes were classified as one vehicle type. The vehicle class composition used for these modeled scenarios was 60 percent SOVs, 30 percent HOVs, and 10 percent trucks. Transit vehicles were included in the vehicle mix for these scenarios.

Freeway/Ramp Volume

Freeway volumes dynamically change throughout the day. Since DSP is capable of running dynamic traffic assignment, a specified freeway volume was not input into the model. Instead, time-dependent origin-destination matrices were used and traffic was routed on various paths based on shortest-path theory. Freeway and ramp volumes changed dynamically based on the characteristics of the freeway conditions. When an incident occurred on the freeway, the model rerouted vehicles to different paths using an iterative process that constantly shifted vehicles to different paths until equilibrium is reached.

Severity of Simulated Accidents

The modeled scenarios included two simulated accidents occurring within the simulated time period. The first incident occurred at time period 20 for a duration of 30 minutes. The severity of the first accident restricts freeway traffic flow from four lanes to one, as shown in Figure 36. The second incident occurred at time period 6, also with a duration of 30 minutes. The second incident restricts freeway flow by 25 percent, closing only one lane. Both simulated accidents occur on the same section of freeway. Data results from the baseline model show that hourly entry volume for the on-ramp adjacent to the accident area ranged from 500 to 1200 vehicles per hour.

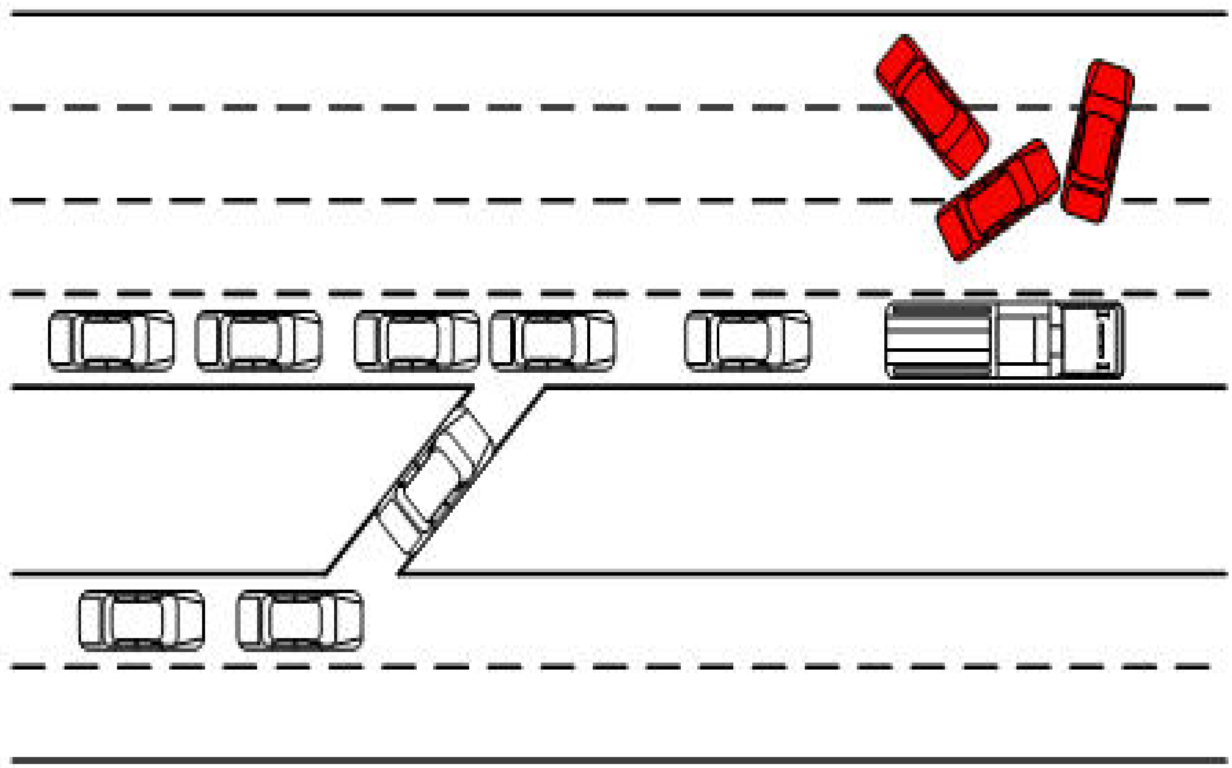


Figure 36. Incident Lane Reduction.

Performance Measures for Incident Management (DYNASMART-P)

In the context of managed ramps in support of incident management, the ultimate effectiveness of ramp management is gauged not only by the balance of traffic flow around the incident area, but also the flow of traffic in the surrounding areas. Based upon the capabilities of the DSP model output, volume and speed were used as performance measures. These two measures-of-effectiveness were used to gauge the performance of various vehicle class restrictions during each of the defined incident scenarios.

Volume

As with any freeway facility, hourly volumes are dynamic and are constantly changing. Volume comparison can validate how traffic is diverted in and around the incident location.

Lower volume through the incident location means that the freeway travel time has significantly increased and caused vehicles to find alternate paths.

Speed

Speed was also used as a performance measure for the defined set of scenarios. The distribution of speed along a corridor shows how a facility operates during periods of congestion caused by an incident. Variations in speed can be caused by volume on a freeway facility in conjunction with the number of vehicles entering at merge points. The higher the freeway speed, the more inclined vehicles are to use freeway ramps to enter the facility.

Network Performance

Researchers performed a comparative analysis for all defined incident management scenarios. Overall performance measures included average overall travel time and average stop time. It must be noted that the network performance of these scenarios includes all data collected within the entire defined network. The defined network included the freeway facility, frontage roads, and all ingress and egress points, as well as all surrounding arterials.

Incident Model Preparation (DYNASMART-P)

The first task for researchers was to create a DSP model to test the various defined scenarios. The research team chose a section of IH-35W corridor between I-10 and I-20 in Fort Worth, Texas, and replicated a 5-mile portion of the freeway and surrounding arterials. The study area included five on- and five off-ramps entering and exiting the freeway corridor, respectively. Average speed on the freeway corridor is 65 mph, and 40 mph on all frontage roads and arterials. For simplicity, traffic control for all signalized intersections was kept at default settings defined by DYNASMART-P. Signalized intersections use an actuated signal with a cycle length of 120 seconds. Service flow rates for arterials and ramps were set to 1800 passenger cars per hour per lane (pcphpl) and freeway flow rates were set at 2200 pcphpl. Speed limit for work zone areas was kept at 65 mph. There are five on-ramps in the modeled section of I-35 northbound and the second and third ramps from south to north were used for management analysis.

The existing versions of DSP would not allow differentiation of vehicle classes within the simulation. Therefore, a modified version of DSP was tested using ramp management in support of managed lanes as a case study. The most advanced feature of this mesoscopic model was its time-dependent multi-mode choice assignment which allowed dynamic pricing and lane closure to multiple vehicle classes while simultaneously running DTA. This feature allowed the research team to analyze various managed lane strategies including vehicle class restrictions, specific user class access, lane closure, and variable pricing.

DTA is an important DYNASMART-P component. DTA is a process to describe the outcome of driver route choice (and/or departure time choice) behavior influenced by various factors including congestion levels, user cost of roadway, and roadway traffic information. One common DTA paradigm postulates that drivers consider a generalized cost including their perceived value-of-time, travel time between origin-destination, and associated pricing of roadways.

The concept of multi-mode choice assignment is the model's ability to differentiate various vehicle classes as opposed to just one composition. Current microscopic simulation models can differentiate various vehicle classes within one composition and can distinguish different paths for each vehicle class that travels from the same origin-destination. However, these microscopic simulation models lack one important characteristic, the ability to reroute certain vehicle classes during the simulation in support of incident or congestion management. The current state-of-the-art microscopic simulation models can close specific links to certain vehicle classes, but only for the entire defined simulation period while utilizing its DTA capabilities. They cannot close specific links in the middle of simulation (i.e., in support of incident or congestion management) while still assigning vehicle paths dynamically. Current mesoscopic models today are able to close specific links during the simulation period but are not able to differentiate vehicle classes and therefore cannot close the links to specific vehicles during simulation.

Here is where the challenges arise within this research. Both microscopic and mesoscopic simulation tools have deficiencies in support of the modeling of managed freeway ramps for incident and congestion management. Therefore a new capability is introduced and implemented in DYNASMART-P. As depicted in Figure 37, the multi-mode choice assignment generally follows the typical simulation DTA algorithmic procedure, the traffic assignment is delineated into different assignment modes with shortest paths with different generalized costs that consider the value-of-time and toll cost. When a certain restriction is imposed to a certain mode at a certain location, an infinite cost is imposed at that location for that specific mode and this high penalty is reflected in the time-dependent shortest path calculation for that specific mode. The same process is applied to all applicable modes in the traffic composition. Once all vehicles are assigned, they are loaded into the network to be simulated. The process is repeated until convergence or until reaching the maximal number of iterations (53).

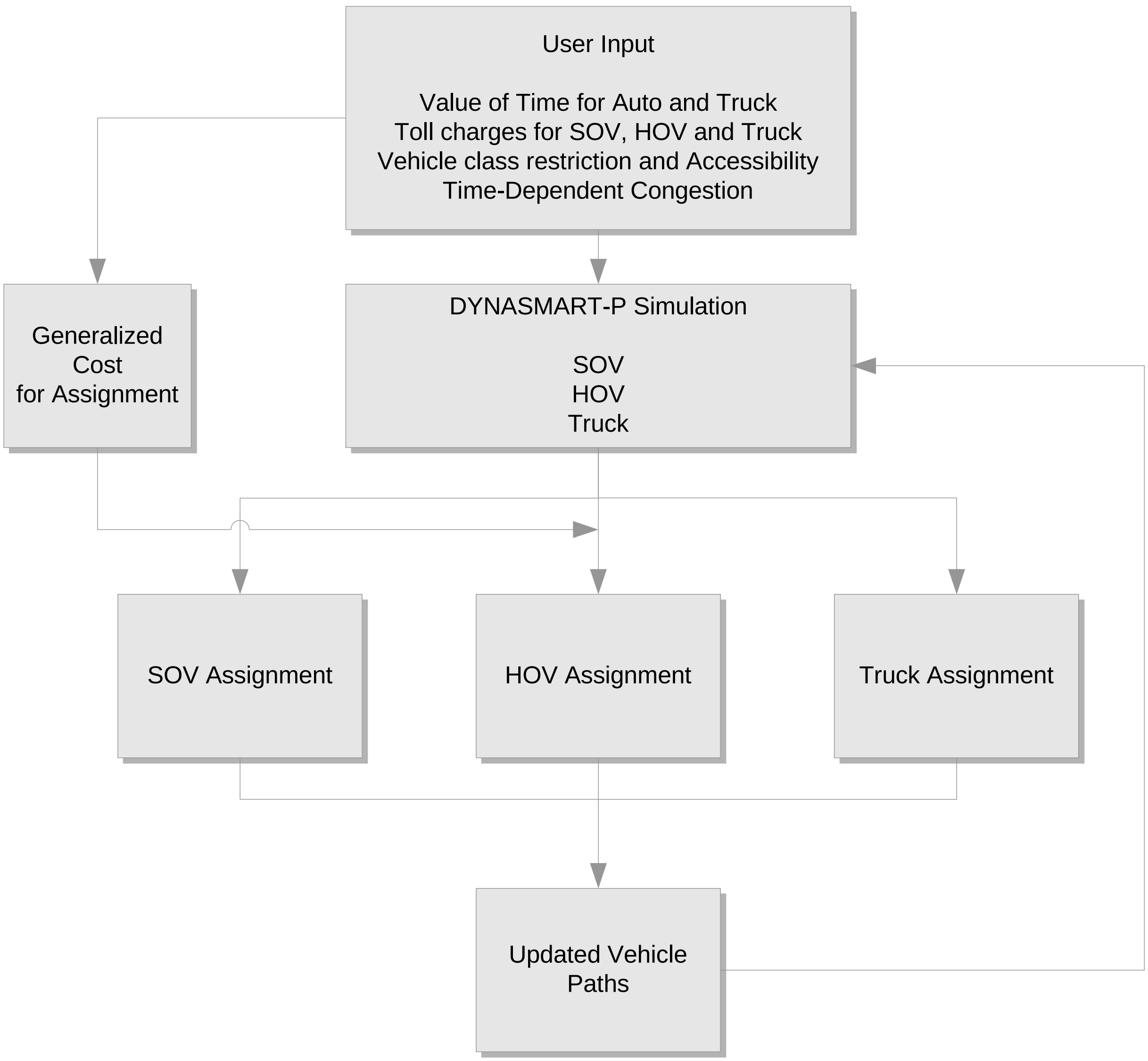


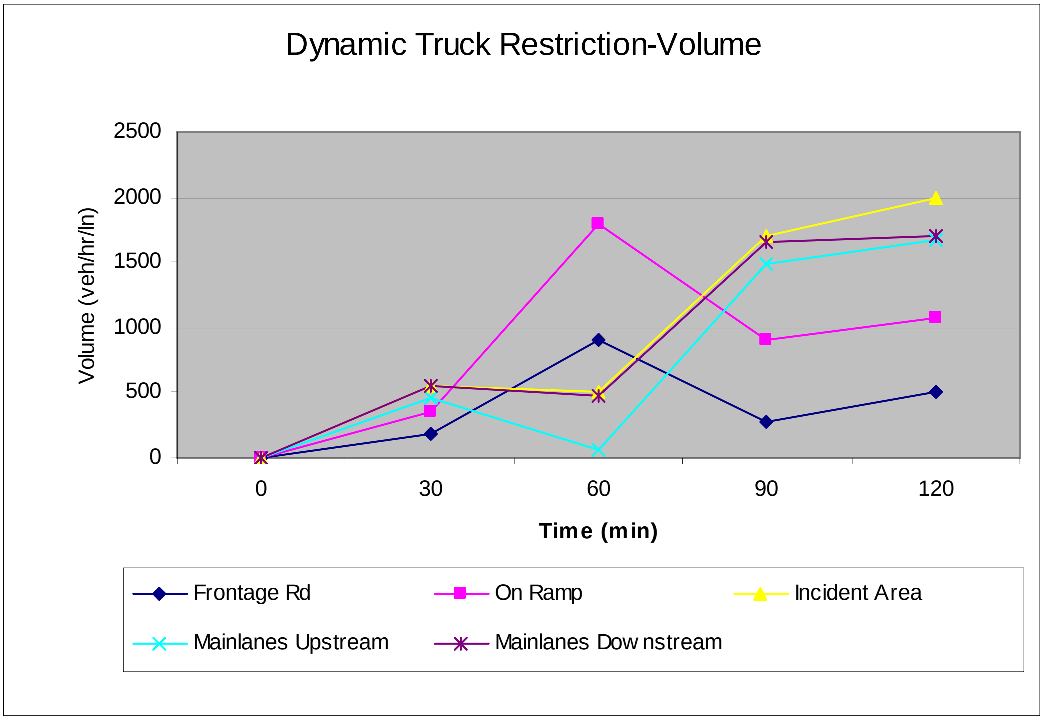
Figure 37. Multi-Class Analysis Framework.

Scenario Set Description for Incident Management (DYNASMART-P)

The scenario sets included managing the immediate upstream ramp of the incidents. The scenario sets also included truck restrictions, HOV ramps, ramp closure, and variable pricing. Three different pricing schemes were used for the variable pricing scenarios. The following sections describe each defined scenario set modeled.

Truck Restrictions

Dynamic truck-restricted ramps entail closing one defined freeway ramp concurrently with simulated accidents. Trucks are restricted from entering the freeway facility during time periods 20-50 and 60-90 minutes although the model is capable of closing ramps to specific vehicle classes at any time interval and for any duration. Again, an inflated generalized cost for trucks was introduced at the specified time intervals thereby creating an unfavorable path and prohibiting heavy vehicles from using these predetermined ramps. Figure 38 illustrates the aggregated traffic volume and speed. Mainlane traffic volume upstream of incident area ranges from 60 to 465 vehicles per hour during the first accident time period. On-ramp traffic volume, during the second accident time period, decreases significantly when restricting trucks from the managed ramp. Mainlane travel speed in the incident area was consistently higher for dynamic truck restrictions when compared to the baseline model. This result is readily apparent when comparing the hourly volume utilizing the on-ramp for baseline and dynamic truck restrictions. Truck-restricted on-ramps allow less volume to enter the freeway facility at the incident area on-ramp.



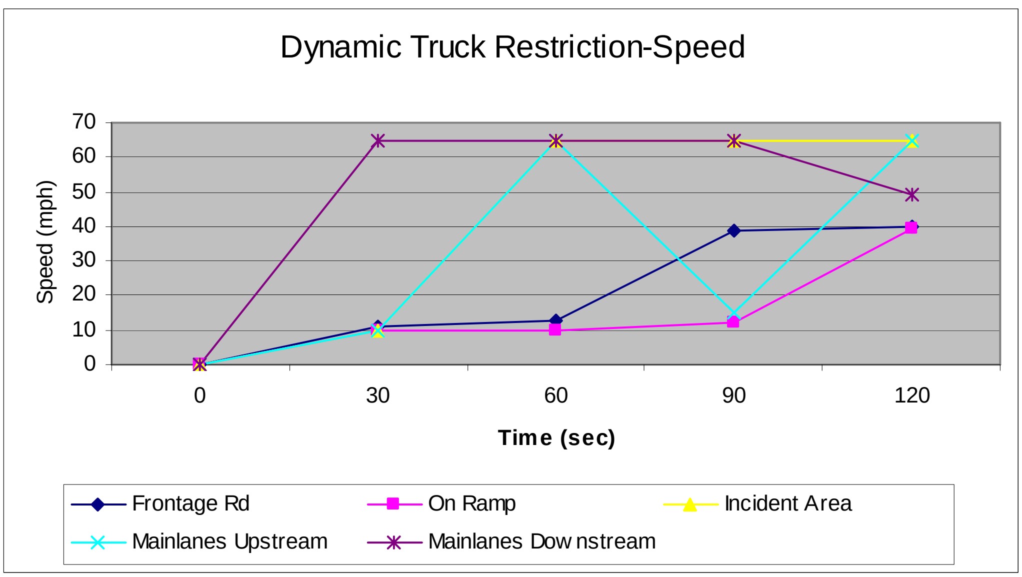
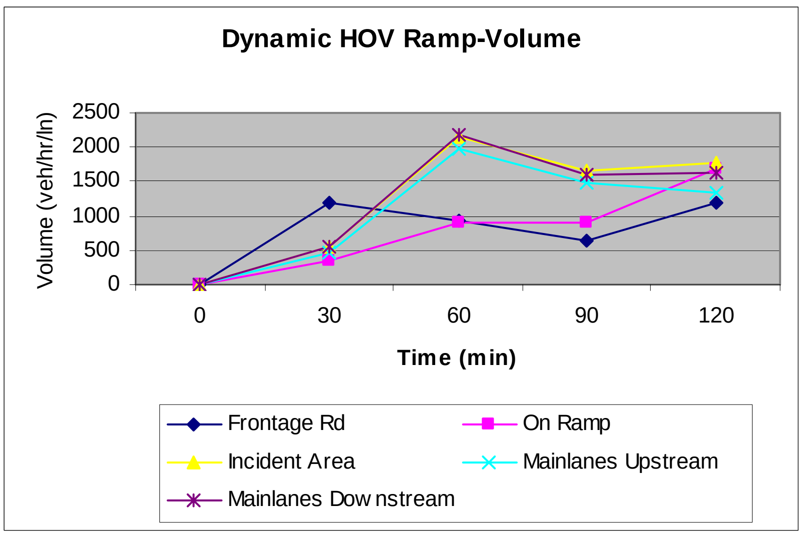


Figure 38. Dynamic Truck Restriction Performance Measures.

Dynamic HOV Ramp

Dynamic HOV ramp consists of closing a designated freeway ramp to trucks and SOVs simultaneously during the defined accident time intervals. Only HOVs are allowed to utilize the designated managed ramp during the defined accident time interval. Therefore, 70 percent of traffic is being diverted away from the on-ramp during incident time intervals. This result is consistent with vehicles rerouting their trips based on congestion levels and travel time. Figure 39 shows performance levels for both volume and speed when managing the designated on-ramp with truck and SOV restrictions. The dynamic HOV ramp showed considerably lower travel speeds and higher hourly volumes on the frontage road when compared to the baseline model. Incident area hourly volume for the dynamic HOV ramp on the freeway mainlane incident area approached saturation level of 2200 vehicles per hour in the open lane. This result would indicate that less turbulence at the on-ramp merge area allows greater flow of traffic to push through the incident area.



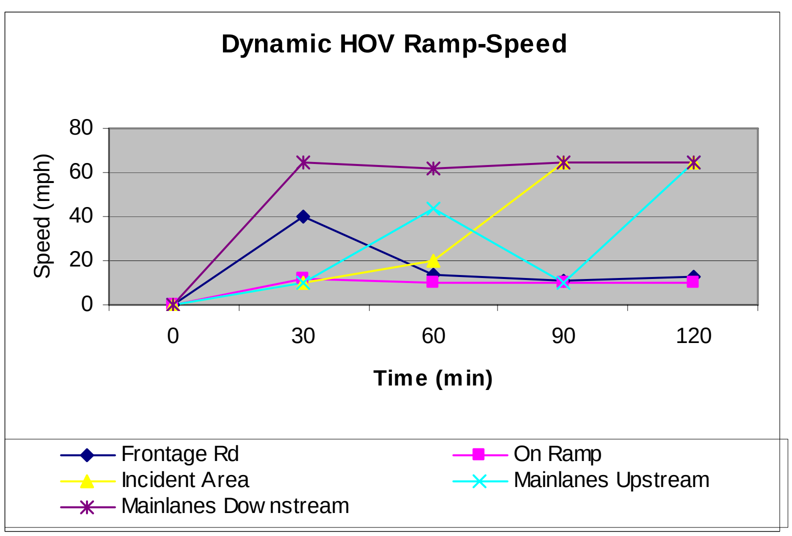


Figure 39. Dynamic HOV Ramp Performance Measures.

Dynamic Ramp Closure

Dynamic ramp closure restricts all vehicles from entering the managed freeway on-ramp during the simulated incident intervals. All vehicles must either bypass the managed on-ramp to an upstream or downstream entrance or reroute to the shortest path based on travel time. Speed on frontage road was relatively consistent, ranging from 36 to 40 mph. However, hourly traffic volume on frontage roads between 30 minutes and 90 minutes decreased to virtually zero. Researchers interpreted that the majority of vehicles using the managed on-ramp diverted away from the freeway altogether. Figure 40 is a graphical representation of the performance measures defined including speed and volume. Dynamic ramp closure had a vast improvement of on-ramp and frontage road travel speed when compared to the baseline model. Volume on freeway mainlanes in the incident area was also higher during the periods of dynamic closure, allowing more mainlane vehicles to push through the only open lane.

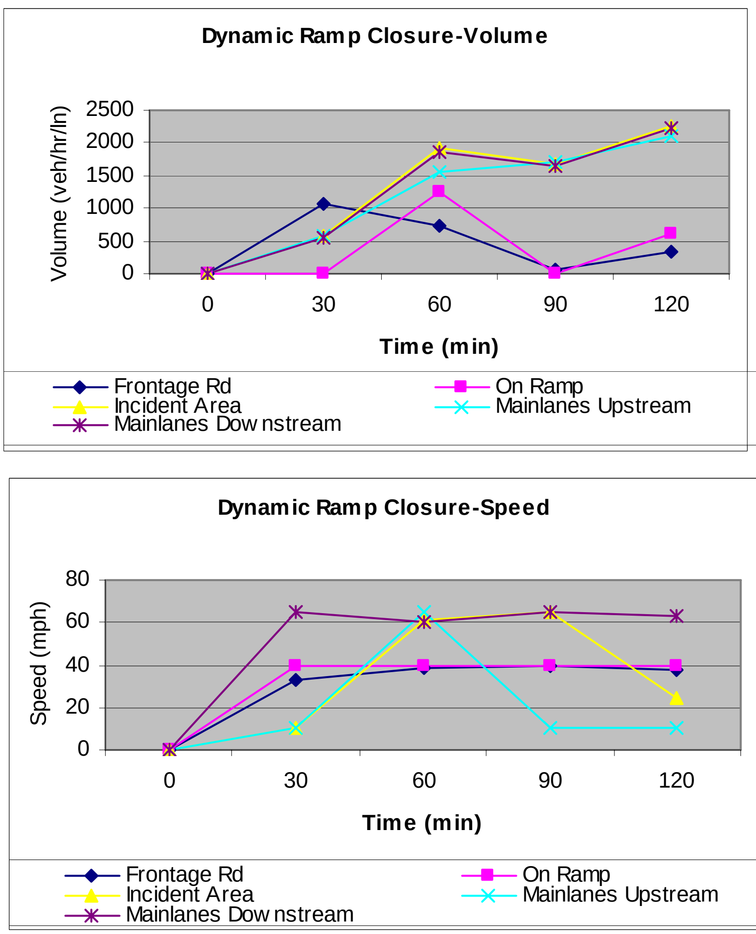


Figure 40. Dynamic Ramp Closure Performance Measures.

Dynamic Variable Pricing (HOT)

The dynamic variable pricing scenario consists of three different HOT models, each with different tolling rates. Tolling charges are implemented on a specified managed ramp simultaneously and continue for the duration of the incident. Toll charges are assessed to SOVs and trucks. HOVs can enter the managed ramp without charge. It must be noted that toll charges can be altered at various rates for SOVs, HOVs, and trucks. It must further be noted that tolling intervals can be varied with sensitivity analysis to help relieve congestion caused by shockwave of accident. Table 40 shows the tolling rates used for each of the three defined HOT scenarios.

Table 40. High-Occupancy Toll Rates – Incident Management.

Scenario	SOV	Truck	HOV
1	$0.10	$0.20	$0.00
2	$0.15	$0.25	$0.00
3	$0.20	$0.30	$0.00

HOT tolling scenarios show how sensitive drivers are to tolling rates. The managed ramp has higher volumes with a higher toll rate. This result is indicative of the fact that truck traffic composes 10 percent of all traffic and has a higher value-of-time. This occurrence indicates the driver's willingness to pay additional toll charges in order to save travel time. Since the managed ramp is immediately upstream of the incident, additional volume flow at this junction creates a bottleneck location where there is only one lane of traffic open. Therefore, the scenario with the highest toll rate attracts drivers to the managed ramp and decreases freeway volume on the freeway mainlanes upstream of the incident, as shown in Figure 41. On-ramp volumes were considerably higher for tolling scenarios when compared to the baseline model. The tolling rate of $0.20 for cars and $0.30 for trucks had the highest on-ramp entry volume of the three tolling scenarios.

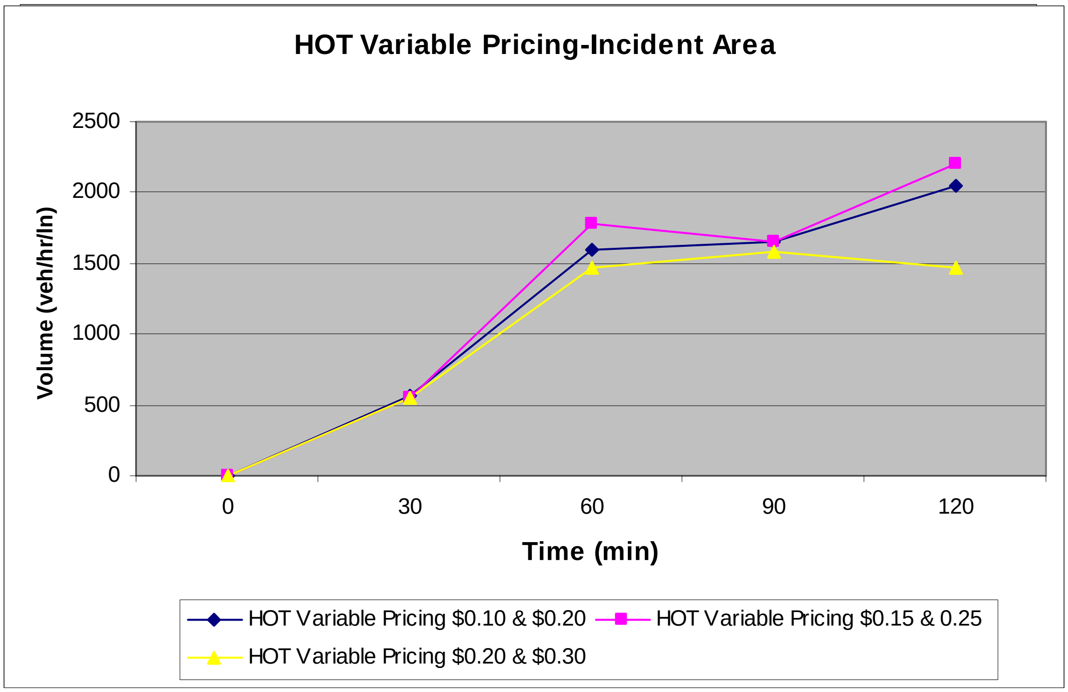
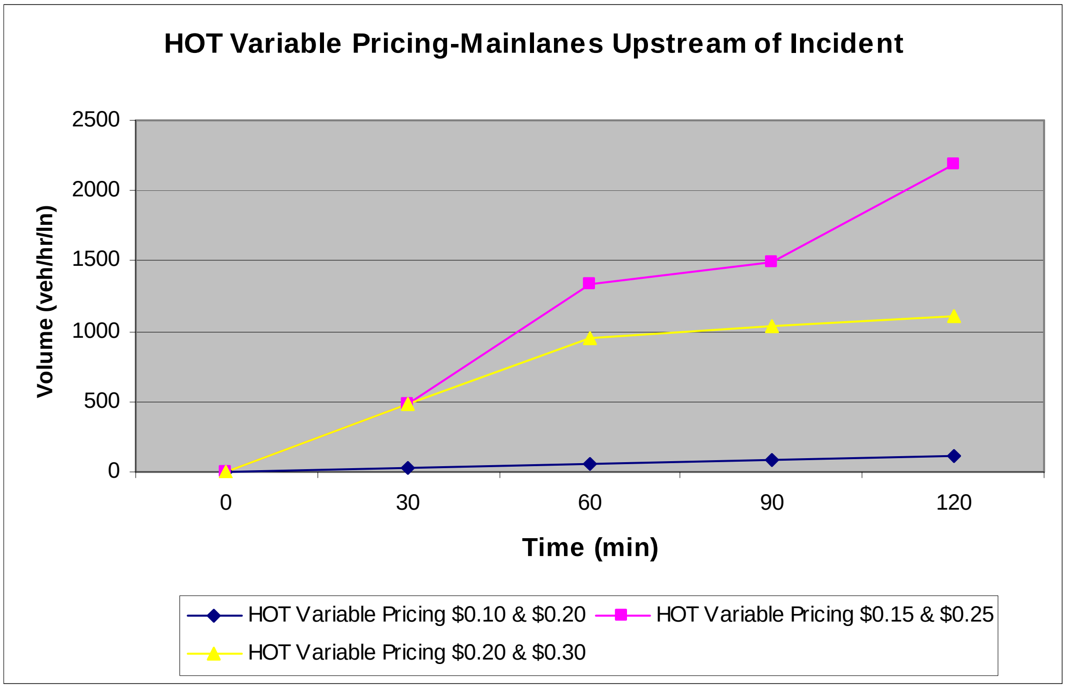


Figure 41. Tolling Scenarios – Volume.



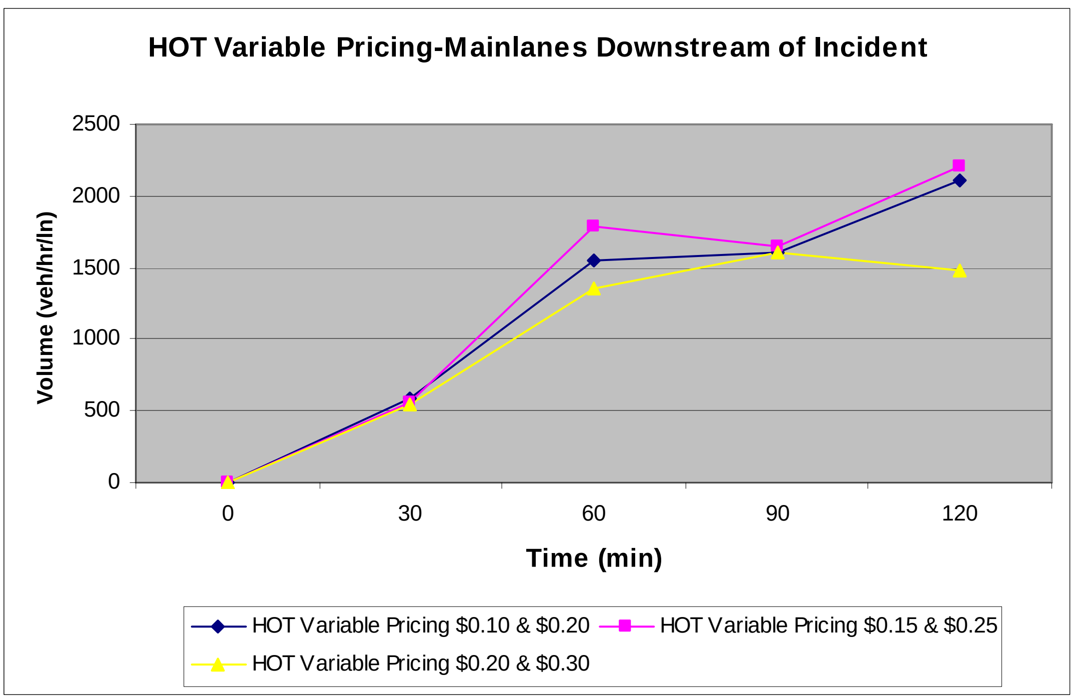


Figure 41. Tolling Scenarios – Volume (Continued).

DSP Scenario Comparison

Researchers performed a comparative analysis for all six incident management scenarios defined as well as a baseline model. Measures-of-effectiveness for freeway mainlanes in and around an incident area would be inconclusive since freeway capacity is reduced by 75 percent.

In order to get an accurate assessment of how each ramp strategy performed, it was necessary to do a system-wide network performance. Analysis showed that when the freeway ramp was closed dynamically during the duration of the accident, overall average travel time ranked better than all other alternatives, as shown in Figure 42. Total ramp closure created a better balanced flow of traffic on the open freeway mainlane and therefore reduced the overall travel time. Figure 43 showed that the highest variable pricing rate had the highest average stop time. This result is proof of the fact that price elasticity dictates routing decisions for motorists (54).

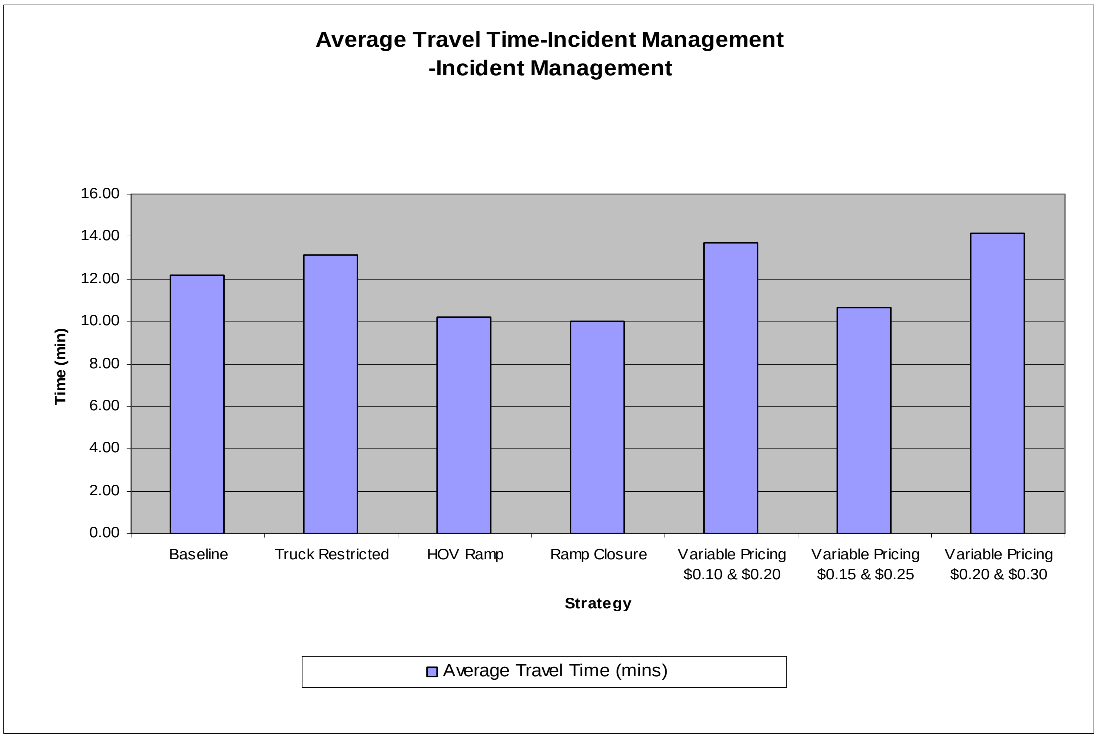


Figure 42. Average Network Performance – Incident Management.

Figure 43. Comparative Analysis of Average Stop Time – Incident Management.

Model Result Comparison (Incident Management)

Model output results for both VISSIM and DYNASMART-P exhibited similar patterns. The VISSIM model was extremely limited in functionality and capabilities but did give researchers insight on how fast queue lengths grow and travel time increases as successive ramps are managed upstream. DYNASMART-P gave an overall bigger picture of traffic patterns and traffic diversion caused by an incident. Pricing scenarios in DSP gave researchers insight on how sensitive drivers are to toll charges. DSP also gave a detailed analysis of traffic patterns associated with route choice diversions to decrease travel times.

Ramp closure in response to a freeway incident had the most optimal results when comparing average travel time. DSP also showed optimal results when analyzing overall average travel times for all vehicles in the network. Both models drew the same conclusions for truck-restricted ramps. Restricting trucks from entering a freeway facility in response to an incident was actually detrimental to overall system performance. Trucks comprised only 10 percent of the total vehicles in the networks yet they are much larger to maneuver. Restricting trucks from entering a freeway created havoc on the frontage and adjacent arterial roads.

However, analysis did show that certain pricing schemes actually performed worse than the truck-restricted scenario. This result leads the researchers to believe that price elasticity plays a major role on traffic diversion. When toll rates are high, vehicles immediately search for alternate paths downstream of the incident. When toll rates are low, vehicles flood the managed ramps and actually create bottleneck situations in and around the incident area. Therefore, sensitivity analysis with a well-calibrated model is needed before optimal results can be obtained when analyzing pricing as a ramp management strategy.

Special Event Management

Freeway Mainlanes

A section of IH-10 adjacent to the University of Texas at El Paso was used as a case study to analyze managed ramp strategies in support of special event management. There are four freeway mainlanes in the westbound direction of IH-10. The corridor speed limit is 60 mph and all lanes are general-purpose lanes. Grades for mainlanes and ramps are negligible. The campus entrance is exit ramp 18A. Figure 44 is an aerial image/VISSIM model of the corridor section and adjacent arterials including campus street network. Traffic volumes entering the campus on the first week of the new semester replicate a special event. After the first week, commuters destined for UTEP reroute to alternative paths. Traffic for the first week of the new semester is similar to traffic patterns exhibited during football games.

Figure 44. Aerial Image of IH-10 and UTEP Campus.

Freeway Mainlanes (Special Event Management)

A section of IH-10 westbound between downtown El Paso and exit ramp 16 at Executive Center was recreated in a VISSIM simulation model. This section of freeway has four lanes and sits adjacent to the University of Texas at El Paso. The University campus main entrance is located at exit ramp 18A (Schuster Avenue). The preceding exit ramp 16 at Executive Center is the limiting exit ramp downstream of the campus and serves as an alternative route during peak hours of congestion.

Vehicle Mix

The freeway vehicle mix for special event management was composed of vehicles that were destined for the university campus. The defined vehicle classes modeled were student, faculty, staff, visitor, and ambient (pass-by vehicles). The defined exit ramp not only serves as the campus entrance, but also a route for surrounding homes and businesses. Data collection was performed at all intersections surrounding the campus that included vehicle and pedestrian counts. The campus parking and transportation section provided the proportion of vehicle mix. This mix was identified by the number of parking stickers issued at the beginning of the semester. The campus vehicle mix composed of 85.percent student vehicles, 9.4 percent staff vehicles, and 5.4 percent faculty vehicles. Visitor traffic was calculated by the number of daily passes issued by the campus entrance guard. Only faculty and staff vehicles are allowed in the actual campus. Student vehicles must park in exterior parking lots that surround the campus. Therefore, turning percentages of vehicles bypassing campus were taken from faculty and staff and considered ambient traffic.

Freeway Volume

Traffic volumes vary on IH-10 throughout the day, especially in and around the UTEP campus. Traffic congestion is especially heavy during the first week of school of the fall semester. There are alternative entrances into the campus but most vehicles traverse through the main campus entrance that is off the Schuster Avenue exit of IH-10. Freeway traffic volume was estimated at 2000 vehicles per hour per lane. Actual traffic counts were taken at the terminal intersection off the Schuster Avenue exit, as shown in Table 41. Pedestrian counts were also taken at the same location to further help in model calibration.

Table 41. Traffic Volumes for Schuster Avenue Exit Ramp.

Sun Bowl/Schuster												
Existing Peak Volume												
Tuesday												
Time	EB			WB			NB			SB		
	LT	Thru	RT	LT	Thru	RT	LT	Thru	RT	LT	Thru	RT
8:15 am - 8:30 am	8	242	29	16	0	30	0	34	30	47	93	0
8:30 am - 8:45 am	4	167	52	11	0	32	0	47	28	51	93	0
8:45 am - 9:00 am	12	182	39	26	0	85	0	88	26	64	128	0
9:00 am - 9:15 am	12	92	30	17	0	54	0	57	18	23	67	0
Total	36	683	150	70	0	201	0	226	102	185	381	0
Time	EB			WB			NB			SB		
	LT	Thru	RT	LT	Thru	RT	LT	Thru	RT	LT	Thru	RT
11:30 am - 11:45 am	14	45	25	15	0	55	0	59	12	12	36	0
11:45 am - 12:00 pm	36	135	50	15	0	115	0	102	21	38	78	0
12:00 pm - 12:15 pm	47	113	42	23	0	153	0	131	18	41	69	0
12:15 pm - 12:30 pm	44	73	34	43	0	135	0	125	20	20	45	0
Total	141	366	151	96	0	458	0	417	71	111	228	0

Ramp Merge Condition

The exit ramp leading into the campus has no deceleration lane and traffic tends to spill back onto the freeway mainlanes during specific time periods of the morning. This spillback is the cause of numerous rear-end collisions on the freeway. In many instances, vehicles try to bypass the queued vehicles and cut directly into the queued line at the exit ramp creating further speed reductions on adjacent freeway mainlanes.

Determination of Performance Measures for Special Event Management

In the context of managed ramps in support of special event management, the ultimate effectiveness of ramp management is gauged not only by the balance of traffic flow around the defined exit ramp, but also the flow of traffic on adjacent freeway mainlanes. For special event management, the performance measures evaluated were queue length, delay, speed, and travel time. These measures-of-effectiveness were used to gauge the performance of specific vehicle class restrictions in support of special event management.

Queue Length

During special events, traffic converges to their destinations in a short time period. As a result, queuing can propagate rather quickly on freeway exit ramps. This queuing can lead to rear-end collisions, congested traffic areas, and bottleneck areas on adjacent freeway mainlanes. For this reason, the research team chose queue length as one of its performance measures. The ability to estimate the propagation of vehicle spillback by managing the exit ramp of a special event area can give stakeholders insight on which type of vehicles to restrict or give accessibility. Queue length was measured from a stop bar at the terminal intersection.

Delay

Delay is one of the most scrutinized performance measures by travelers. Especially when vehicles are destined to a special event, delay becomes even more critical. Any change in traffic congestion can have major impacts on vehicle delay. Consequently, the research team chose delay as a one of its performance measures. Delay was measured from upstream freeway mainlanes to the exit ramp.

Speed

Speed changes in and around a freeway exit ramp are dynamic and can vary greatly due to any disruption of traffic flow. Freeway exit ramps that experience heavy volumes in short time periods can easily alter the speed of freeway mainlanes. This imbalance of speed can increase the chances of collisions. The research team measured speed on freeway mainlanes adjacent to the exit ramp for the defined model scenarios.

Travel Time

Off-ramp queuing and speed changes around a special event area can affect travel time for vehicles bypassing the event. Peak-hour congestion combined with a special event can compound the problem and increase travel time dramatically. Therefore, travel time was also used as a performance measure for the research team. Travel time was measured on a 4-mile section of IH-10 adjacent to the university campus.

VISSIM Model Preparation (Special Event Management)

The first task for the researchers was to create a VISSIM model to test the defined scenarios. The research team chose a section of IH-10 in El Paso, Texas, and replicated a 4-mile portion of the freeway in the westbound direction adjacent to the university campus. The entire university street network was also included in the model because the exit ramp serves as the main campus entrance. The second step was to input data into the model that would replicate a special event. Peak traffic volumes during the first week of school in the fall are like a special event. During the first week of school, commuters destined for the university use the main campus entrance. After the first week of school, drivers tend to change their travel patterns and either use an alternate path to the university and/or leave at different time periods. However, the first week of school creates havoc in and around the campus, especially on the freeway and, more importantly, the Schuster Avenue exit ramp.

The next step was to calibrate the model so it would replicate traffic conditions during the first week of school. The city provided signal timings, and researchers used green time allocations for frontage road traffic. Speed distribution for the freeway ranged from 52.8 to 74.6 mph, as shown in Figure 45. The majority of all vehicles traveling on the freeway had speeds below 70 mph with only a small percentage traveling above 70 mph. Speed reduction areas were needed as part of the calibration process. Vehicles traveling on roadways perpendicular to the freeway must decelerate when making right turns onto the frontage road. A speed reduction range of 2.5 to 15.5 mph was used. For vehicles exiting the freeway via off-ramps, a speed reduction range of 36 to 42.3 mph was used. A deceleration rate of -6.562 ft/s^2 was used in all speed reduction areas. Driver behavior parameters were kept at default settings.

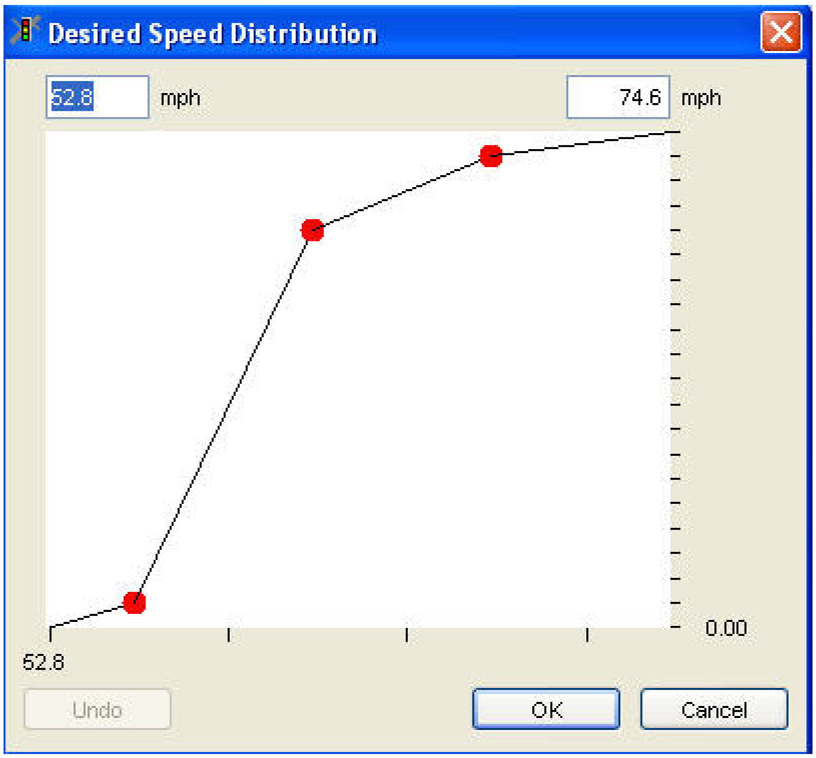


Figure 45. VISSIM Speed Distribution for Special Event Management.

The next step for modelers was to develop a mix of vehicles and features in the VISSIM model that would replicate traffic conditions during peak hours of the new school year. This task became challenging in terms of vehicle types and percentages. Data were collected in and around the campus and traffic was composed of student, faculty, staff, visitor, and ambient traffic. Traffic composition percentages were based on the number of parking stickers issued by the university. Once traffic percentages were calculated for each vehicle class, traffic was assigned statically to destination parking lots. Routing percentages were based on volume entering parking lots in and around the campus. Since faculty and staff are allowed to park inside the campus, percentages for these two vehicle classes that did not enter the university were considered ambient traffic. The campus police provided visitor counts which were based on the number of passes issued during the designated time period. Since only a relatively small percentage of trucks use the Schuster Avenue exit ramp during morning rush hour, no heavy vehicles were included in the model. The VISSIM model was simulated for one hour (3600 seconds).

Scenario Set Description for Special Event Management

The scenario sets included managing the Schuster Avenue exit ramp (exit 18A) in the westbound direction with two different types of vehicle class restriction. Figure 46 shows the defined scenario sets that were modeled and analyzed. It must be noted that each scenario included 10 different random seed runs. Output data from all 10 random seeds were then averaged into tabular and graphical formats.

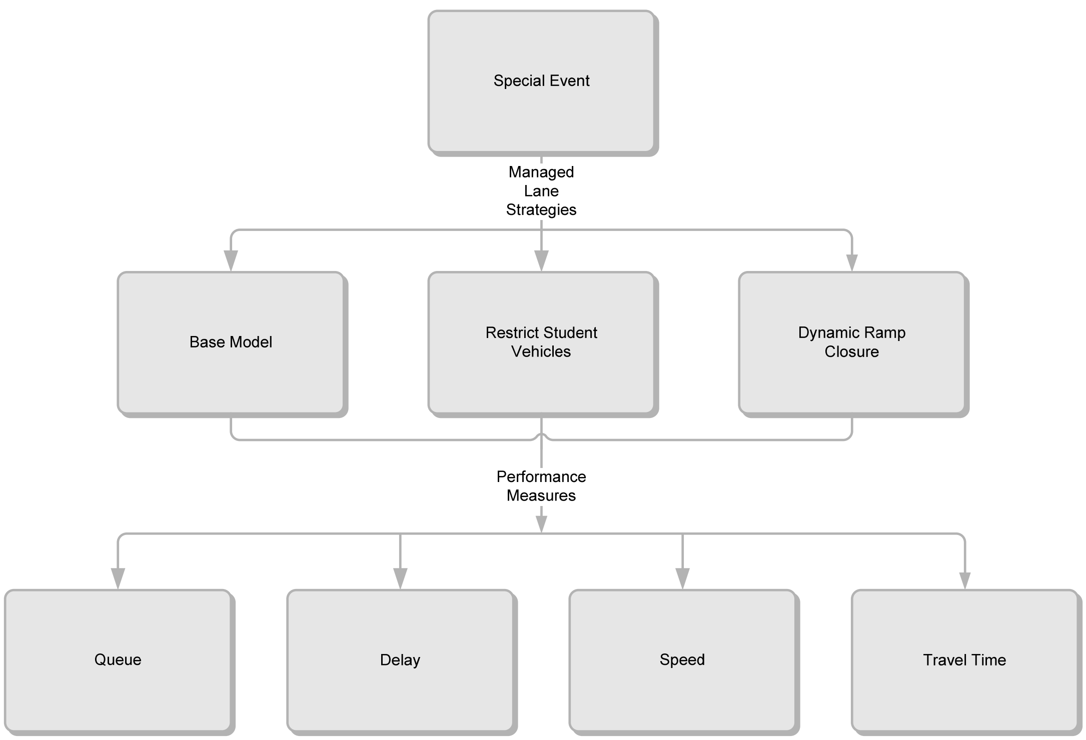


Figure 46. Flow Chart of Special Event Management Scenarios.

Results

Researchers created two distinct scenario sets and compared them to a base case (do nothing) model. Each scenario required multiple random seed runs and the average was taken for each defined performance measure. The two ramp management scenarios created were restricting student vehicles from exiting and restricting all vehicles. Ramp management strategies were dynamic ramp restrictions so it was necessary to place a loop detector in the middle of the exit ramp. When vehicles began to queue onto the loop detector, the model would divert specified vehicle classes away from the Schuster Avenue exit. Figure 47 is an image of the Schuster Avenue exit ramp.

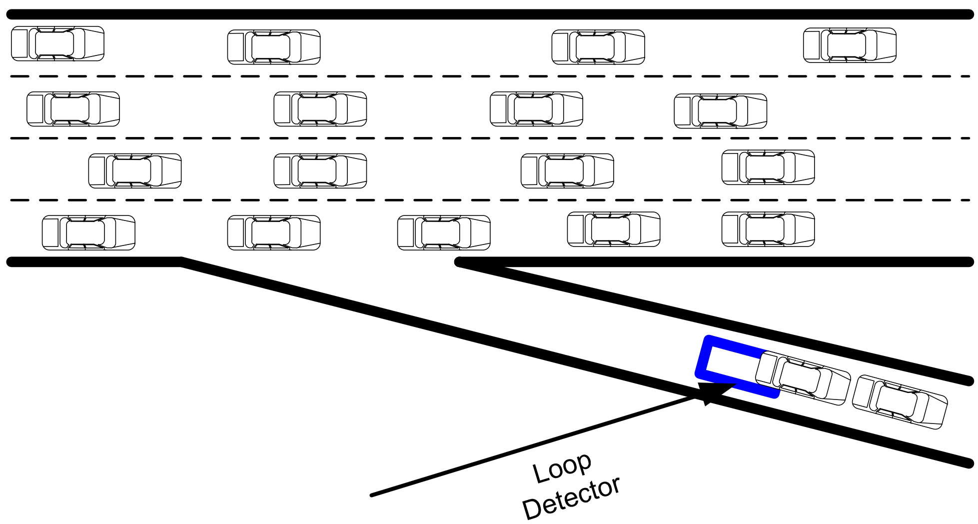


Figure 47. Schuster Avenue Exit Ramp.

Student Restricted

The first scenario was to dynamically restrict student vehicles from entering the university campus at the Schuster Avenue exit. When queuing reached the midpoint of the exit ramp, student vehicle classes were automatically rerouted and forced to continue on the Interstate. The goal was to prevent the queued vehicles from spilling back onto the freeway mainlanes. As the queue dissipated, student vehicles were allowed to utilize the exit ramp again. Output performance measures were compared to a base case (do nothing) model and consisted of ramp queue length, average freeway travel time on a predefined section, average speed upstream of the exit ramp, and average delay measured at the terminal intersection.

All Vehicles Restricted

The second scenario modeled was restricting all vehicles from exiting the Schuster Avenue off-ramp when spillback onto freeway mainlanes started to occur. As with the student-restricted scenario, all vehicles were automatically rerouted and forced to continue on the Interstate and bypass the exit ramp. Performance measures for all vehicles restricted were identical to the student-restricted scenario. Output statistics were tabulated into Excel and graphed for comparison.

Scenario Result Comparison (Special Event Management)

When both scenarios were compared to the base case model, researchers noticed significant impacts. A comparative analysis of average freeway speed dropped below 15 mph when no ramp management strategies were implemented. Restricting students and restricting all vehicles considerably increased freeway speed to approximately 50 mph. Speeds for ramp managed scenarios fluctuated between both, as shown in Figure 48.

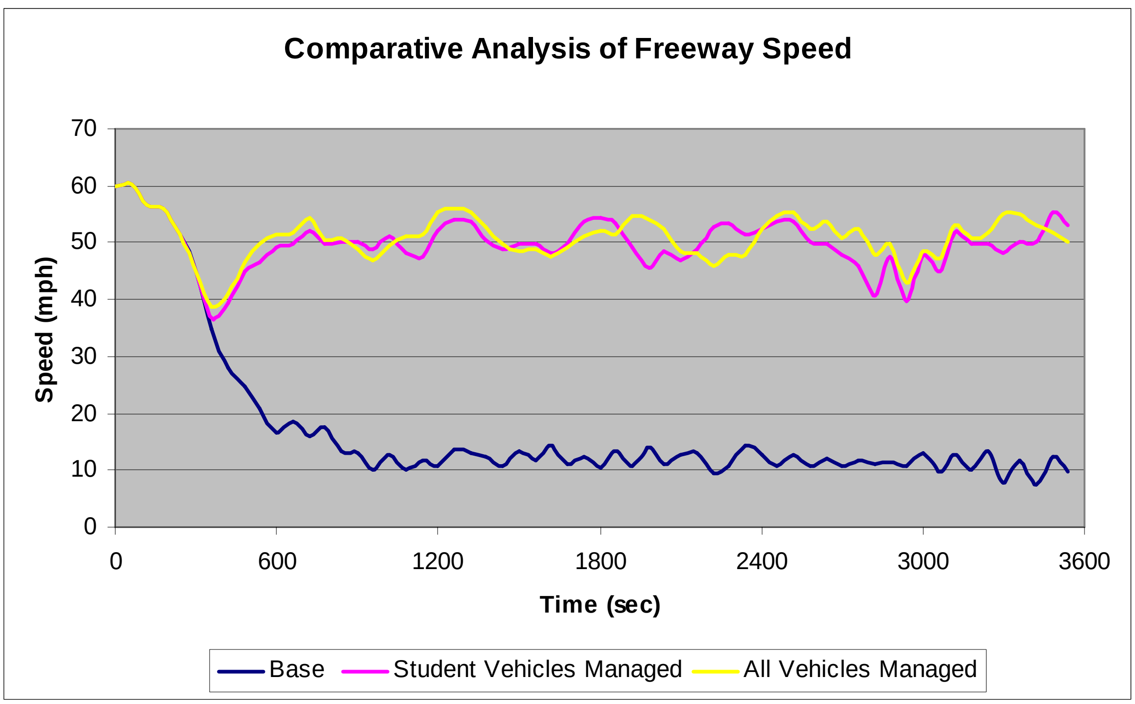


Figure 48. Comparative Analysis of Freeway Speed – Special Event Management.

Queue length was also tabulated and plotted in Excel. Ramp storage from the stop bar at the terminal intersection was approximately 900 ft to the loop detector. Queue length exceeded the storage capacity in the base case model and continued to spill back during the entire simulation. Both ramp management scenarios drastically reduced the queue length. The length of the queue fluctuated but stayed relatively short and did not surpass the storage capacity of the off-ramp, as shown in Figure 49.

Results from VISSIM showed that dynamic ramp closure performed the best when compared to vehicle class restrictions. Significant improvements to speed, queue length, delay, and travel time were apparent in the simulation models. This result brings forth the question of how dynamic restrictions and closures can be implemented. Since the model automatically changes the routes of new vehicles entering the network, this gave researchers insight as to a minimum distance for an upstream DMS. It must be noted that in reality, all traffic does not obey messages placed on the DMS. Therefore, further research is needed on optimal locations of DMS to maximize traffic flow or minimize traffic disruption caused by off-ramp queue spillback resulting from congestion from special events.

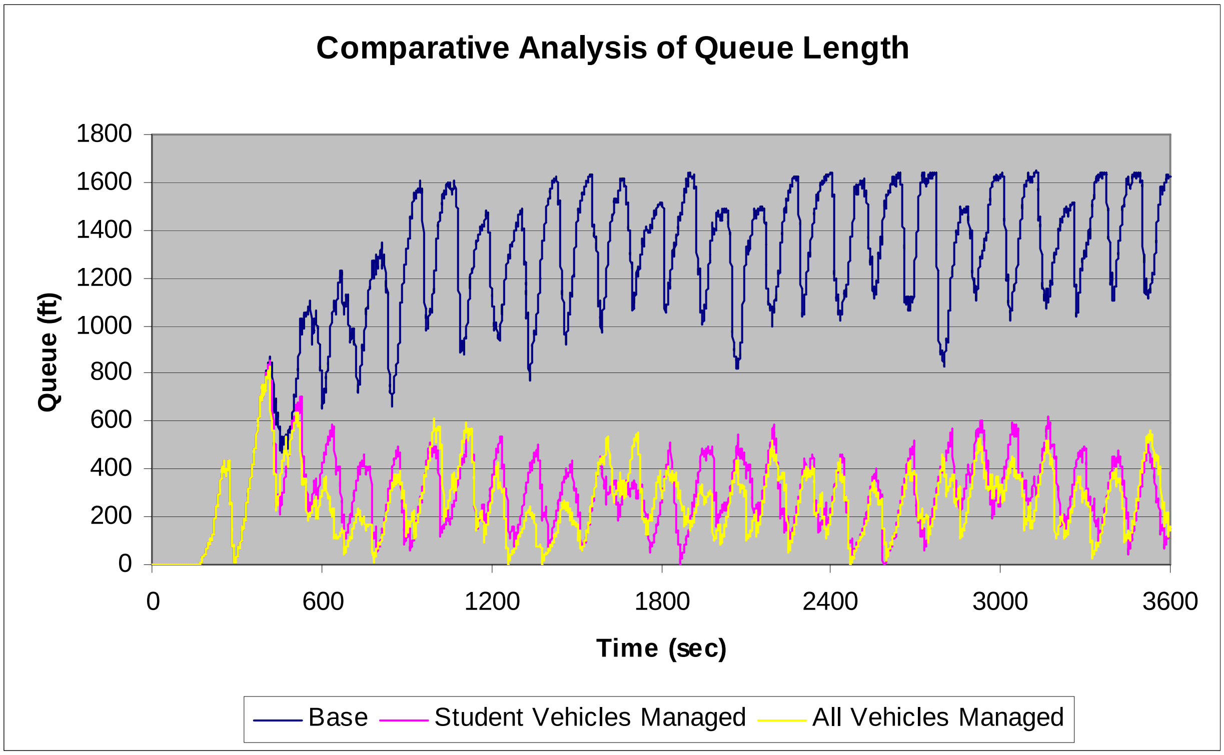


Figure 49. Comparative Analysis of Queue Length – Special Event Management.

MODELING MANAGED RAMPS IN SUPPORT OF MANAGED LANES

A variety of reasons exist for agencies to pursue managed ramps. The common motivations for ramp management are examined in this study and include ramp metering (and, in extreme conditions, closure) to preserve quality of expressway flow; speed or vehicle-type restrictions due to horizontal or vertical limitations along the ramp or in the vicinity of the ramp along the expressway; vehicle restrictions in support of mobility alternatives, such as bus-only and/or high-occupancy vehicle-only ramps; and, hybrids or combinations of select strategies. Strategy implementation may also vary by time of day, as in cases where ramp metering is utilized only during peak periods of demand.

Another motivation for managing ramps is in support of managed lanes that exist within an expressway corridor. Often the management of these ramps is less visible than directly managed ramps and the strategies are as subtle as ramp location to "feed" eligible vehicles to the managed portion of the facility. As an example, visualize a medially located managed lane along an expressway corridor through an industrial portion of a city. The managed lane permits only trucks and there are expressway general-purpose entrance/exit ramp pairs every half mile. Several ramps are available for trucks to enter the expressway, but trucks are managed by having them enter the expressway at a ramp a mile upstream from the location where a slip ramp provides access from the expressway general-purpose lanes into the barrier-separated truck-only managed lane. If this control was not applied, trucks entering at the first ramp upstream of the managed entrance would have insufficient distance to weave to the managed lane entrance without adversely affecting general-purpose lane speed.

Since this portion of the managed ramp analysis is devoted to expressway access ramps that support managed lanes within the expressway corridor, the management techniques deployed at the ramp are linked to the function and restriction of the managed lanes. Typical forms of managed lanes in Texas include HOV lanes, express (limited access) lanes, and tolled lanes, though some research in the state has been directed to investigating the potential for truck-only managed lanes *(52)*.

Purpose

The motivation for a detailed examination of operations issues associated with managing ramps to support an expressway's managed lanes function(s) is to provide reasonable design values for ramp placement given the geometric and traffic demand environment of the expressway facility, the type of managed lanes in the corridor, and the type of controls placed on the ramp. Researchers also wanted to ensure that the use of any procedure developed for this purpose would either directly or indirectly indicate whether the type of management strategy being considered for a ramp was viable in terms of not adversely affecting quality of flow on the expressway.

Previous and related studies with similar objectives were performed for TxDOT in the areas of overall managed lanes design and ramp placement (*55*) and, to some extent, truck lane utilization (*52*). Those investigations used simulation extensively as a means of identifying the operational impacts of ramp placement design decisions and generating performance measures for various managed lane scenarios. Both to leverage that experience for managed ramp scenarios and to provide design guidance to the extent possible across the myriad possible combinations of expressway and ramp geometry (i.e., expressway and ramp traffic demand levels, expressway and ramp vehicle mixes, and managed ramp strategies), researchers employed simulation in the current study. As in past studies, the VISSIM simulation model (*51*) was used in the analysis of study scenarios.

Managed Ramp Scenarios Supporting Managed Lanes

The research team faced competing concerns of desiring to provide utilitarian output for a broad range of possible managed ramp scenarios and keeping a practical limit on the number of scenarios analyzed. Researchers made the fundamental decision to focus on only those scenarios involving expressway ramps on the marginal (right) side of the expressway whose vehicles would weave to the medial (left) side of the expressway to access the facility's managed lane(s). Beyond this simplifying assumption, which reflects all of the Texas managed lanes experience to date, researchers made an effort to analyze the largest range possible of geometric and volume conditions for the expressway lanes and the managed ramp. The various factors researchers ultimately chose were based on their experience with previous, similar studies (*52*, *55*) and the input of the TxDOT Project Monitoring Committee; all are discussed below.

Number of Expressway Mainlanes

Mirroring the majority of expressway miles found in urbanized areas in Texas, researchers limited their simulation analyses to scenarios that featured three or four expressway lanes across which managed ramp traffic would weave to reach a managed lane access point. Though it is certainly realistic to expect that managed lanes could be found along expressways with a greater number of lanes, analysts used the guidance of previous and practical experience to limit the number of mainlanes modeled. This decision was based in no small part on the fact that the modeling results were ultimately intended to be used on a "per lane" basis, which would limit the utility of ranges of scenarios with many different expressway mainlanes.

Expressway Vehicle Mix

As managed lanes are primarily an urban phenomenon, researchers chose a set of three vehicle mixes generally representative of urban expressway conditions. Since such facilities often include transit presence and trucks, a "normal mix" was chosen to include 90 percent automobiles, 5 percent trucks, and 5 percent buses. The second mix was for expressways that either did not allow trucks or had limited or no truck use during peak periods. This "no trucks" vehicle mix included 90 percent automobiles and 10 percent buses. Finally, a truck-intensive mix was chosen for urban expressways serving interstate and intrastate trade traffic and/or industrialized regions within an urban area. This "high truck" mix had 80 percent automobiles, 15 percent trucks, and 5 percent buses. In all scenarios analyzed, the researchers assumed that 95 percent of all expressway traffic was general-purpose lane through traffic and that 5 percent of expressway traffic entered the managed lanes.

Expressway Volume

As every motorist knows, traffic volumes vary drastically by time of day and from facility to facility. Technically speaking, thousands of different volume levels exist. Practical limitations on resources for both analyzing and presenting results for different volume levels led researchers to model only those conditions associated with facility design. Accordingly, only two volume levels were chosen: moderately loaded and heavily loaded. The moderately loaded network was intended to provide results for conditions where future year volumes resulted in a performance level of service "D" *(50)* – a typical design objective. The heavily loaded network volume level was chosen for the more demanding weaving environment imposed when intervehicle maneuvering/weaving opportunities are limited and congestion is possible. Analysts selected a flow rate of 1000 vehicles per hour per lane to represent moderate flow and a rate of 1400 vehicles per hour for heavily loaded conditions.

Presence of Intermediate Expressway Ramp

Given the length of weaving sections between expressway general-purpose ramps and a downstream (medial) managed lanes access point/ramp, which can range between approximately one-quarter mile and several miles, researchers identified the need to allow for the presence of additional ramps along the expressway between the general-purpose entrance ramp and the managed lanes ramp. Analysts identified a vast range of possible real-world configurations. Limiting the options for practical reasons, analysts chose to have an intermediate ramp in half of all scenarios and to not have the intermediate ramp in the other half. In the scenarios featuring the ramp, it was an exit ramp located 1500 ft downstream of the general-purpose entrance ramp. In all cases where the intermediate exit ramp was modeled, analysts assumed that 10 percent of expressway traffic used the ramp.

Ramp Merge Condition

Three basic geometric configurations exist for the junction of an entrance ramp and an expressway's general-purpose lanes: a forced, or direct, merge; an acceleration lane; and, a full auxiliary lane. In a forced merge, the ramp simply merges into the rightmost expressway lane and only a short taper provides a physical transition onto the expressway. Ramp motorists must adjust their speed so as to maximize their opportunity for a smooth merge while simultaneously searching for a "gap" in expressway traffic. Where an acceleration lane exists, the situation is somewhat similar, but a short supplemental lane is provided on the expressway to better allow entering traffic to adjust speed and negotiate a "gap" in expressway traffic. Acceleration lane length was fixed at 500 ft for all (acceleration lane) scenarios. A full auxiliary lane is the most generous geometric accommodation for ramp traffic in that entering traffic has its own lane. This lane may be dropped at the next (downstream) expressway exit ramp or may continue as a lane addition on the expressway.

Ramp Vehicle Mix/User Group

Just as the expressway mainlanes had a select set of generally representative vehicle types, the managed ramp also has a set of vehicle types/user groups. To represent conditions where no heavy vehicles of any type are allowed to use a ramp as a result of one or more management strategies being applied, an “all automobile” group was used. Similar to the expressway, a “normal” mix of 90 percent automobiles, 5 percent buses, and 5 percent trucks was developed. As ramps in some of the larger urban areas in Texas are used in support of HOV operations, which can include HOT users and single-occupant toll (SOT) users, an “HOV/HOT/SOT/Bus” vehicle mix was developed. This mix included 85 percent automobiles and 15 percent buses. Finally, recent Texas research with truck lanes illustrated a need for a “truck only” mix that was composed of 100 percent heavy vehicles.

Ramp Volume

Two variations were used for ramp traffic. The justification for ramp volume variability is the same as the rationale provided for mainlane volume variability: analysis of design-level volumes for potential future year conditions and detailed investigation of operations under more intensive demand and weaving conditions. Ramp volumes used by researchers were 375 vehicles per hour and 750 vehicles per hour, respectively.

Proportion of Managed Ramp Traffic Weaving to Managed Lanes

One of the primary purposes of the current modeling effort was to identify the ability of a managed ramp to support expressway corridor managed lane operation. In accordance with this need, two different percentages of ramp traffic were modeled as weaving traffic from the ramp to the managed lanes. Researchers selected the percentages of weaving traffic as 25 percent and 50 percent of total ramp volumes. In cases where a downstream intermediate ramp was located between the managed ramp and the managed lanes access point, researchers assumed no managed ramp traffic would use the expressway general-purpose ramp.

Per Lane Spacing to Managed Lanes Entrance

The prevailing variable of importance to the managed ramp to managed lanes weaving exercise is the weaving distance necessary to provide relatively non-turbulent expressway flow amidst the managed ramp to managed lane weaving maneuvers. Based on experience, the research team acquired from previous managed lanes research employing the same types of modeling tools (55) a three-value range of 500, 1000, and 1500 ft per lane. Combining the per-lane spacing chosen and the number of expressway lanes used in the modeling experimentation, an overall managed ramp to managed lane access point weaving distance range of 1500 to 6000 ft was analyzed.

Determination of Performance Measures

In the context of managed ramps that support managed lanes within an expressway corridor, the relative success of the managed lanes themselves ultimately gauge the efficacy of ramp management. In turn, objectives for managed lanes depend heavily on the communities in which projects are found. Texas experience to date has deployed managed lanes to varying degrees to increase average vehicle occupancy (Houston and Dallas HOV lanes), increase expressway safety (Houston, Austin, Dallas/Fort Worth, and San Antonio truck lane restrictions), generate revenue from the sale of excess capacity for more reliable travel times (Houston HOT lanes), and facilitate long-distance trips (express lanes with restricted access in many cities).

Speed

At the heart of any given managed lanes strategy is the explicit goal of maintaining high speed for the managed lanes (56). In essence, while the goal of the overall managed lane is linked to community and stakeholder needs and objectives, the performance of the managed lane is judged by its ability to maintain quality higher-speed travel. As a result, the research team selected speed as the primary indicator of the level of performance for managed ramps scenarios supporting managed lanes. The use of speed as a performance indicator has the additional benefit of being readily and directly understood by the motoring public, unlike more industry-specific terms such as density and flow rate.

Speed Differential and Safety

One of the primary contributing factors to safety issues arising along higher-speed roadways is speed differential. In the case of uncongested expressway traffic, the most readily identifiable locations where speed differentials occur are in the vicinity of entrance and exit ramps, where motorists either attempt to decelerate to exit ramp speed or accelerate from entrance ramps in order to match pace with through vehicles on the expressway. Weaving situations offer additional complexity that the driver must negotiate as drivers must contend with searching for gaps searching and acceptance across multiple lanes and possible speed differentials between weaving and expressway through traffic.

Traffic engineering research shows that crash potential increases as the speed differential increases (*57*). Figure 50 demonstrates this phenomenon, which relates speed differential and crashes for both full access-controlled expressway ("Freeway" in the figure) and non-access controlled arterial roadways. Essentially, as the speed differential increases the crash rate increases at an exponential rate. The impact on safety resulting from speed differentials is further documented in national practices and standards for roadway design (*58*), from which Figure 51 is extracted. Figure 50 and Figure 51 are notably consistent in associating lower speed differentials with lower crash rates and indicating a speed differential of approximately 10 mph as the transition point above which the crash rate or ratio begins to increase rapidly with increasing speed differential.

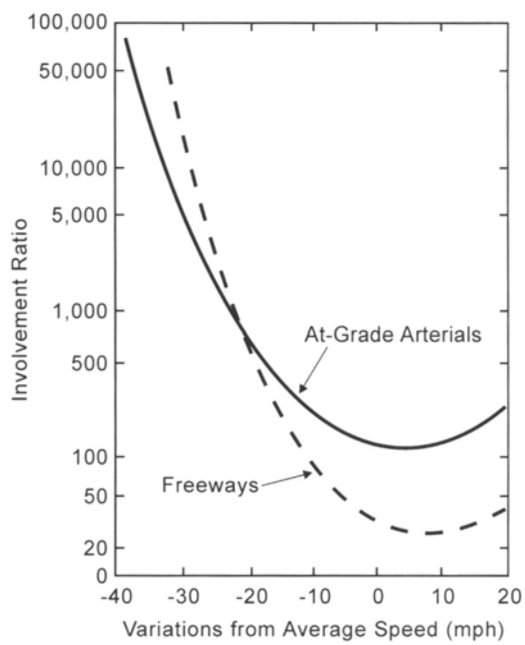


Figure 50. Crash Rate as a Function of Speed Differential (Adapted from *57*).

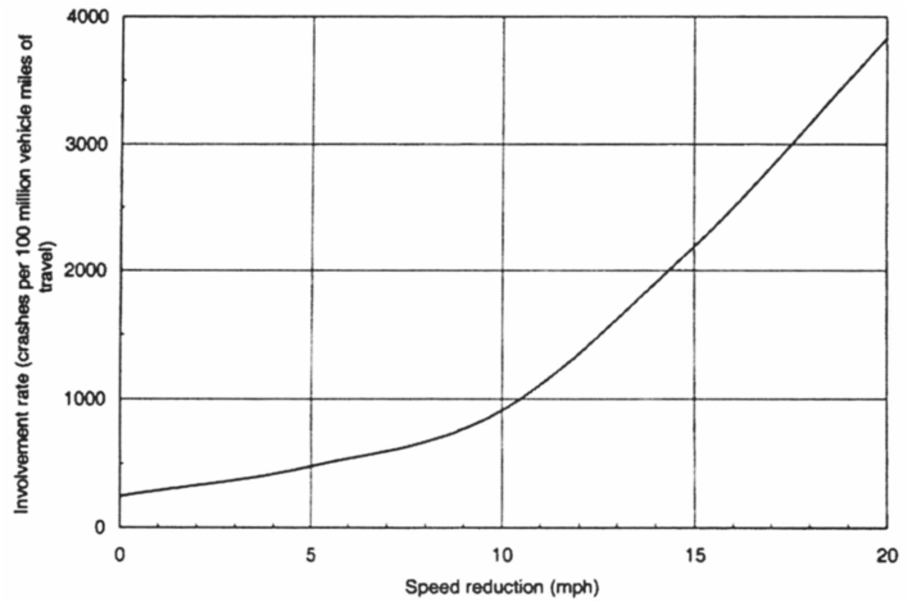


Figure 51. Crash Involvement Rate of Trucks for Which Running Speeds Are Reduced Below Average Running Speed of All Traffic (*58*).

Researchers used speed and speed differential in several ways in the course of analysis performed on the simulation output data from ramp modeling to support managed lanes. While all speed results are ultimately included in Appendix B, only those conditions with speed differentials of less than 10 mph are considered desirable and viable for design. Each set of simulation results was subjected to two tests: speed differential between approaching expressway traffic and traffic within the managed ramp weaving area, and speed differential between expressway through (i.e., non-weaving) and ramp-to-managed lanes (weaving) traffic. If either level of speed differential was observed to be in excess of 10 mph, researchers do not recommend that scenario as a potential managed ramp design condition.

VISSIM Model Preparation

Among the first model development tasks was configuring the VISSIM simulation model for the traffic environment typical of Texas expressway conditions. Previous research (*59*) led the analysts to immediately change the driving behavior parameter "waiting time before diffusion" in VISSIM from its default of 60 seconds to 1 second. If this change is not made, vehicles unable to maneuver to an exit ramp in a timely fashion will block expressway through lanes until reaching the maximum wait time and an unrealistic expressway bottleneck occurs. Analyst experience also led to a change in the exit ramp "look ahead" distance, or the distance when ramp-bound vehicles on the expressway begin to maneuver to the exit ramp lane. The default value of 656 ft (200 meters) resulted in all vehicles traveling too close to ramps before maneuvering into the exit lane, again resulting in artificial congestion. A value of 1968 ft (600 meters) is more consistent with real-world exit ramp advanced notification signing and resulted in representative real-world vehicle behavior.

The next challenge to modelers was the development of vehicle mixes and features in the VISSIM model that were representative of vehicles operating on Texas roadways. This task is relatively simple in terms of automobiles and buses, since automobile performance is common across many countries and bus performance also does not vary widely. The size and configuration of trucks, however, is much different in European countries than in the United States in general. Since VISSIM was developed in Germany, many of its truck and trailer size, axle configuration, and weight characteristics are not well mated to heavy vehicles in the United States.

Several classifications systems are used to stratify trucks. Table 42 shows both the "Texas 6" and FHWA systems. Previous research *(52)* was the guide in determining what types of trucks were typically found in Texas and what percentages of the truck traffic stream each comprised. The source of these data were TxDOT Automatic Traffic Recorder Stations (Table 37), which record traffic volumes and classification on a year-round basis and provide permanent historical records of traffic conditions. Again, the research team used previous research on truck roadways in Texas *(52)* to identify heavy vehicles' properties and develop simulated counterparts in VISSIM. Table 42 is the result of combining the Texas truck type percentages in its fleet with characteristics of these trucks. Adapting each of these truck types into VISSIM employing its default truck and trailer features is shown in Table 39. Information contained in Table 42 and Table 39 was ultimately coded into VISSIM to create a representative Texas truck fleet. In any simulation where trucks were a part of the vehicle stream, those trucks are distributed according to the percentages shown and have the characteristics noted.

Table 42. Truck Characteristics Applied to Texas Truck Fleet – Managed Lanes Facility Preference.

Truck Class	Relative Flow	Length (ft)	Width (ft)	Weight (lb)		Power (hp)	
				Min.	Max.	Min.	Max.
5	0.082	27.89	8	15,000	46,000	220	260
6	0.009	27.89	8	20,000	53,000	220	300
7	0.001	30.94	8	25,000	52,000	250	300
8	0.019	36.13	8	28,000	66,000	315	380
9	0.835	60.22	8	30,000	80,000	380	480
10	0.006	55.39	8	32,000	87,000	415	490
11	0.039	70.69	8	35,000	92,000	440	500
12	0.009	67.24	8	35,000	106,000	505	525
13	0	92.35	8	35,000	120,000	570	580

To complete the vehicle mix coding in VISSIM, it is necessary to create "compositions" of each vehicle mix. As an example, the "normal" vehicle mix for expressways and ramps is composed of 90 percent automobiles, 5 percent trucks, and 5 percent buses. The user configures the proportion of each vehicle type before any simulations begin. When it is time to use a particular mix, the analyst simply selects it from the list of available traffic compositions. In accordance with the traffic scenarios outlined above, the traffic mixes "normal," "no trucks," and "high truck volume" were developed for the expressways and the mixes "normal," "all automobile," "trucks only," and "HOV/HOT/SOT/Bus" were developed for the ramps.

In all cases, the model was a relatively simple construction that included the expressway through lanes, the general-purpose entrance ramp, a downstream intermediate ramp (if present), and the downstream managed lanes entrance ramp. The length of each roadway segment and the number of lanes was fixed by the scenario. One important entry analysts had to specify was the speed distribution on the links making up the roadway network being modeled. In order to replicate conditions on urban expressways in Texas, a free-flow speed range between 65.0 and 74.6 mph (VISSIM speed distribution 90) was chosen.

To provide a more complete visual example of the appearance of some of the models researchers built for the managed ramps scenarios, several figures have been provided. Figure 52 presents the case where an intermediate exit ramp is found between the managed entrance ramp and the managed lanes access ramp. The managed ramp itself features a forced merge condition onto the expressway through lanes. Figure 53 illustrates the ramp merge condition where an acceleration lane is provided. A full auxiliary lane is shown in Figure 54. Note that since no downstream intermediate ramp is shown in this example the auxiliary lane becomes a full lane addition onto the expressway.

The final step in preparation of performing the analytical simulation runs for all scenarios was the establishment of travel time detection zones. Speed can be directly detected using sensors that are placed along expressway segments, but such sensors produce speed measures only at the point where they are located rather than along an entire segment. Speed values can also be generated in VISSIM for specific segments of roadway. However, these speeds can only be collected for all vehicles or for pre-specified groups of vehicles along the link. As it was necessary to collect space mean speed rather than point speeds and to separate expressway through traffic speed from ramp weaving speeds, travel time zones were used. Knowing the travel time output for both weaving and non-weaving traffic and the length of the travel time detection zones, researchers were able to compute average space mean speed for both traffic streams. Figure 55 shows travel time zone limits and Table 43 provides their corresponding zone lengths.

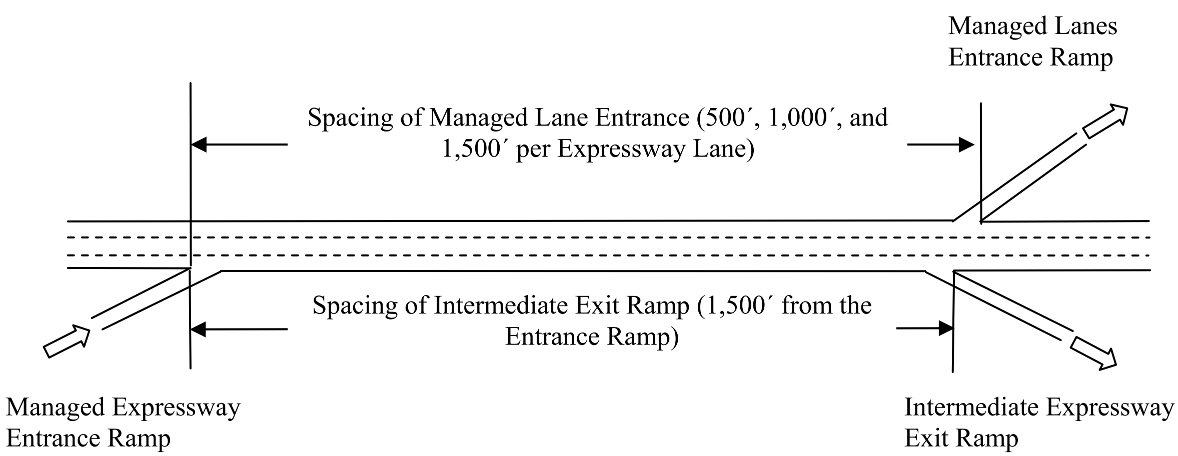


Figure 52. Expressway with Forced Merge Ramp (with Intermediate Ramp).

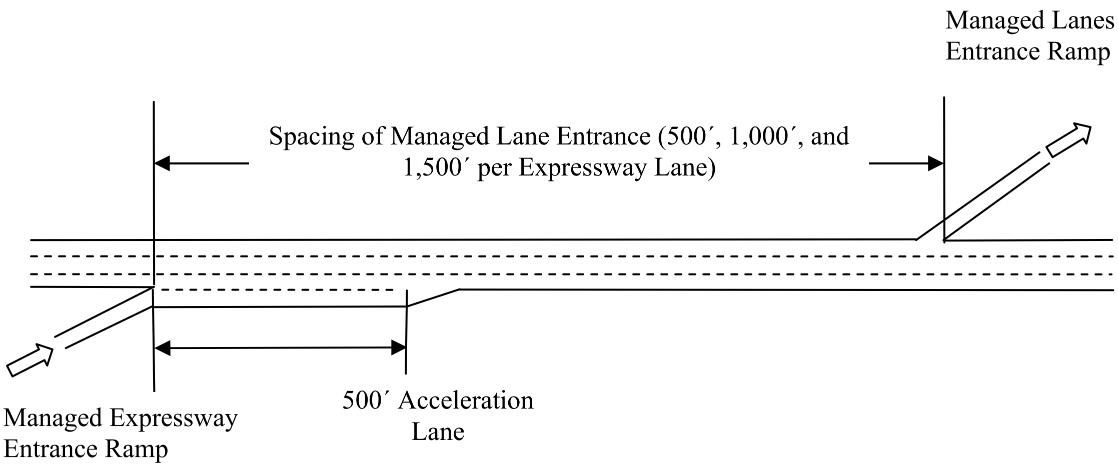


Figure 53. Expressway with Acceleration Lane Ramp Merge (without Intermediate Ramp)

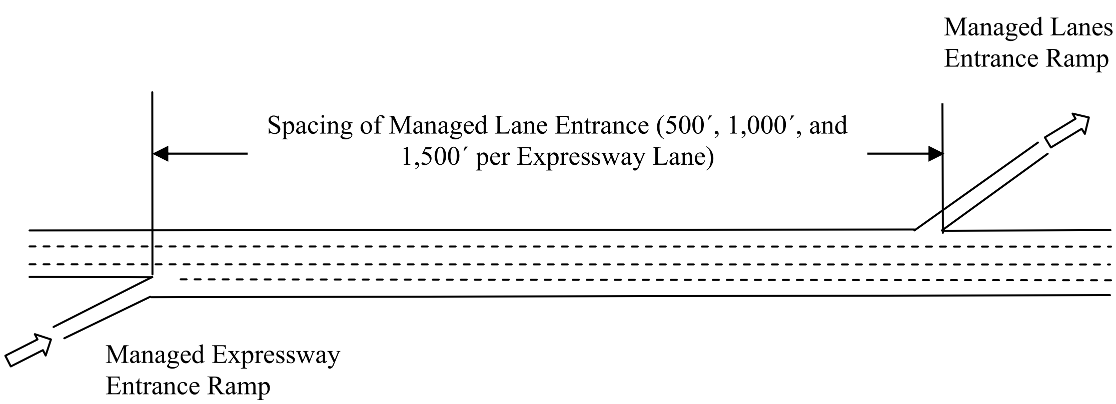


Figure 54. Expressway with Full Auxiliary Lane Ramp Merge (without Intermediate Ramp).

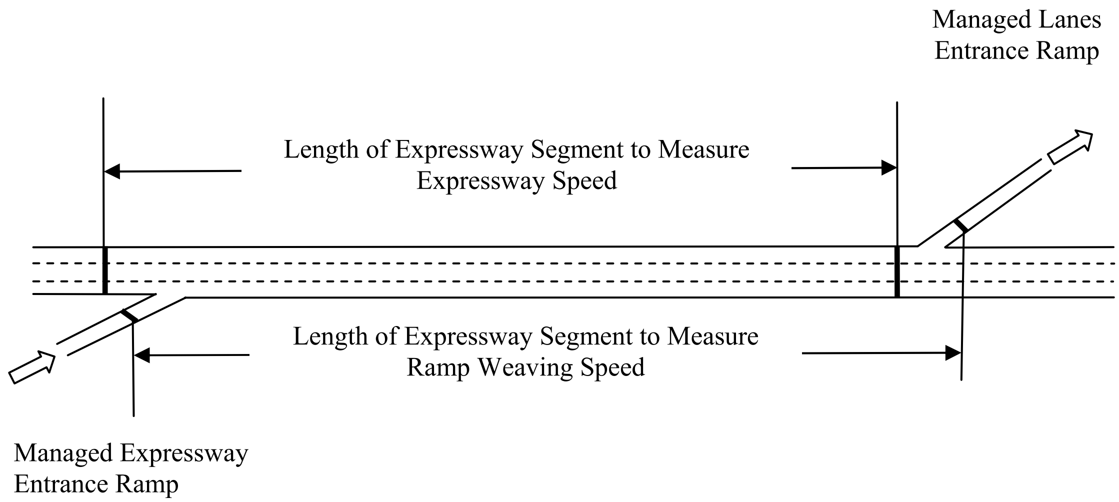


Figure 55. Segment Lengths for Expressway and Ramp Weaving Speed Measurement.

Table 43. Length of Expressway Segment for Speed Measurement.

Managed Ramp to Managed Lanes Ramp Spacing (per lane)	Length of Expressway Segment for Measuring Vehicle Speed (ft)	
	Expressway (3 mainlanes)	Expressway (4 mainlanes)
500 ft	**1,600**	**2,100**
1,000 ft	**3,100**	**4,100**
1,500 ft	**4,600**	**6,200**

Note: Segment length is same for measuring expressway mainlane speed and ramp weaving speed in each case.

Results

Researchers created unique combinations of each individual model feature described earlier (see Managed Ramp Scenarios Supporting Managed Lanes). In total, 3456 simulation input files were coded. Unique geometric files were created for each basic ramp and mainlane geometry condition and then search-and-replace methods were used to create variations on these files with different traffic mixes, volume levels, and ramp weaving percentages. Custom programs were developed to run each file three times with a different random number seed and then extract the expressway through lane speed and managed ramp weaving speed from each output file VISSIM generated. A spreadsheet was developed to produce final average speeds for each scenario and generate graphs to interpret the output.

When all variables affecting the managed ramp to managed lanes scenarios are considered, the modeling results exist in a space of nine dimensions. Researchers employed various graphical techniques, including three-dimensional renderings, in an attempt to relate the results of the simulation effort in a comprehensive manner. The outcome of these efforts was neither clear nor useful to interpret results across modeled variables. As an alternative to showing all results at once, the research team developed two methods to present the simulation output and provide users with a means of applying the findings to their design situation. First, two-dimensional figures have been developed to present the findings of all simulations for key variables. Second, example applications have been developed to demonstrate the use of the simulation output – found in Appendix B – for several unique design situations.

Proportion of Trucks on the Expressway

The researchers divided the vehicle mix on the expressway mainlanes into three categories: no trucks (90 percent auto, and 10 percent bus); normal mix (90 percent auto, 5 percent bus, and 5 percent truck); and high truck volume (80 percent auto, 5 percent bus, and 15 percent trucks). Figure 56 shows expressway mainlane speeds and ramp weaving speeds under the three ramp merge conditions and for the percentage of truck traffic on the expressway. As the expressway truck percentage increased, expressway through lane speeds and ramp weaving speeds decreased for all ramp merge conditions. Expressway mainlane speeds and ramp weaving speeds were higher where the ramp merge featured an auxiliary lane.

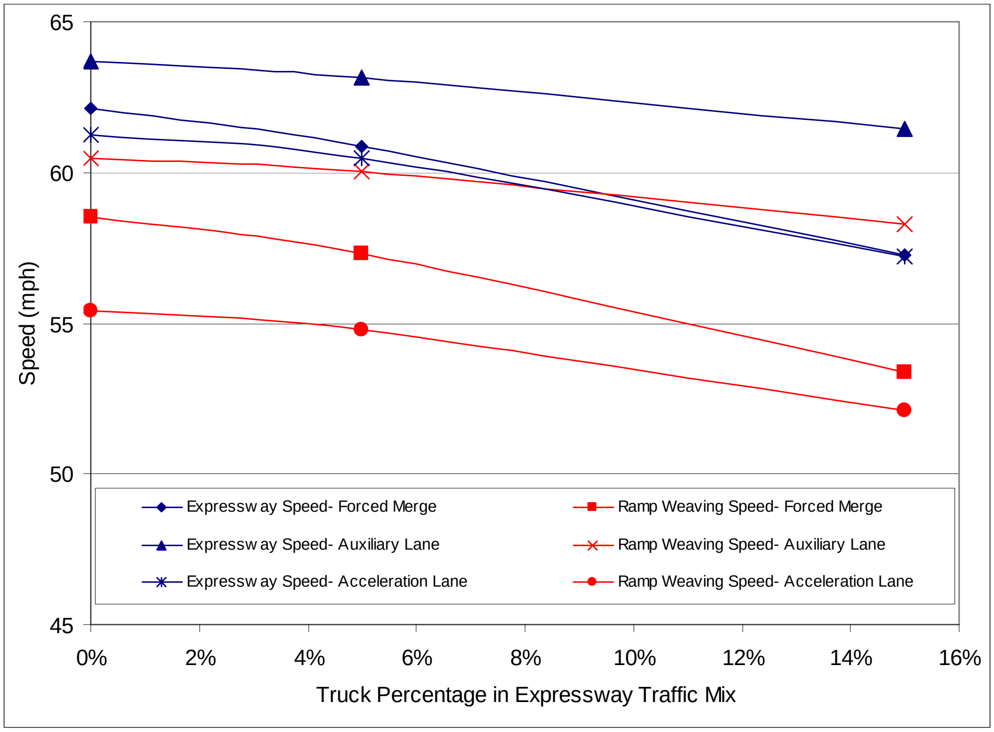


Figure 56. Expressway and Ramp Weaving Speeds with Different Expressway Truck Mixes.

Space between Managed Ramp to Managed Lanes Access Point

As specified in the scenarios' descriptions, analysts employed ramp spacings of 500 ft, 1000 ft, and 1500 ft per expressway lane for the simulations. Expressway mainlane speeds under various ramp merge conditions and ramp spacings are shown in Figure 57. Mainlane speeds are observed to increase with spacing increases between the managed ramp and the managed lane access ramp. Ramp weaving speeds and ramp spacing per expressway mainlane for all three ramp merge conditions are shown in Figure 58. Ramp weaving speeds also increased with an increase in spacing entry ramp to expressway and entry ramp to the managed lane.

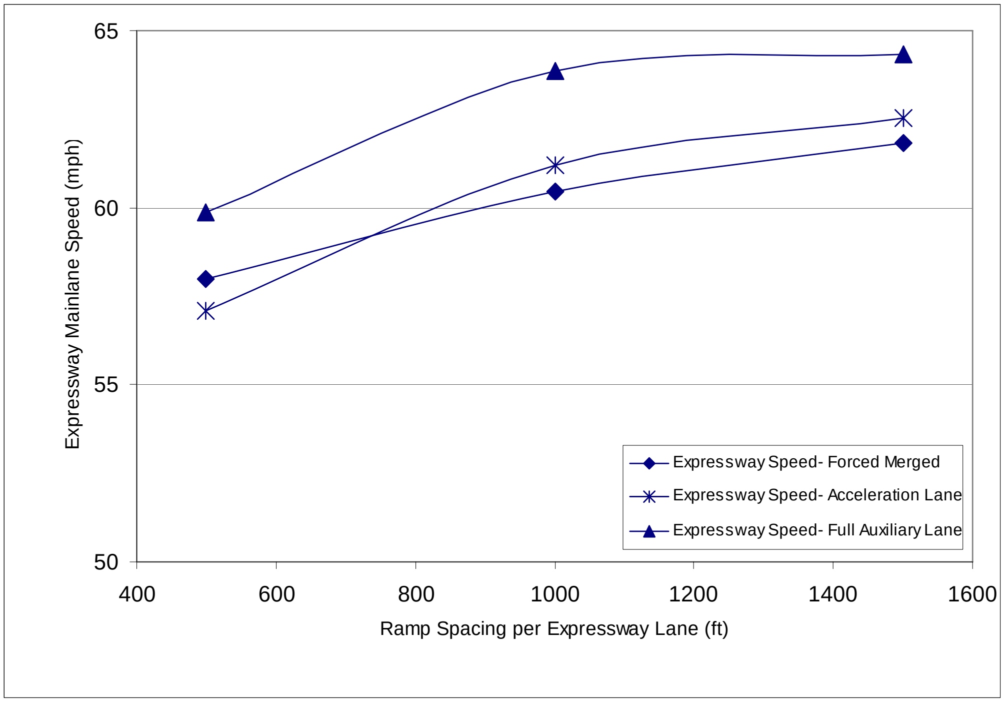


Figure 57. Expressway Mainlane Speeds with Different Ramp Conditions and Ramp Spacing.

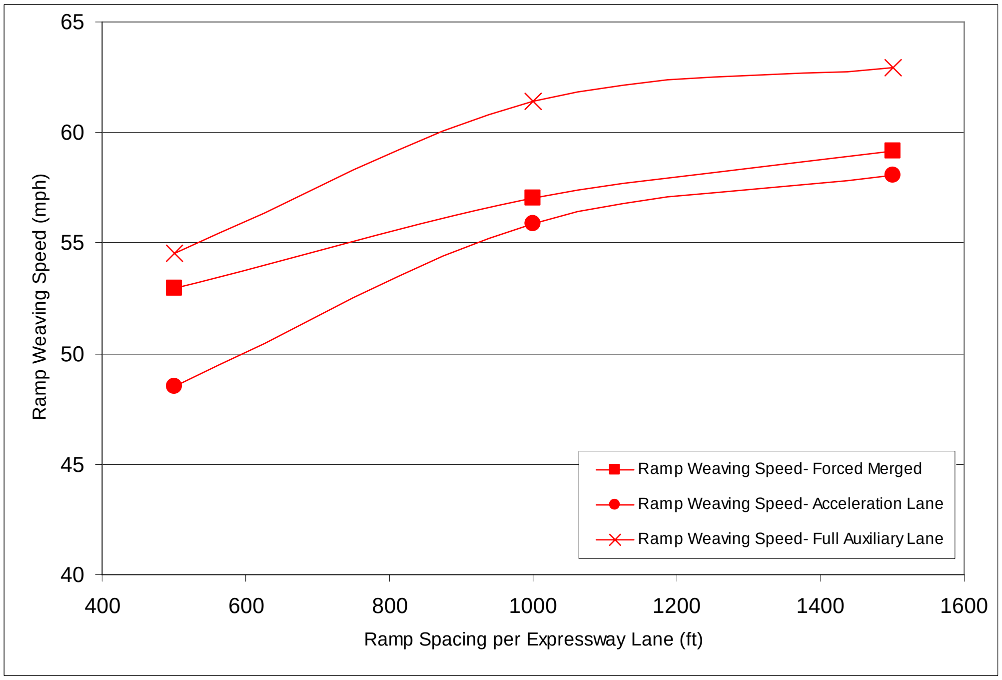


Figure 58. Ramp Weaving Speeds with Different Ramp Conditions and Ramp Spacing.

Proportion of Automobiles on the Ramp

Four managed ramp vehicle mixes were developed for simulation. These vehicle mixes included: all automobiles (100 percent auto), normal mix (90 percent auto, 5 percent bus, and 5 percent truck), HOV/HOT/SOT/Bus only (85 percent auto and 15 percent bus), and trucks only (100 percent truck). Expressway mainlane speeds were observed to increase with an increase in the proportion of automobiles found in the ramp traffic mix. Similarly, ramp weaving speeds increased with an increase in the ramp auto proportion. Expressway mainlane speeds and ramp weaving speeds, broken down by the three ramp merge conditions, are shown in Figure 59 and Figure 60, respectively.

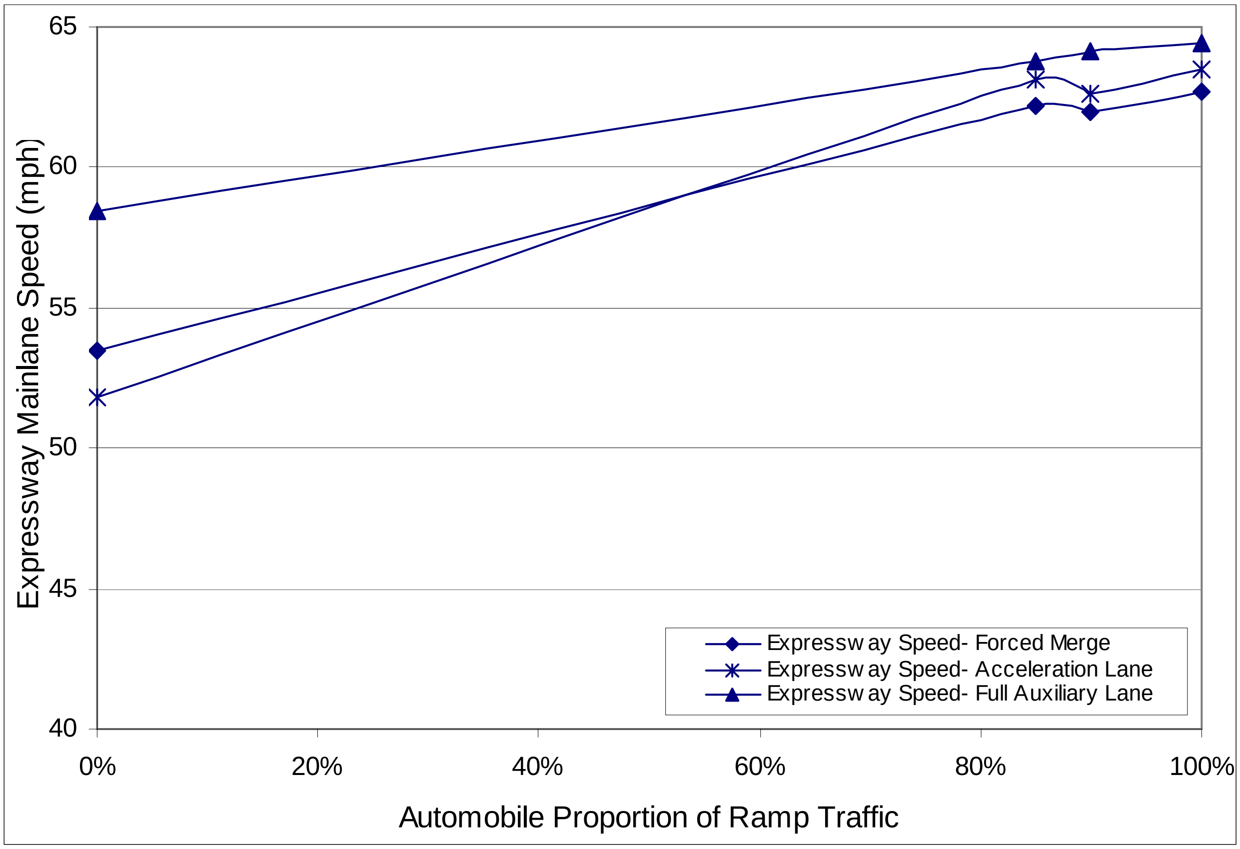


Figure 59. Expressway Mainlane Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

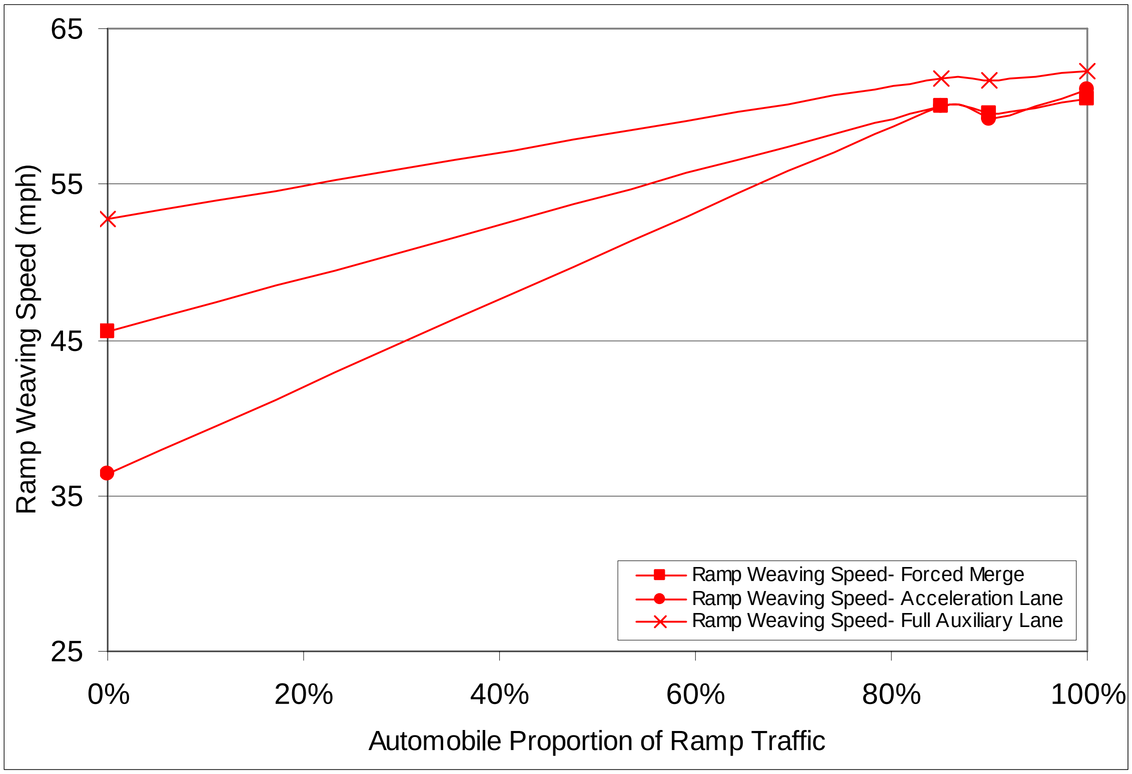


Figure 60. Ramp Weaving Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

Expressway mainlane speeds and ramp weaving speeds under the three ramp spacing conditions are shown in Figure 61 and Figure 62, respectively. Expressway speeds and ramp weaving speeds are both noted to increase with increases in weaving distance and increase in the proportion of automobiles found on the ramp.

The "truck only" ramp vehicle mix performs better with a full auxiliary lane than the other two types of ramp merge conditions. The speed difference is approximately 7 mph between the full auxiliary lane and acceleration lane ramp merge conditions for a ramp composition of 100 percent trucks. The speed difference reduced to approximately 1 mph for a ramp featuring only automobiles in the vehicle mix. Expressway mainlane speed was approximately 52 mph with 100 percent trucks on the ramp and the speed increased to approximately 64 mph with 100 percent automobiles on the ramp for a ramp with an acceleration lane. The differential of ramp weaving speed between two ramp conditions, full auxiliary lane and acceleration lane, is approximately 17 mph for 100 percent trucks on the entrance ramp. The speed differential of ramp weaving speed for these two ramp merge conditions is approximately 1 mph if 100 percent automobiles are found on the ramp.

Full auxiliary lanes yield higher ramp weaving speeds for both 100 percent truck and 100 percent automobile vehicle mixes on the entrance ramp. The difference in the ramp weaving speed between the acceleration lane and forced merge ramp condition is greater when the ramp serves 100 percent truck traffic. Ramp weaving speed differentials are observed to decrease as the truck proportion on the ramp traffic decreases. The difference is marginal when truck proportion in traffic mix reaches zero, i.e., 100 percent automobiles on the ramp.

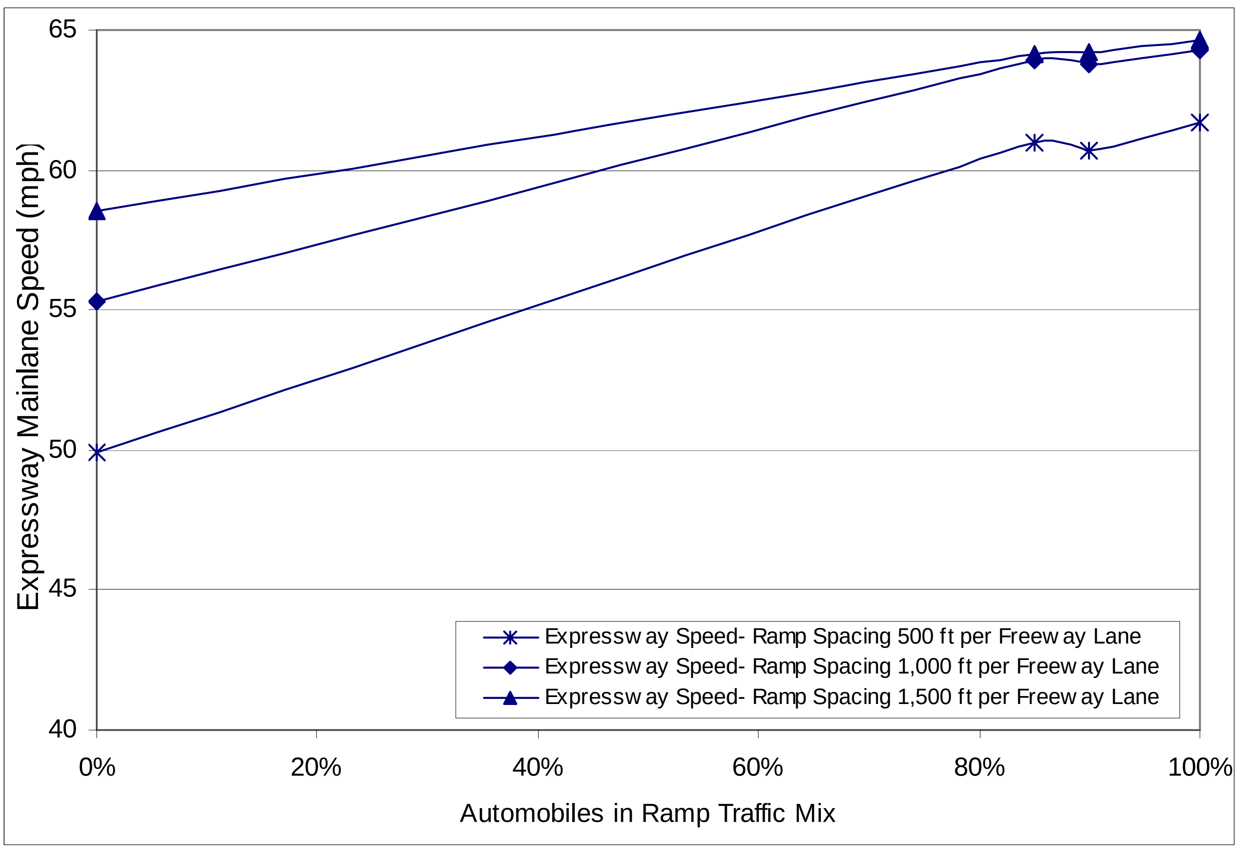


Figure 61. Expressway Mainlane Speeds with Varying Automobile Proportions and Ramp Spacing.

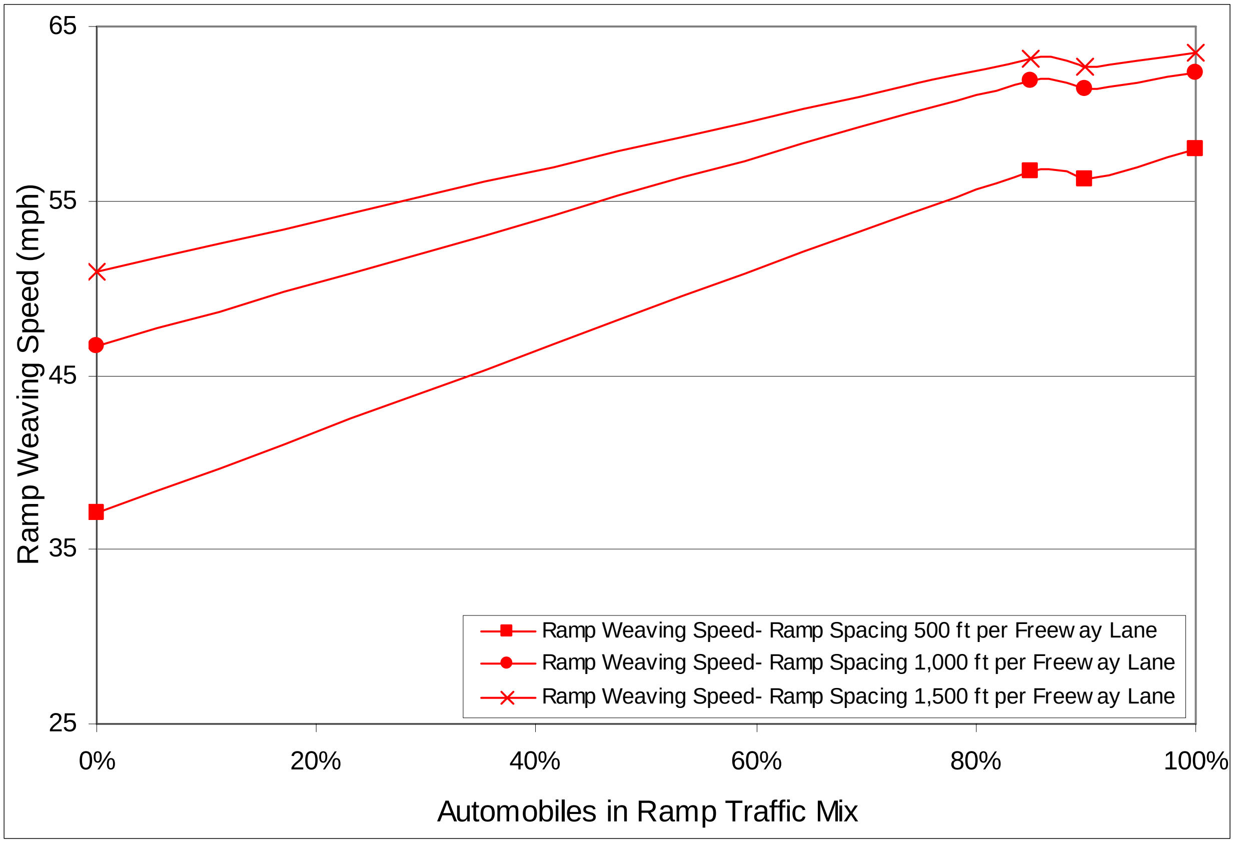


Figure 62. Ramp Weaving Speeds with Varying Automobile Proportions and Ramp Spacing.

Expressway Volume Level

As outlined in the scenario descriptions, all models included expressway traffic conditions at either nominal (1000 vehicles per hour per lane) or higher volume (1400 vehicles per hour per lane) flow levels. As expected, expressway mainlane and ramp weaving speeds were greater when the volume level was less demanding in terms of volume-to-capacity ratio. Both expressway mainlane and ramp weaving speeds are shown in Figure 63 with different ramp merge conditions and expressway flow levels.

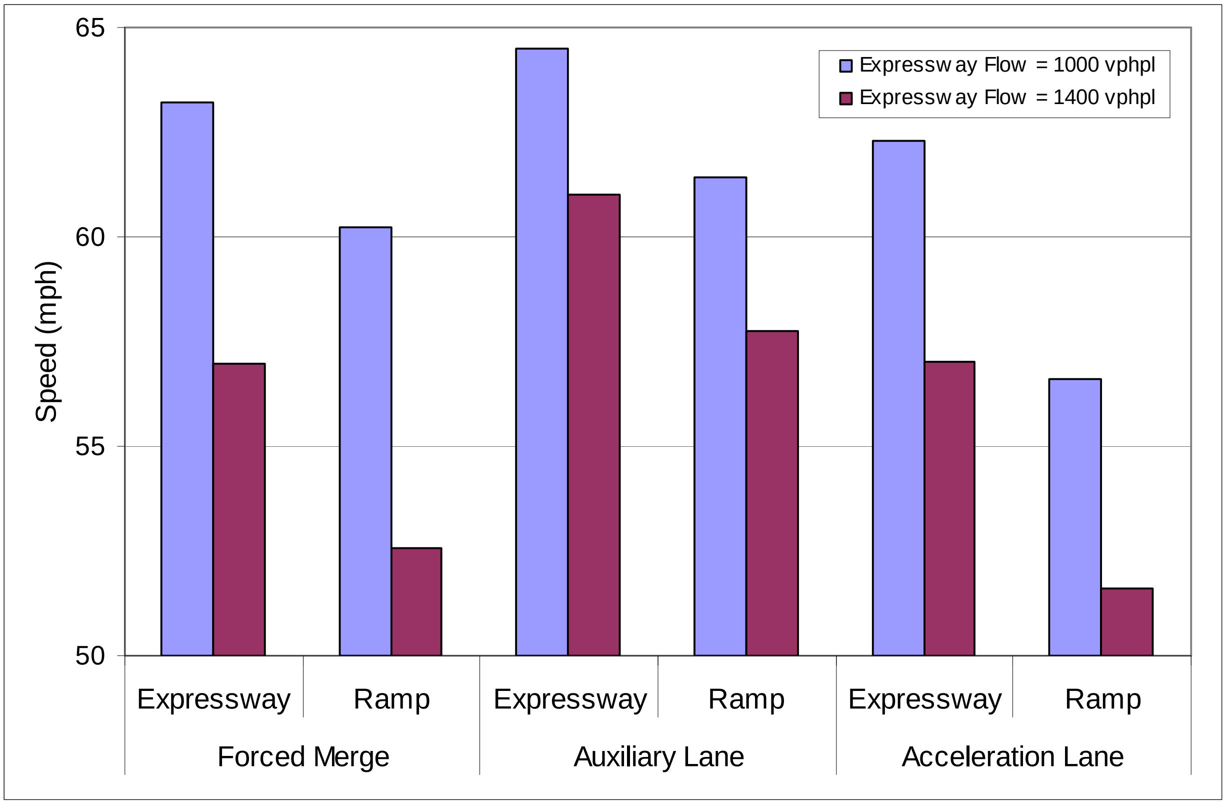


Figure 63. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Expressway Flow Levels.

Presence of an Intermediate Ramp

The presence of an intermediate ramp between the expressways managed entrance ramp and the entrance ramp to the managed lanes decreased the expressway mainlane and ramp weaving speed. Both expressway mainlane and ramp weaving speeds were lower for all ramp merge conditions in the presence of intermediate ramps. Expressway mainlane and ramp weaving speeds are shown in Figure 64 with and without the intermediate ramp and across different ramp merge conditions.

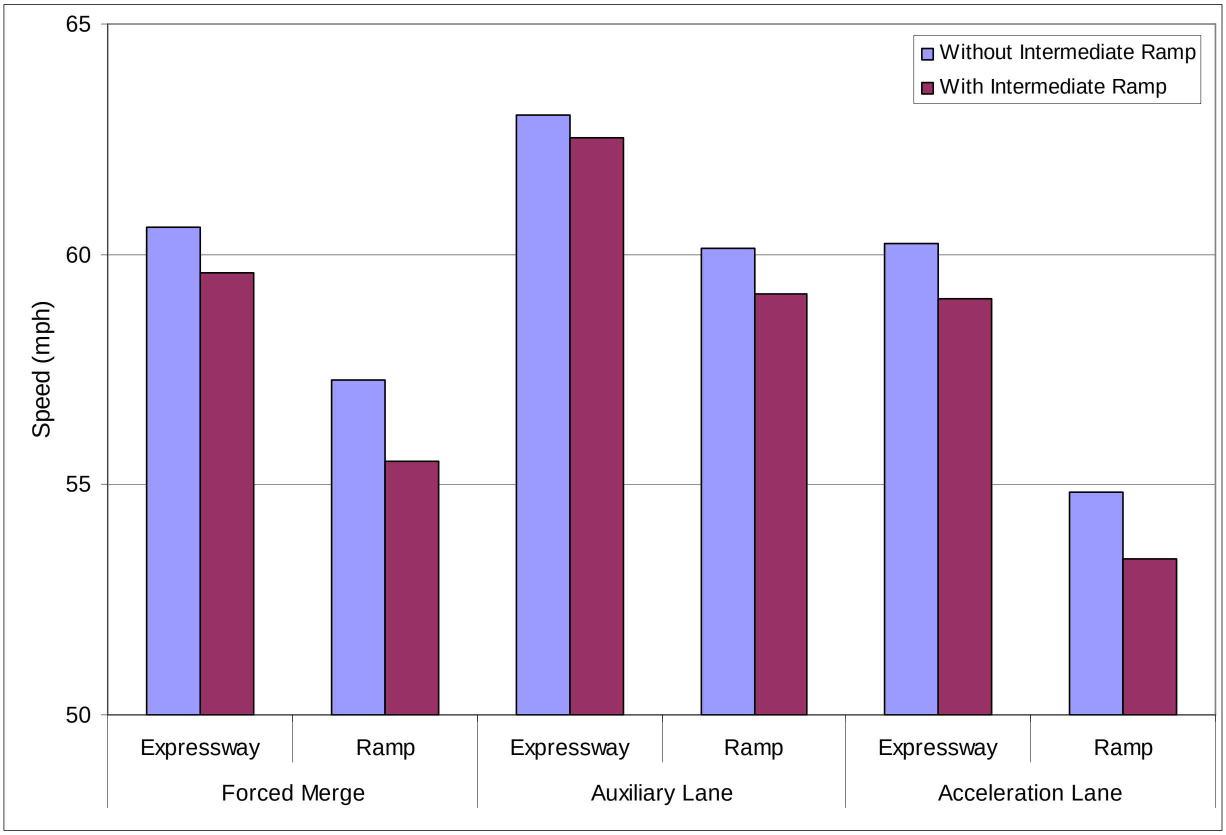


Figure 64. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Intermediate Ramp Scenarios.

Entry Ramp Flow Level

Two levels of managed ramp flow were used in the simulations: 375 and 750 vehicles per hour per lane. The extent to which higher ramp flows had an impact on freeway and ramp weaving speed performance is shown in Figure 65. The output is also organized to demonstrate differences ramp merge condition had under the different ramp flow scenarios.

Proportion of Ramp Traffic Weaving to Reach the Managed Lane

To ascertain the impact that different quantities of weaving traffic from the managed ramp to the managed lanes access point had on overall operations, cases were designed with 25 percent and 50 percent of ramp traffic weaving to reach the managed lane. The significance of the weaving traffic proportion on expressway mainlane and ramp weaving speeds is shown in Figure 66, which organizes results by managed ramp merge condition.

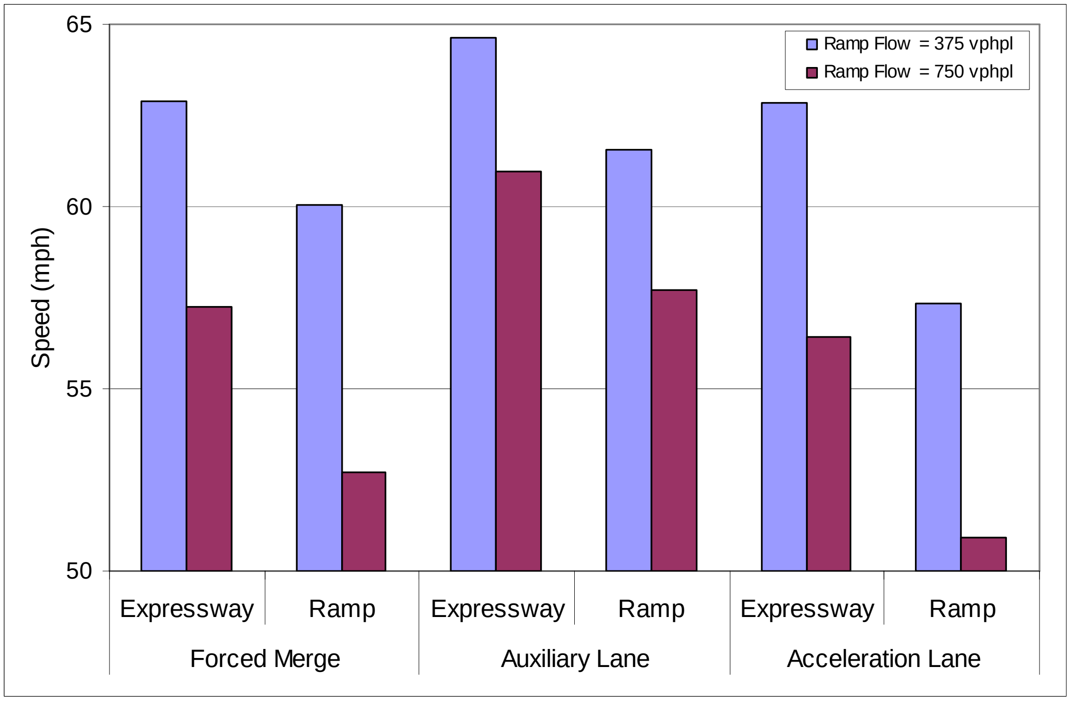


Figure 65. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Ramp Flow Levels.

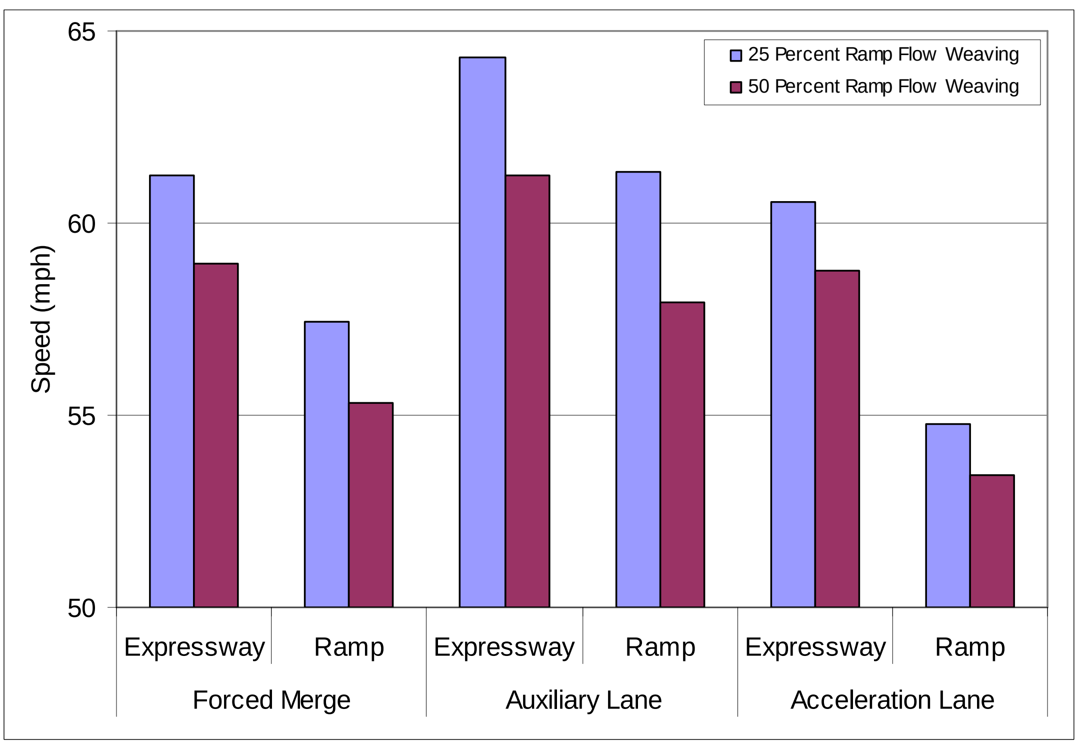


Figure 66. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Proportions of Ramp Traffic Weaving to the Managed Lane.

Example Applications

While the results of the previous section are helpful to researchers for documenting the general impacts of various traffic flow mixes and managed ramp design decisions on overall expressway and weaving traffic performance, they are not useful when trying to formulate a specific design for a unique managed ramp application. To achieve this practical objective, the results of all simulation exercises are contained in Appendix A. This section of the report is designed to guide one in using those results to produce and refine design values for most of the possible managed ramp design conditions one encounters. Three example applications are outlined to step the user through the process of applying the expressway and weaving speeds found throughout the many tables of the Appendix B to one's unique needs.

Application 1: Truck-Only Managed Ramp

Managed ramp condition: Trucks only to allow for usage of upstream entrance into "Truck Only" lane on left-hand side of expressway mainlanes.

Freeway Conditions:

- No. of expressway mainlanes: three (3)
- Vehicle mix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: moderate expressway volume (1000 vphpl)
- Assume there is no intermediate ramp between entrance ramp and entry into trucks-only lane (managed lane) upstream

Entrance Ramp Conditions:

- Ramp merge condition: acceleration lane
- Vehicle mix/user group: trucks only
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 50 percent

Determine: Recommended spacing of managed lane entrance upstream of freeway entrance ramp (see Figure 67).

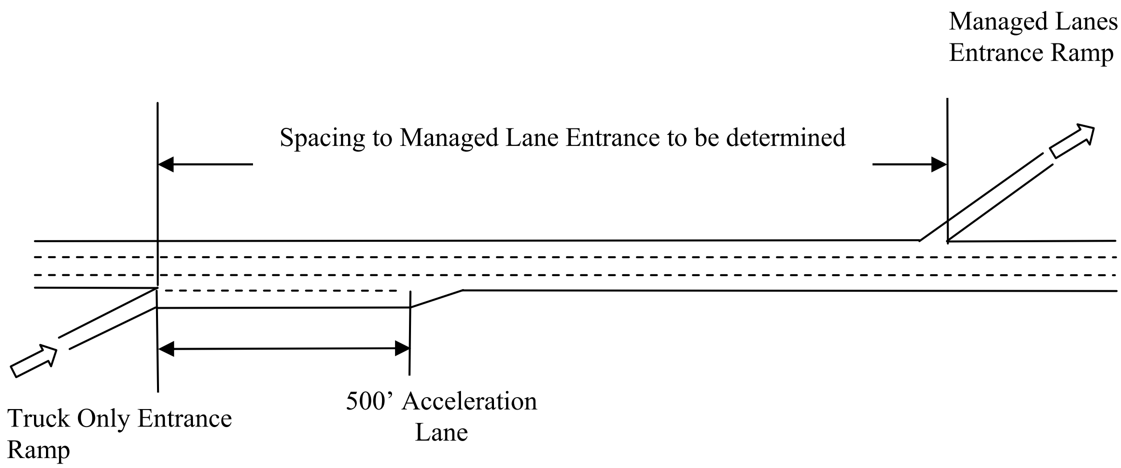


Figure 67. Truck-Only Managed Ramp Example.

Approach:

- Relevant Tables: Table B-7, Table B-9, and Table B-11
- Referring to Ramp Merge Conditions – Acceleration Lane, without Intermediate Ramp:
    - Ramp Condition of "No Auto" and 375 vph representing moderate ramp volume (or 375 vphpl). The volume accessing the managed lane is 188 vph (or 50 percent).
    - Expressway Condition of Three lanes. Under three-lane expressway condition identify the column with "5% truck" and 3000 vph.

For 500 ft per expressway lane spacing (Table B-7):

> The results from Table B-7 show speeds of expressway vehicles as 60 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 41 mph. Even though expressway speeds were still reasonably high, there is a 19 mph speed differential in speeds between these two vehicle groups. This difference is above the threshold of 10 mph speed differential imposed for safety reasons.

Similarly, looking up Table B-9 for a 1000 ft per expressway lane spacing:

> The results from Table B-9 show speeds of expressway vehicles as 61 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 47 mph. There is a 14 mph speed drop in speeds between these two vehicle groups. Even though this provides a safer operating scenario than with the 500 ft per lane spacing, it still does not meet our criteria of a less than 10 mph speed differential.

Similarly, looking up Table B-11 for a 1500 ft per expressway lane spacing:

> The results from Table B-11 show speeds of expressway vehicles as 64 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 53 mph.

> There is an 11 mph drop in speed between these two vehicles. Even though this provides a safer operating scenario than with both the 500 and 1000 ft per lane spacing, it is still not considered a "safe enough" operating scenario using a threshold of a 10 mph speed difference.

The engineer will therefore have to consider a minimum spacing of 1500 ft per lane between the managed ramp and the entrance to the managed lane downstream.

Consider a scenario where you had four expressway mainlanes instead of three:

Then from Table B-7, again, looking in the column under the Expressway conditions with four expressway mainlanes and 5 percent trucks with 4000 vph (representing nominal expressway flow) we get the following:

Expressway vehicle speeds 57 mph, ramp weaving traffic speeds 39 mph – an 18 mph drop in speeds.

Table B-9 for a 1000 ft per lane spacing results in a 63 mph and 50 mph – a 13 mph drop in speeds

Table B-11 for a 1500 ft per lane spacing results in a 64 mph and 54 mph – a 10 mph drop in speeds.

Again, just as in the case of the three-lane expressway configuration, a minimum of 1500 ft per lane spacing needs to be used to accommodate the "Truck Only" managed ramp.

Application 2: Weaving Distance Required for Auto-Only Managed Ramp

Managed ramp condition: Only auto – trucks excluded due to grade or other geometric considerations.

Expressway Conditions:

- No. of expressway mainlanes: Three (3)
- Vehicle mix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: moderate expressway volume (1000 vphpl)
- Assume there is an intermediate ramp between the managed entrance ramp and entry into managed lane upstream

Entrance Ramp Conditions:

- Ramp merge condition: forced merge
- Vehicle mix/user group: auto only
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 25 percent

Determine: Distance downstream to locate entry into managed lane to allow for vehicles using auto only managed ramp access to managed lane (see Figure 68).

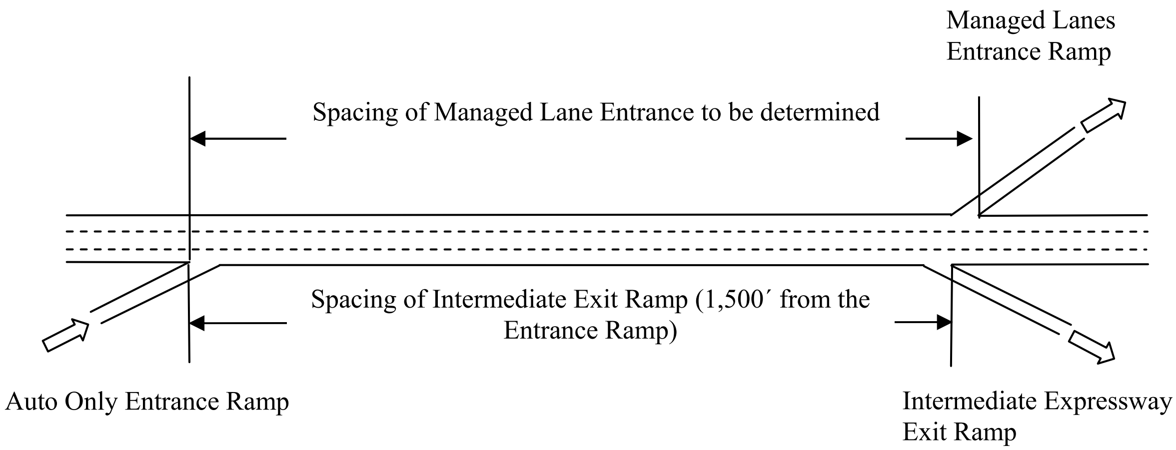


Figure 68. Auto-Only Managed Ramp Example.

Approach

- Relevant Tables: Table B-2, Table B-4, and Table B-6.
- Referring to Ramp Merge Conditions – Forced Merge, with Intermediate Ramp:
  - Ramp condition of "All Auto" and 375 vph representing moderate ramp volume (or 375 vphpl). The volume accessing the managed lane is 94 vph (or 25 percent).
  - Expressway condition of three lanes. Under three-lane expressway condition identify the column with "5% truck" and 3000 vph (nominal expressway flow of 1000 vphpl).

The results from Table B-2 show speeds of expressway vehicles as 66 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 64 mph. Both expressway vehicles and weaving ramp vehicles maintained reasonably high speeds. There is just a 2 mph speed drop in between these two traffic flows. This difference is below the threshold of 10 mph speed differential and is considered an acceptable operating scenario.

Thus, a minimum of 500 ft per lane spacing for the conditions outlined above provides for a safe operating environment for both weaving and expressway traffic.

Consider a scenario where the managed ramp is at a flow level of 750 vphpl and all other factors remain the same as in the case above:

Referring again to Table B-2, we look across the row with "All Auto" and this time with the 750 vph volume. We select a 188 vph weaving volume, and since all expressway conditions remain the same we get a result of 64 mph for expressway mainlanes traffic and 62 mph for managed ramp weaving traffic. Again, both speeds are appreciably high and there is only a 2 mph drop in speeds – an acceptably safe operating environment. Thus, just as in the case with moderate ramp volumes, a minimum of 500 ft per lane spacing should be enough to provide a reasonably safe weaving environment.

Application 3: HOV/HOT/SOT Managed Ramp

Managed ramp condition: High-occupancy vehicles (HOV)/High-occupancy toll (HOT)/Single-occupant toll (SOT), and buses only entrance ramp (85 percent auto and 15 percent bus)

Expressway conditions:

- No. of expressway mainlanes: Three (3)
- Vehicle mix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: high expressway volume (1400 vphpl)
- Assume there is an intermediate ramp between managed entrance ramp and entry into HOV/HOT/SOT lane

Entrance Ramp Conditions:

- Ramp merge condition: full auxiliary lane
- Vehicle mix/user group: high-occupancy vehicles (HOV)/high-occupancy toll (HOT)/single-occupancy toll (SOT), and buses only on ramp (85 percent auto and 15 percent bus)
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 50 percent

Determine: Distance downstream to place entrance into HOV/HOT/SOT lane (see Figure 69).

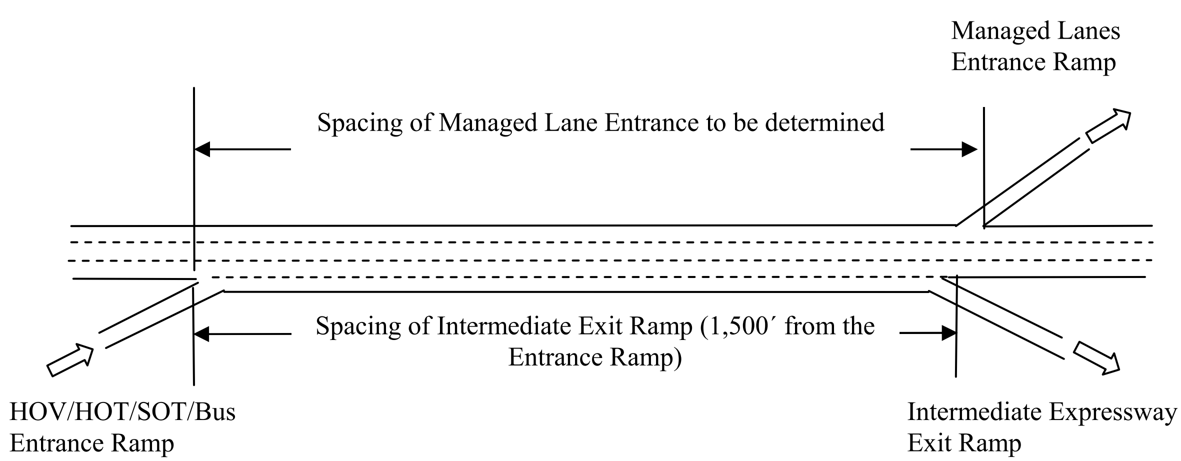


Figure 69. HOV/HOT/SOT/Bus Managed Ramp Example.

Approach

- Relevant Tables: Table B-14, Table B-16, and Table B-18

- Referring to Ramp Merge Conditions – Full Auxiliary Lane, with Intermediate Ramp:
  - Ramp Condition: Look across "85% Auto" and 375 vph representing moderate ramp volume (375 vphpl). The volume accessing the managed lane is 188 vph.
  - Expressway Condition: Under three-lane expressway condition identify the column with "5% truck" and 4200 vph (1400 vphpl).

Table B-14 shows speeds of expressway vehicles as 63 mph with speeds of weaving traffic from the managed ramp to the managed lane as 60 mph. Both expressway vehicles and weaving ramp vehicles maintained reasonably high speeds. There is just a 3 mph speed drop in speeds between these two flows. This difference is below the threshold of the 10 mph speed differential and is considered a safe operating scenario.

Thus, a minimum of 500 ft per lane spacing for the conditions outlined above provides for a safe operating environment for both weaving and expressway traffic.

Consider a scenario where there is a heavy truck percentage on the expressway mainlanes. All ramp conditions remain the same, but under the three-lane expressway condition identify the column with "15% truck" and 4200 vph (1400 vphpl).

Referring again to Table B-14, we look across the row with "85% Auto" and 375 vph representing moderate ramp volume. The volume accessing the managed lane is 188 vph.

Under the three-lane expressway condition with "15% truck" and 4200 vph, we maintain the 25 percent weaving volume (188 vph), and since all expressway conditions remain the same we get a result of 61 mph for expressway mainlanes traffic and 57 mph for managed ramp weaving traffic. We observe that both speeds have dropped from the previous scenario with the weaving speeds much lower than the assumed free-flow speeds on the expressways (about 65 mph). However, there is only a 5 mph difference in speeds from expressway mainlane vehicles and the managed ramp to managed lane weaving vehicles. This difference in speeds is considered as acceptable and below the 10 mph threshold set.

Thus, even with the increase in truck traffic on the expressway mainlanes, a minimum of 500 ft per lane spacing can be used to provide a reasonably safe weaving environment.

MODELING MANAGED RAMPS IN SUPPORT OF RAMP SAFETY

In past years, transportation engineers have been using innovative approaches and technologies to deal with traffic congestion on highways. Managed lane strategies have become more prevalent in addressing congestion and safety issues. However, in spite of advances in Intelligent Transportation Systems and improved practices of traffic operations, traffic management continues to be one of the most challenging issues in maintaining satisfactory mobility on Texas highways *(60)*.

Currently, agencies can use simulation models to forecast the traffic patterns that are based on predictive changes in the transportation network. Scenario 4 consists of multiple simulations that restrict various vehicle types on a predetermined on-ramp to alleviate congestion and improve the safety conditions on IH-10. The on-ramp chosen (Paisano Drive) is located in El Paso, Texas, on IH-10 westbound. The freeway mainlanes upstream of the on-ramp continuously experience heavy traffic congestion. The Paisano Drive ramp has a relatively high grade and a short acceleration lane. The on-ramp is approximately 2800 ft upstream of the IH-10/US 54 interchange. Vehicles destined for either US 54 north or Juarez, Mexico, begin to merge to the far right lane where the Paisano Drive on-ramp enters IH-10, creating a bottleneck location. Scenario 4 analyzes different combinations of vehicle type restrictions and relates the output measures-of-effectiveness including density, acceleration, speed, and delay as they pertain to safety for IH-10 drivers.

Purpose

Scenario 4 analyzes different vehicle class restrictions entering IH-10 through the Paisano Drive on-ramp to verify whether vehicle restrictions improve safety for the freeway mainlanes. The freeway mainlanes were analyzed to evaluate the driving behavior from the cars merging into the far right lane with vehicles entering the facility through the defined on-ramp. The model consisted of multiple vehicle restrictions to obtain the most effective scenario that can provide optimal safety to IH-10 traffic. Regulating the amount of flow through the Paisano Drive on-ramp could improve the safety for the vehicles on the freeway mainlanes upstream and downstream of the merge/weave area.

Ramp Management Scenarios Supporting Managed Lanes

The research team encountered various constraints when trying to simulate ramp closure for certain vehicle types in the middle of the simulation. VISSIM is limited when it comes to the closure of a specific link in the middle of the simulation. Since VISSIM could not close a specific link while utilizing dynamic traffic assignment, static assignment was used. A vehicle actuated simulation script code was then used to dynamically reroute traffic when congestion levels reached a certain specification.

Paisano Drive Ramp Management

Freeway Mainlanes

A section of IH-10 in El Paso, Texas, was replicated from Geronimo Drive to the US 54 interchange. Freeway mainlanes consist of four lanes in the entire area of study. There are currently four on-ramps and three off-ramps on IH-10 westbound between Geronimo Drive and US 54, each of which is a single-lane entry point. Corridor speed limit is 60 mph and all lanes are general-purpose lanes. The network created for the Paisano Drive on-ramp management is shown in Figure 70.

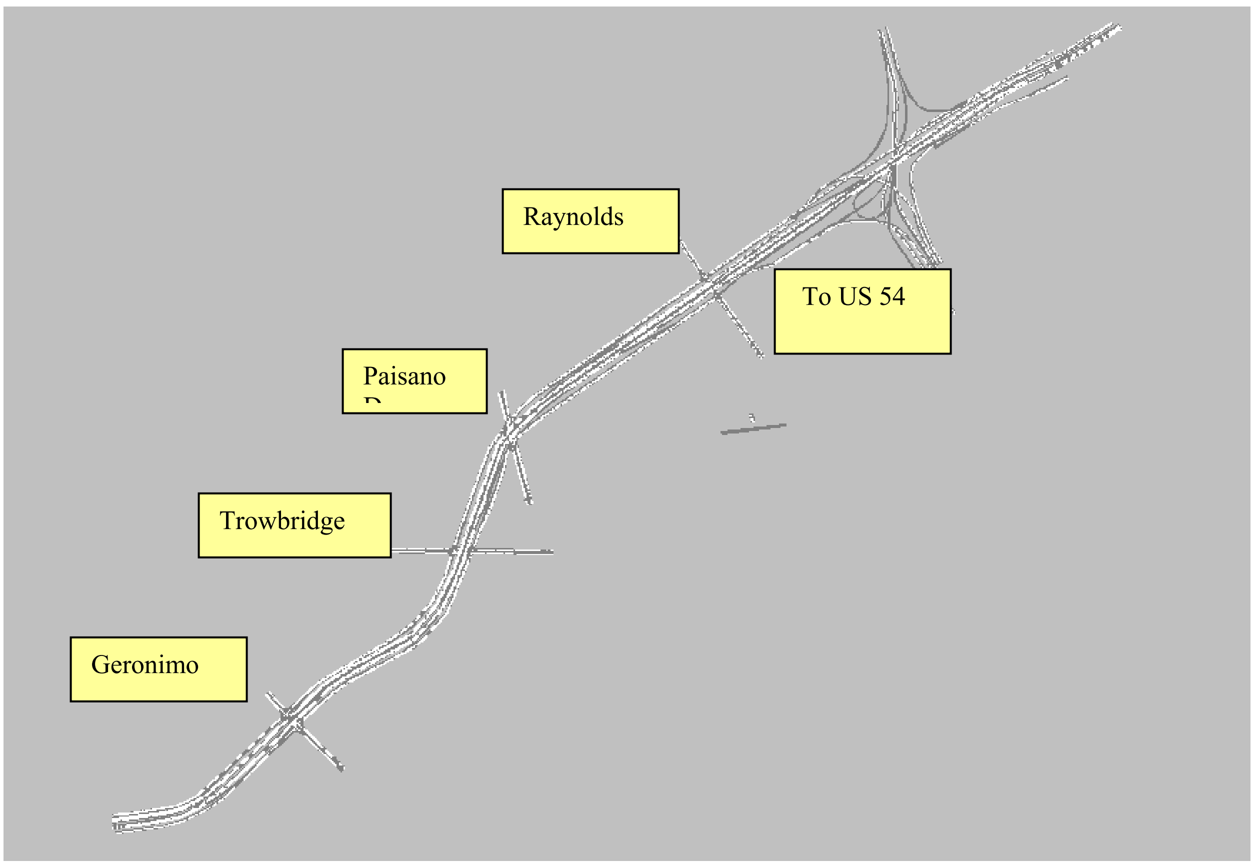


Figure 70. VISSIM Model of IH-10.

Figure 71 illustrates the Paisano Drive on-ramp that was modeled with different scenarios to obtain the optimal safety for the IH-10 users.

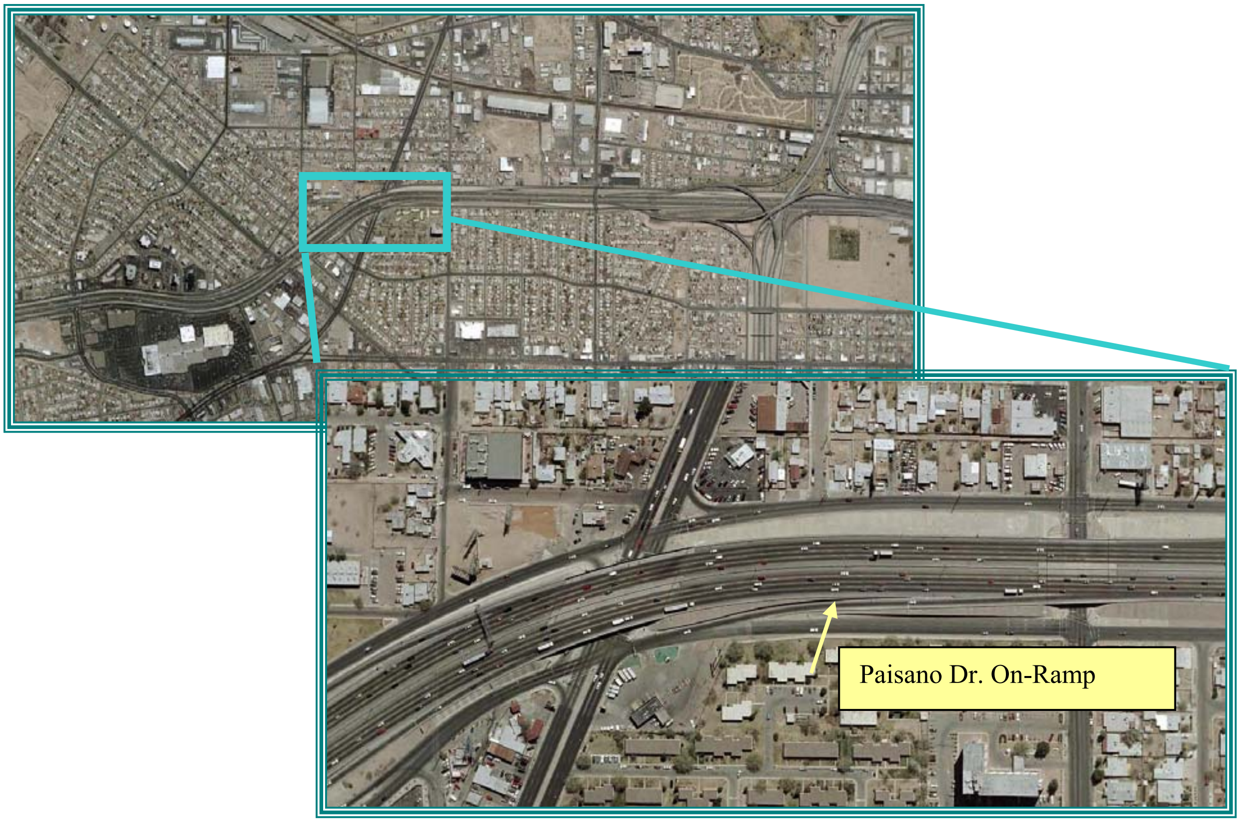


Figure 71. Paisano Drive On-Ramp Location.

Freeway Vehicle Mix

Since IH-10 in El Paso, Texas, is currently a non-tolled facility, all private vehicle classes are classified as one vehicle type. The vehicle class composition in El Paso has a high volume of truck traffic, usually ranging somewhere between 9 and 10 percent. Transit vehicles also have several routes that traverse through this corridor section of freeway. Therefore, a “normal mix” was chosen to include 90 percent cars, 9 percent trucks, and 1 percent buses.

Freeway Volume

Traffic volumes for every freeway facility vary by time of day and by day of week. Due to the various combinations of volumes that can be analyzed at any given time period, the research team chose one specific traffic volume for all modeled scenarios. The throughput freeway volume used for the model was 5855 vph for cars, 586 vph for trucks, and 67 vph for buses. These specific volumes were used as the traffic conditions for the four mainlanes of the IH-10.

Ramp Merge Conditions

Two basic geometric design configurations exist in the IH-10 study area including a direct (forced) merge and the creation of an additional lane (free-flow ramp). In the direct merge areas, vehicles entering the facility on-ramp simply merge directly with the rightmost freeway lane. Vehicles entering the freeway must find an acceptable gap to merge with mainlane traffic and adjust their speed accordingly. In the case of a free-flow ramp, vehicles entering the facility are not subjected to merge conditions and therefore smoother transition of traffic flow is created. The Paisano Drive on-ramp is classified as direct merge.

Vehicle Mix

The freeway vehicle mix used for the freeway mainlanes and on-ramps consisted of one defined traffic composition. A traffic composition defines the vehicle mix of each input flow to be defined for the model network (*51*). Transit vehicles were defined as part of the overall traffic composition. Since El Paso currently has no active managed lanes, HOVs were not used in the analysis.

Ramp Volumes

Entry volumes on each of the defined on-ramps are dynamic and change constantly. Due to the various combinations of traffic volumes that can be analyzed at any given time period, the research team also used one specific set of entry volumes for all six managed ramp scenarios. Table 44 shows the specified volumes for the three freeways on-ramps replicated in the model.

Table 44. On-Ramp Entry Volume.

Name	Ramp Number	Entry Volume (Veh/hr)
Geronimo Dr.	24	640
Trowbridge Dr.	24	435
Paisano Dr.	23B	578

Per Lane Spacing of Entrance Ramps

Spacing between successive on-ramps plays a crucial role in the amount of merging/weaving. Greater distances between successive on-ramps give way to greater gap distances between vehicles entering the facility and mainlane traffic flow. Larger gap distances between vehicles create less turbulence on mainlanes and provide a safer driving condition for the freeway. The spacing between each on-ramp was measured from gore to gore and the distance was recorded below, as shown in Table 45.

Table 45. Spacing between Entrance Ramps.

Location	Distance (ft)
Geronimo Dr. to Trowbridge Dr.	2516
Trowbridge Dr. to Paisano Dr.	1143
Paisano Dr. to Raynolds St.	4455

Determination of Performance Measures for Ramp Management

The Paisano Drive managed on-ramp strategies consisted of analyzing traffic performance and safety conditions both upstream and downstream at the Paisano Drive on-ramp on IH-10. When trying to analyze how "safe" a freeway segment is, the research team focused on three specific performance measures. The most critical performance measure was acceleration/deceleration. Greater rates of change of vehicle speeds indicate a tremendous amount of turbulence on the freeway. When speed begins to drop and density increases, there is a greater potential for a freeway incident.

Acceleration and Speed

The acceleration of the vehicles plays an important role when determining if the driving conditions are adequate on the freeway. Higher deceleration rates that vehicles experience increase the risk of rear-end collisions from trailing vehicles. An analysis of acceleration/deceleration was made for the far right lane of the freeway as well as all four mainlanes of IH-10. Speed was also measured both upstream and downstream of the Paisano Drive on-ramp. Speed measurements were taken for the far right lane of IH-10 as well as an average for all four freeway mainlanes.

Density

Another measurement to be analyzed was density of the four freeway mainlanes. Density measures how closely vehicles are spaced together on a freeway segment. Density was obtained only for the IH-10 mainlanes (as a whole) and not for the individual first lane of the freeway.

The upstream and downstream density of the Paisano Drive on-ramp was acquired for comparison purposes and safety issues.

VISSIM Model Preparation

The first assignment for the researchers was to simulate the Paisano Drive on-ramp area using VISSIM to test various scenarios. The research assistants created a model replicating a portion of the westbound IH-10 corridor between Geronimo Drive and US 54 interchange, including all the on- and off-ramps and frontage road. To account for the change in acceleration due to different slopes, gradients were included in the model for a more realistic simulation. The second step consisted in creating a VAP file for the different scenarios in order to restrict certain vehicle compositions to enter the freeway using the Paisano Drive on-ramp. A VAP file is capable of restricting the traffic of certain vehicle classes into the Paisano Drive on-ramp when the specified occupancy rate is reached. Moreover, with the VAP file, traffic can be diverted as needed to simulate various vehicle class restriction scenarios *(51)*. For this project, a total simulation time period of one hour (3600 seconds) was used. In addition, 10 different random seeds were used in each simulation scenario as recommended by the software developers. Output data, such as Link Evaluation and Data Collection from all scenarios, were averaged into tabular and graphical formats. The output obtained for IH-10 was taken upstream and downstream of the Paisano Drive on-ramp using data collection points.

The next step was to calibrate the model so it would replicate real-world traffic conditions on a typical day on IH-10. City-provided signal timings and green time allocations for frontage road traffic were used. Speed distribution for the freeway ranged from 65 to 74.6 mph. The majority of all vehicles traveling on the freeway had speeds below 70 mph with only a small percentage traveling between 70 and 74.6 mph. Speed reduction areas were needed as part of the calibration process. Vehicles traveling on roadways perpendicular to the freeway must decelerate when making right turns onto the frontage road. A speed reduction range of 2.5 to 15.5 mph was used in all models. For vehicles exiting the freeway via off-ramps, a speed reduction range of 36 to 42.3 mph was used. A deceleration rate of -6.562 ft/s^2 was used in all speed reduction areas. Driver behavior parameters were kept at default settings.

The next challenge for the research team was the development of vehicle mixes and features in the VISSIM model that represented vehicles operating on Texas roadways. This task is relatively simple in terms of automobiles and buses, since automobile performance is common across many countries and bus performance also does not vary widely. The size and configuration of trucks, however, is much different in European countries than in the United States in general. Since VISSIM was developed in Germany, many of its truck and trailer size, axle configuration, and weight characteristics are not well mated to heavy vehicles in the United States.

Several classifications systems are used to stratify trucks. Both the "Texas 6" and FHWA systems are shown in Table 36. Previous research *(52)* was the guide in determining what types of trucks were typically found in Texas and what percentages of the truck traffic stream each comprised. The source of these data were TxDOT Automatic Traffic Recorder Stations (Table 37), which record traffic volumes and classification on a year-round basis and provide permanent historical records of traffic conditions. Again, the research team used previous research on truck roadways in Texas *(52)* to identify heavy vehicles properties and develop simulated counterparts in VISSIM. Table 38 is the result of combining the Texas truck type percentages in its fleet with characteristics of these trucks. Adapting each of these truck types into VISSIM employing its default truck and trailer features is shown in Table 39. Information contained in Table 38 and Table 39 was ultimately coded into VISSIM to create a representative Texas truck fleet. In any simulation where trucks were a part of the vehicle stream, those trucks are distributed according to the percentages shown and have the characteristics noted. A vehicle composition was ultimately created to complete the coding necessary in VISSIM. The distribution of vehicles for the traffic composition included 90 percent cars, 9 percent trucks, and 1 percent buses.

Once the researchers calibrated the model and determined data collection points and input them into the model, they simulated the defined scenarios. The VISSIM output files were then converted to Excel spreadsheets where data were tabulated and graphed for visual comparison.

Scenario Set Description

The scenario sets included managing the Paisano Drive on-ramp with different vehicle type restrictions. Figure 72 depicts the modeling methodology for all defined scenario sets that were analyzed. The flow chart indicates the various mixes of vehicle class restrictions and the types of performance measures analyzed including speed, acceleration, delay, and density. Output data were then averaged into tabular and graphical formats.

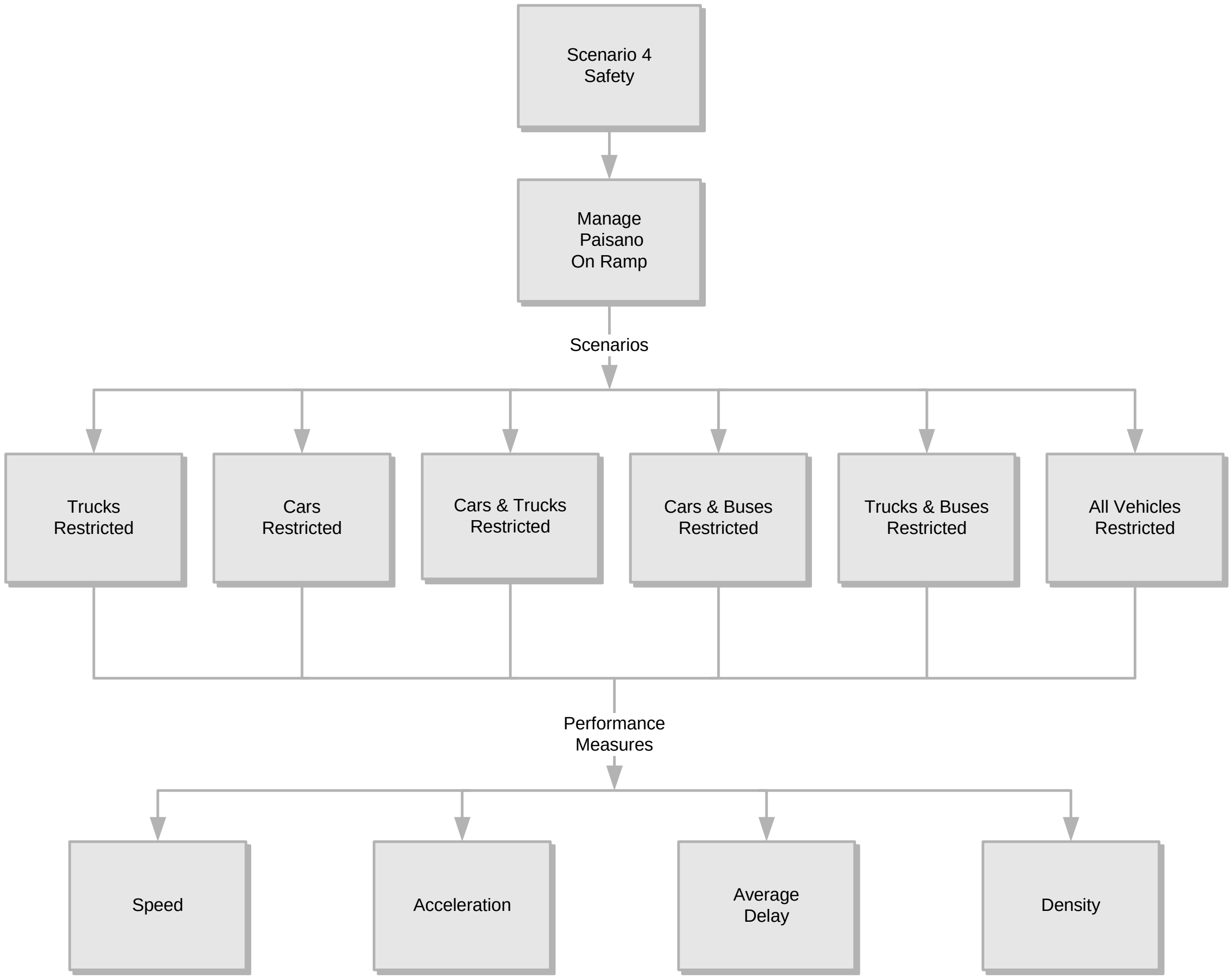


Figure 72. Flow Chart of Paisano Drive On-Ramp Management Scenarios.

Results

The explicit goal of the study analysis was to try and maintain high speed in designated freeway sections with ramp management strategies (*56*). Previous research shows that large fluctuations in speed greatly increase the potential for crashes (*57*). As a result, researchers created various combinations of vehicle restriction scenarios to observe which ones performed the best scenario for optimal safety conditions on the IH-10 corridor. Each scenario was run with 10 random seeds as recommended by the software developers.

In total, 70 simulation runs were coded and completed. Various mixes of vehicle class restrictions were coded using the VAP logic that allowed researchers to use dynamic routing assignment. After analyzing all graphical information from all the defined simulation models, the researchers determined that individual graphs for every defined scenario would lead to confusion in the intended audience. They consolidated and aggregated the data into compressed time intervals. This approach allowed the graphical results to be easily interpreted.

Upstream Freeway Mainlanes

All the vehicles traveling on the freeway mainlanes upstream of the on-ramp decelerate to provide adequate gaps for vehicles entering the freeway. This can be a safety issue because the on-flow to the freeway is interrupted by the vehicles entering the on-ramp. Shown in Figure 73 and Figure 74 are the average speed and average acceleration of all the scenarios, respectively. The flow of mainlane traffic depends upon the inflow rate of vehicles entering the freeway. As various vehicle classes are restricted from the Paisano Drive on-ramp, speed increases upstream of the entry point.

Speed is most influenced when no restriction is applied to the on-ramp since all vehicles are allowed access to the freeway. As various vehicle classes are restricted, freeway mainlane speed increases. Since cars comprised 90 percent of all vehicles in the network, their restriction from the Paisano Drive on-ramp had the most influence on mainlane speed other than total ramp closure. Closing the entire on-ramp proved to be the most optimal in terms of speed performance. Allowing access to only buses or trucks also performed well from a speed distribution standpoint.

However, total ramp closure did show a greater range of acceleration variability. Restricting only cars from entering the facility caused the least amount of speed acceleration and deceleration fluctuation for vehicles traveling upstream of the Paisano Drive on-ramp, followed by car and bus restrictions.

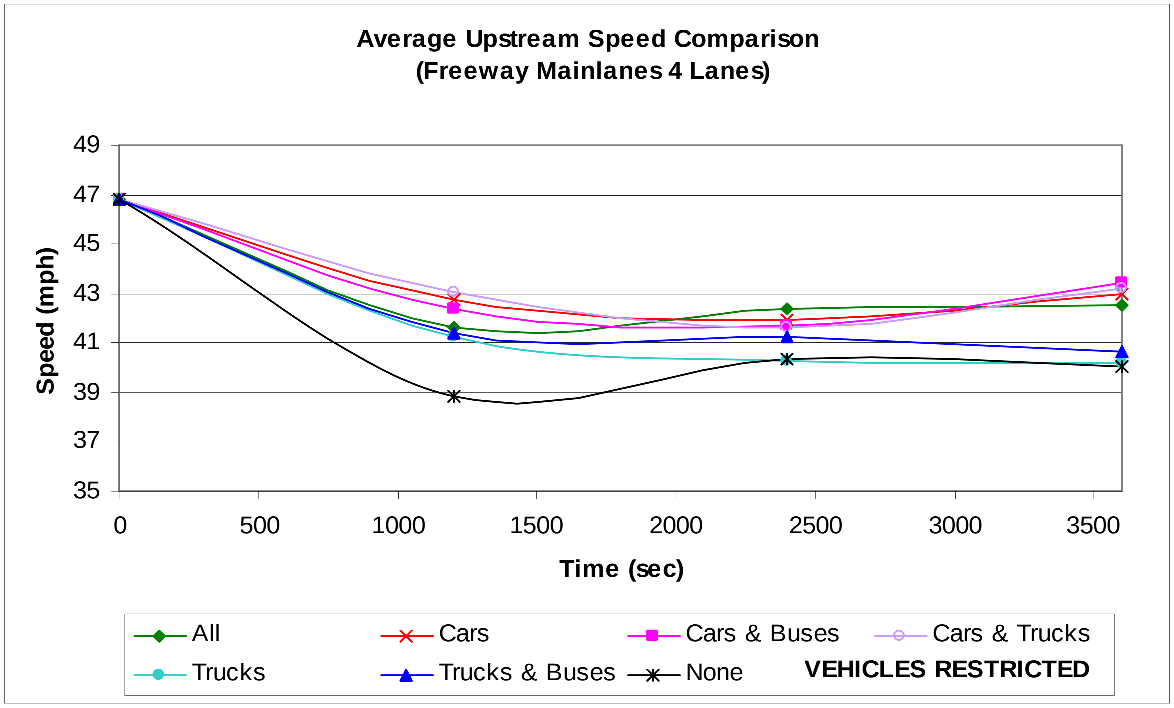


Figure 73. Average Speed – Upstream Mainlanes of the Freeway.

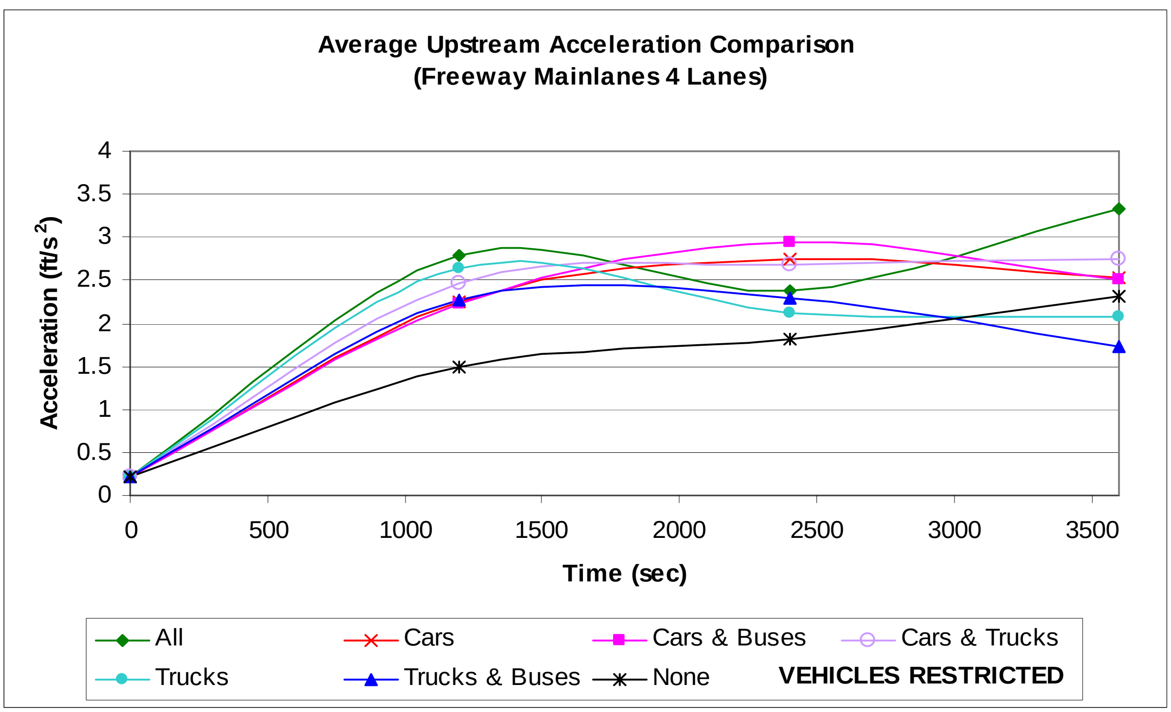


Figure 74. Average Acceleration – Upstream Mainlanes of the Freeway.

Upstream Freeway Right Lane Only

Safety issues are more frequently found in the right lane since vehicles using the on-ramp affect the flow on the freeway. It is important to analyze in depth the right lane traffic because this is where entering vehicles have the greatest effect on the freeway traffic flow. Shown in Figure 75 and Figure 76 are the average speed and average acceleration of all the scenarios, respectively, with emphasis on the far right lane.

The traffic flow on the far rightmost lane was influenced the most when no vehicles were restricted. Once again, allowing all vehicles to enter the freeway facility greatly impacts speed on the far right freeway merge lane. Only allowing trucks and/or buses access showed to have the highest travel speeds on the far right lane upstream of the on-ramp. As congestion builds on the model network, speeds for truck-only and bus-only access levels out at 32 mph. Allowing cars to enter the freeway decreased the average speed on the far right lane upstream of the on-ramp to approximately 27 mph.

Acceleration in the far right lane, however, had the greatest range of variability when all vehicles were restricted from entering the freeway facility. This outcome is due to mainlane traffic speeding up when passing the on-ramp without disruption.

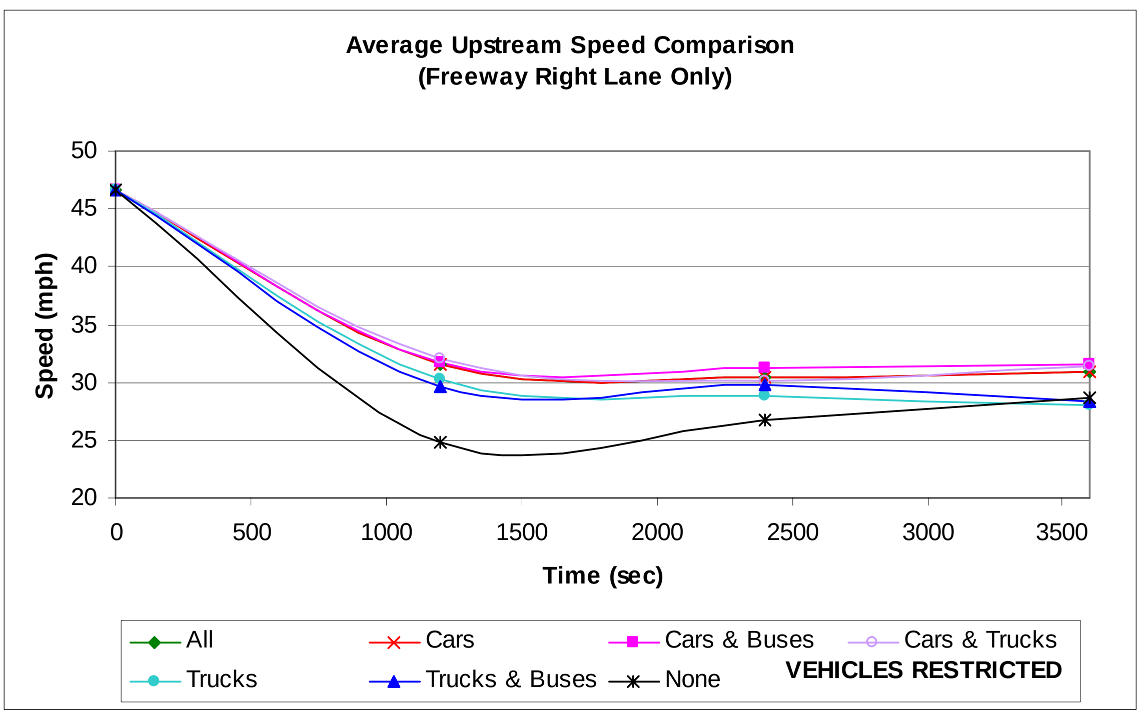


Figure 75. Average Speed – Upstream Right Lane of the Freeway.

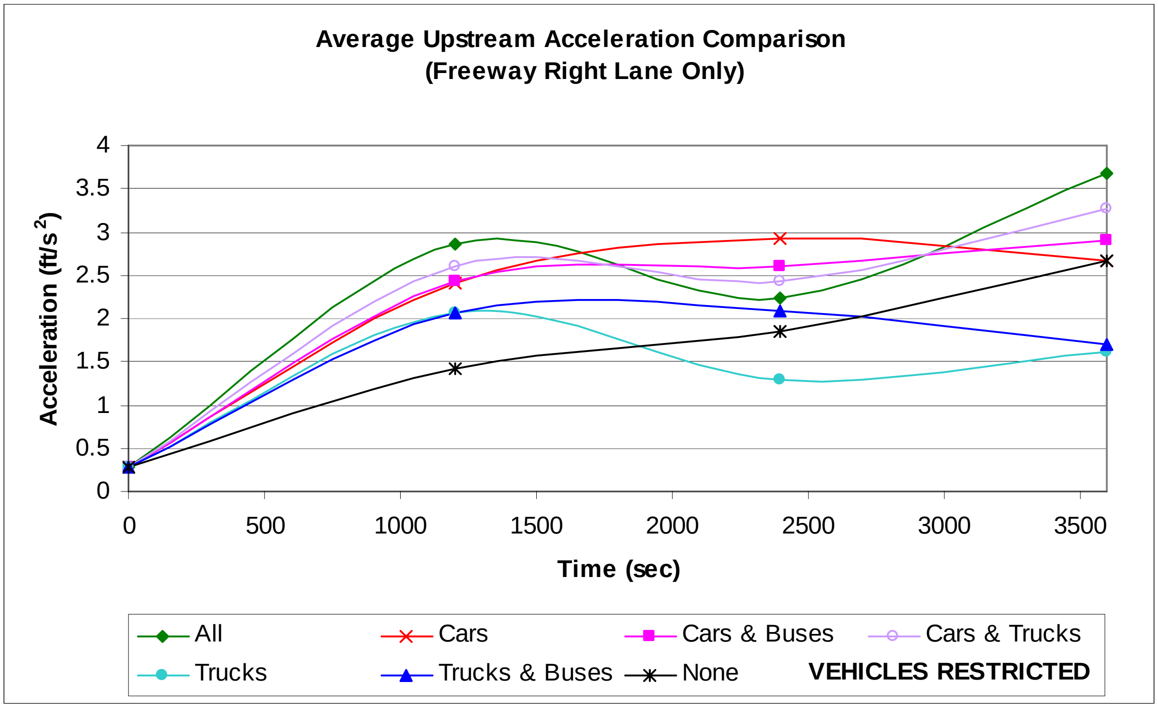


Figure 76. Average Acceleration Upstream – Right Lane of Freeway.

Downstream Freeway Mainlanes

Performance measures were also taken downstream of the weave/merge area created by the Paisano Drive on-ramp. When no vehicles are restricted from entering the freeway, overall mainlane speed dropped to approximately 50 mph. Restricting cars either independently or in conjunction with trucks also performed poorly when compared to alternate vehicle class restrictions, as shown in Figure 77 and Figure 78. When cars are restricted independently or in juxtaposition with other vehicle classes, average speed on all mainlanes ranges from 60 to 62 mph. This condition is more apparent when analyzing average acceleration downstream for the on-ramp. The car-restricted scenario showed the acceleration to level off at approximately 1 ft/sec^2. This result means that there is less fluctuation of the overall traffic speeds and vehicles are flowing smoother when compared to other scenarios. When restrictions of large traffic compositions are regulated from entering the freeway, there is less fluctuation of speed. Hence, restricting the highest vehicle class, cars, created less disruption of freeway mainlanes.

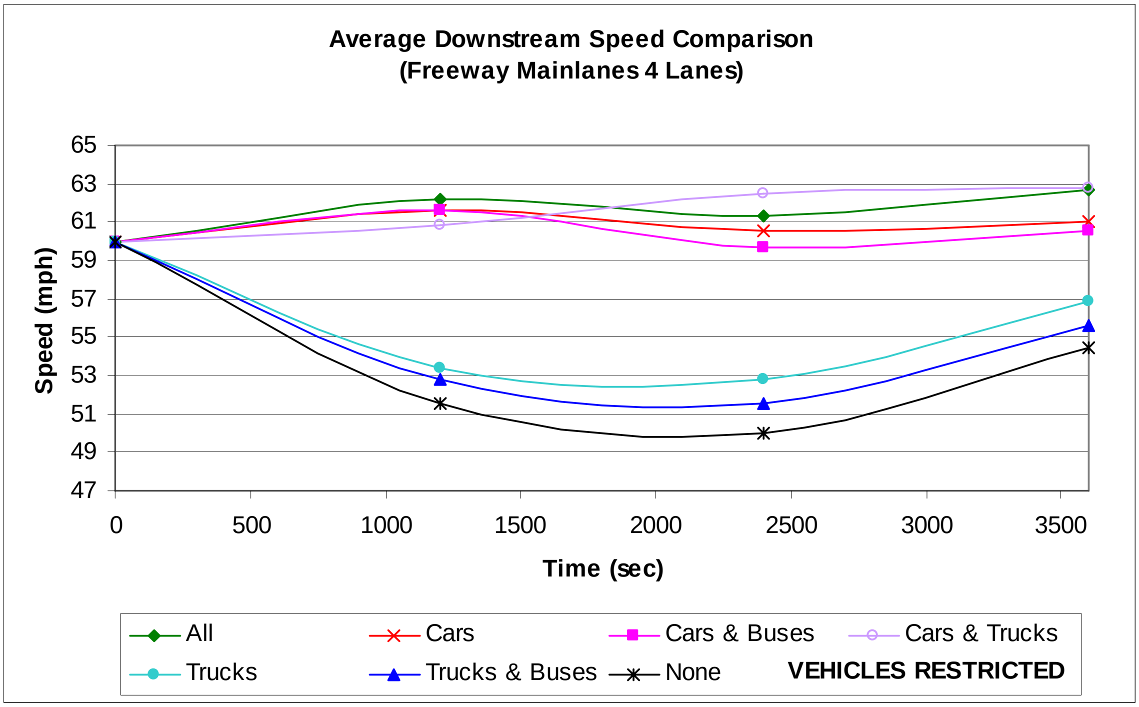


Figure 77. Average Speed – Downstream Mainlanes of Freeway.

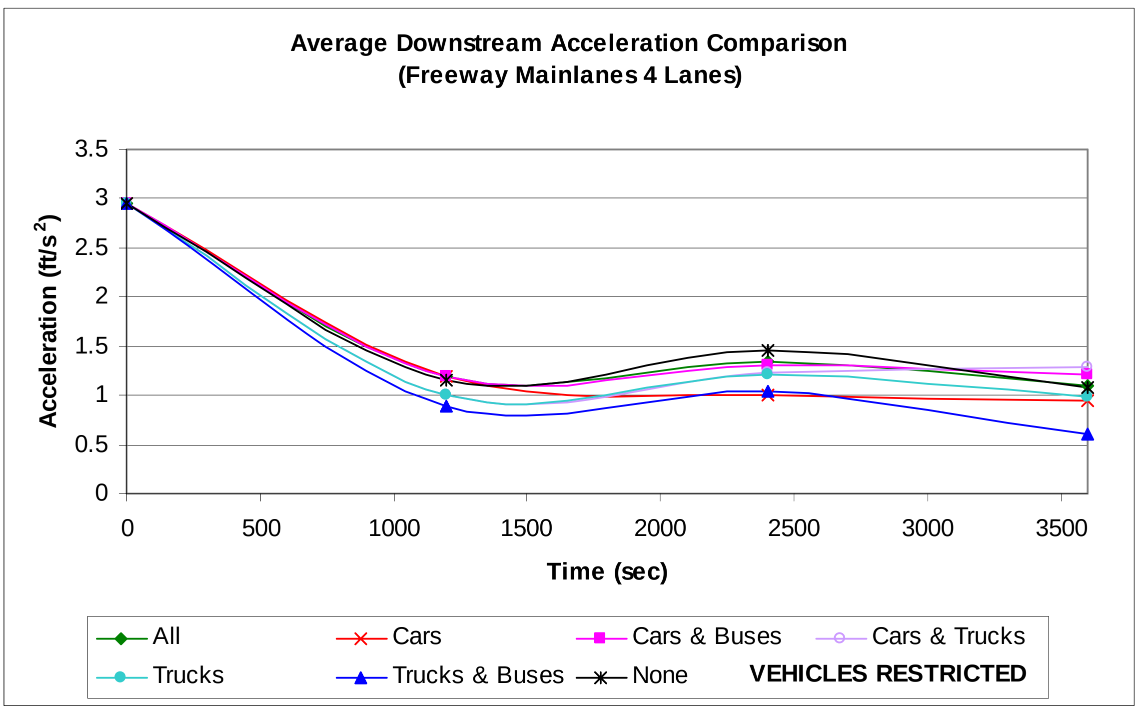


Figure 78. Average Acceleration – Downstream Mainlanes of Freeway.

Downstream Freeway Right Lane Only

Analysis of the far right lane downstream of the Paisano Drive on-ramp was also conducted by the study team. The right lane was analyzed independently since this lane has the greatest amount of turbulence caused by the merging and weaving of vehicles. Shown in Figure 79 and Figure 80 are the average speed and average acceleration of all the scenarios, respectively. The impact on the traffic flow for this lane is affected in the following scenarios: trucks restricted, trucks and buses restricted, and no vehicles restricted. The average speed for the far right lane drops below 40 mph for these three scenarios. Again, since cars compose the highest volume (90 percent), freeway access poses the greatest variability of speed. The remaining scenarios had speed distributions ranging from 53 to 60 mph. The same pattern emerges when analyzing the average acceleration and deceleration. Restricting cars from entering the freeway allowed the downstream vehicles traveling on the far right lane to maintain a more constant speed. Having a constant speed in a merge area provides smoother transition and flow of vehicles and ultimately provides a safer environment for motorists. Refer to Appendix C for a temporal distribution of speed and acceleration aggregated on a 1-second time step.

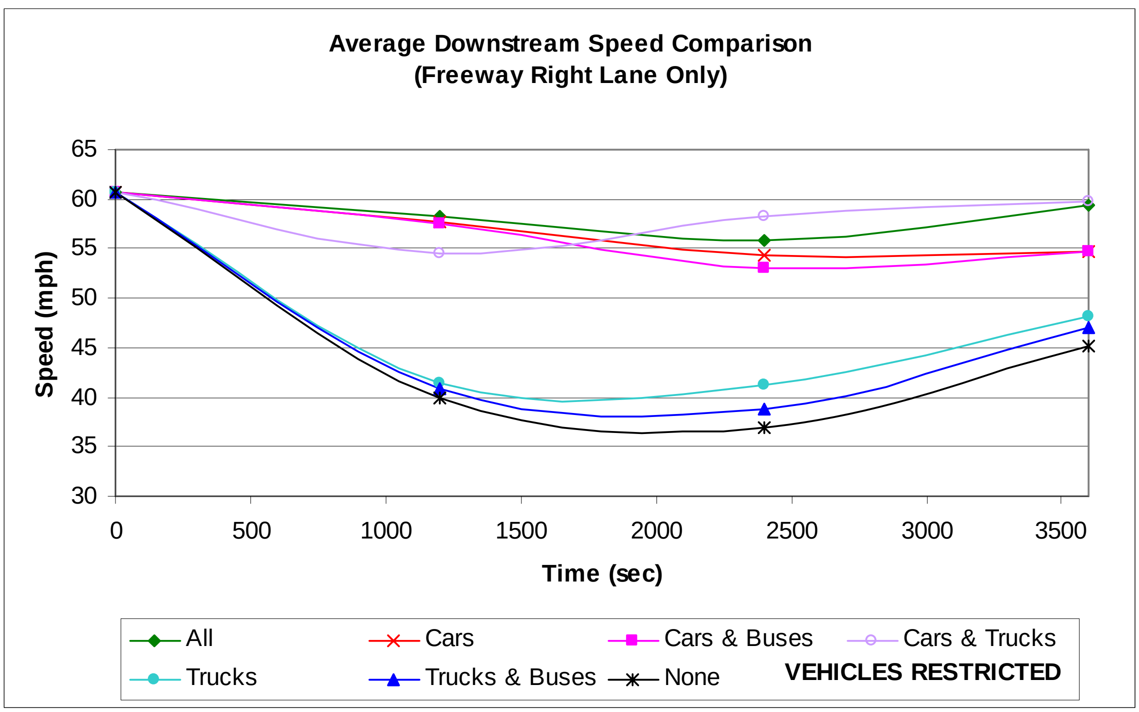


Figure 79. Average Speed Downstream – Right Lane of Freeway.

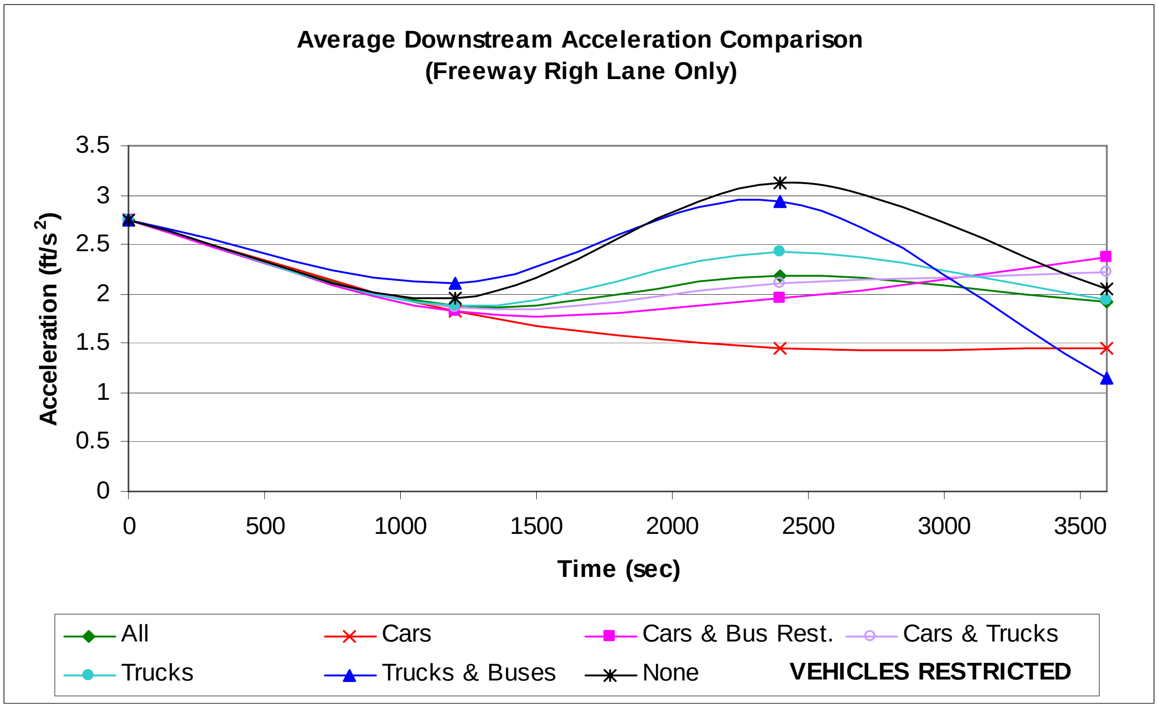


Figure 80. Average Acceleration Downstream – Right Lane of Freeway.

Density and Speed Analyzed by Links Upstream and Downstream

Two links were used to determine the density and velocity on a segment length of 50 ft located upstream (Link 227) and downstream (Link 306) from Paisano Drive on-ramp. These links include the four lanes of IH-10 westbound; shown in Figure 81, where density and speed are evaluated. Higher volume of traffic entering the freeway on-ramp causes vehicles to become more closely spaced and creates higher density upstream of the ramp. This result in turn affects the level of service on the freeway mainlanes. Density downstream of the ramp dissipates as vehicles begin to accelerate back to normal freeway speeds. This condition was readily apparent when analyzing the acceleration patterns between the upstream and downstream mainlanes. The fluctuation of speeds in and around the merge area when LOS reaches an “F” ranking creates an unsafe environment for all vehicles on the freeway *(50)*.

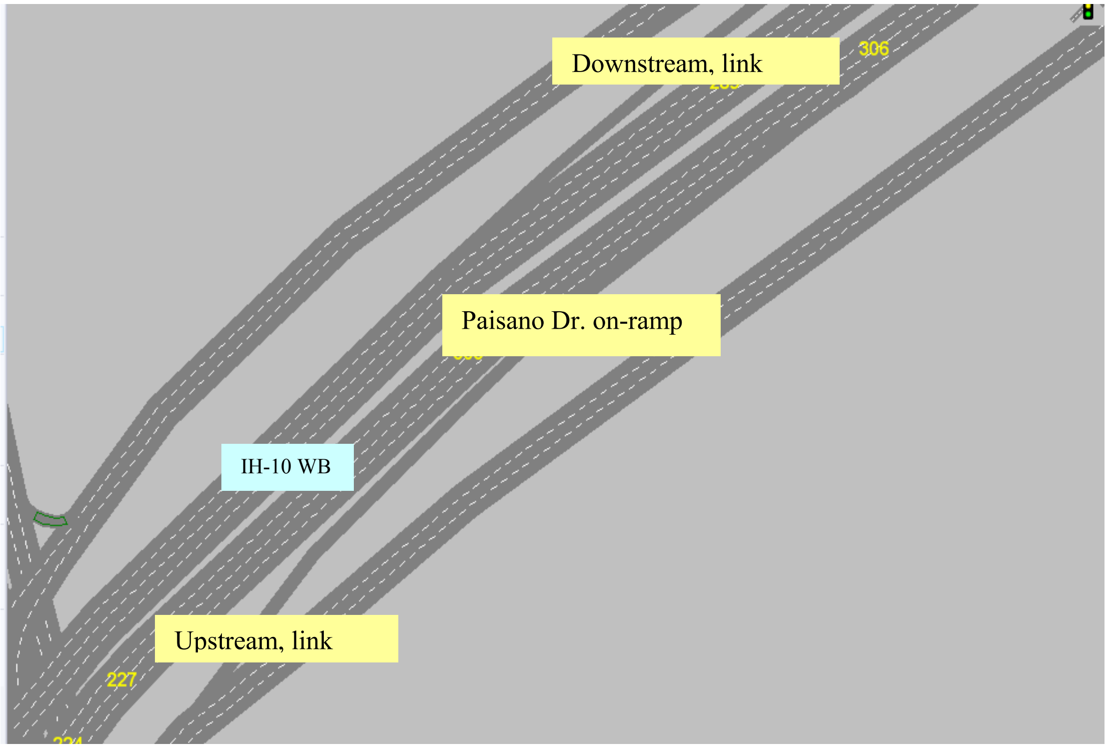


Figure 81. VISSIM Network Segment – Upstream and Downstream Links.

Upstream Lane 1 (farthest right lane)

Comparing all vehicle restrictions for Paisano Drive on-ramp versus the base case "do nothing" scenario, density decreased by 17 percent on the farthest right lane. This decrease represents the highest density reduction compared to the other scenarios, which is shown in Figure 82. This lane also has the highest increase in speed of 21 percent when compared to all other scenarios, as shown in Figure 83.

When ramp closure was not an option, the most ideal ramp management strategy consisted of car and truck restrictions with a 15.4 percent decrease in density followed by car and bus restrictions with a 15.3 percent density reduction. Restricting only cars reduced density by 14.7 percent when compared to the base case scenario. Restricting only cars also increased speed on the far right lane by almost 20 percent. Details of percentage increases and decreases of performance measures can be found in Appendix C. All scenarios that restricted cars independently or in conjunction with other vehicle classes showed a 20 percent increase in upstream mainlane speed and approximately 15 percent decrease in density. Ramp management scenarios that did not restrict cars from entering the freeway showed significantly poorer performance measures when compared to no vehicles restricted. Truck-only restrictions decreased density on the far right lane by 11 percent.

Downstream Lane 1 (farthest right lane)

For the downstream analyses, there was a considerable difference in density compared to the upstream lanes due to the spillback created by vehicles entering the facility. The performance measures followed the same general patterns as the upstream mainlanes. Total ramp closure decreased density on the far right lane by 35 percent when compared to do nothing, as shown in Figure 82. Speed also increased significantly on the far right lane, as shown in Figure 83. Speed is consistently similar for restriction of cars, cars and trucks, and cars and buses, each with an average speed increase of 37 percent when compared to no vehicle restrictions.

The main improvement in density and speed is observed on lane one. The subsequent lanes, lane two, three, and four, have less significant change as compared to lane one, but follow the same pattern as lane one. Lane four had some variation since it is the farthest lane from the on-ramp.

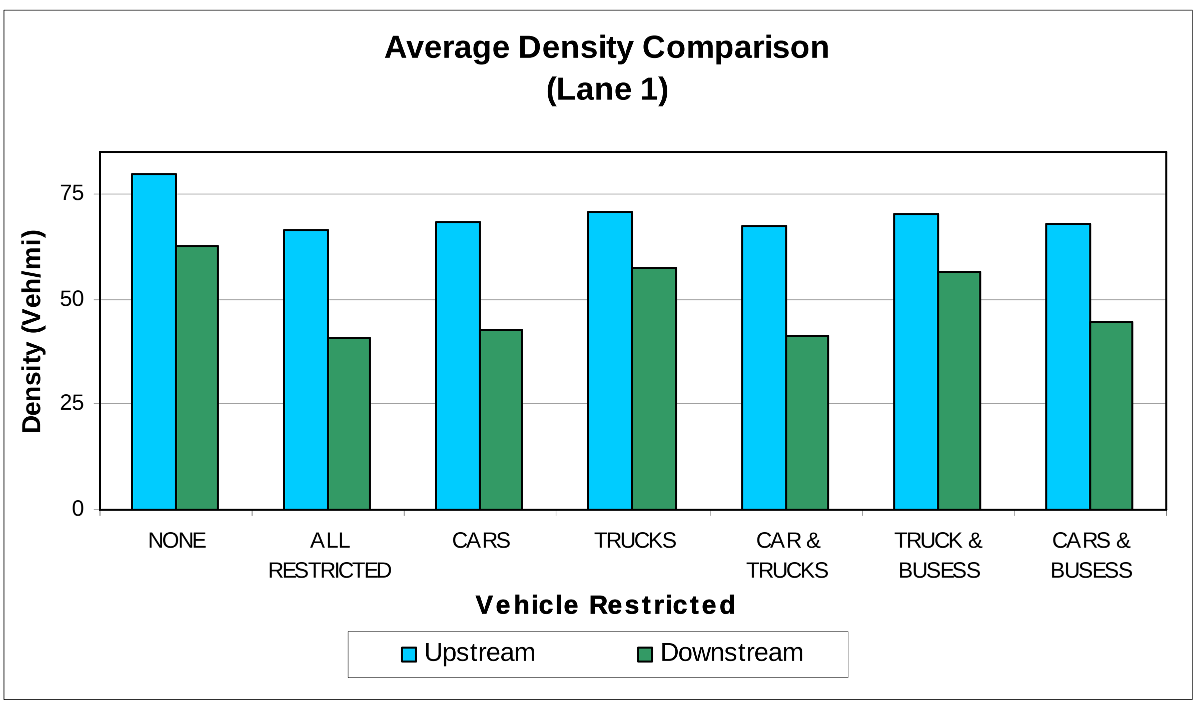


Figure 82. Average Density Comparison for Lane 1 – Upstream and Downstream.

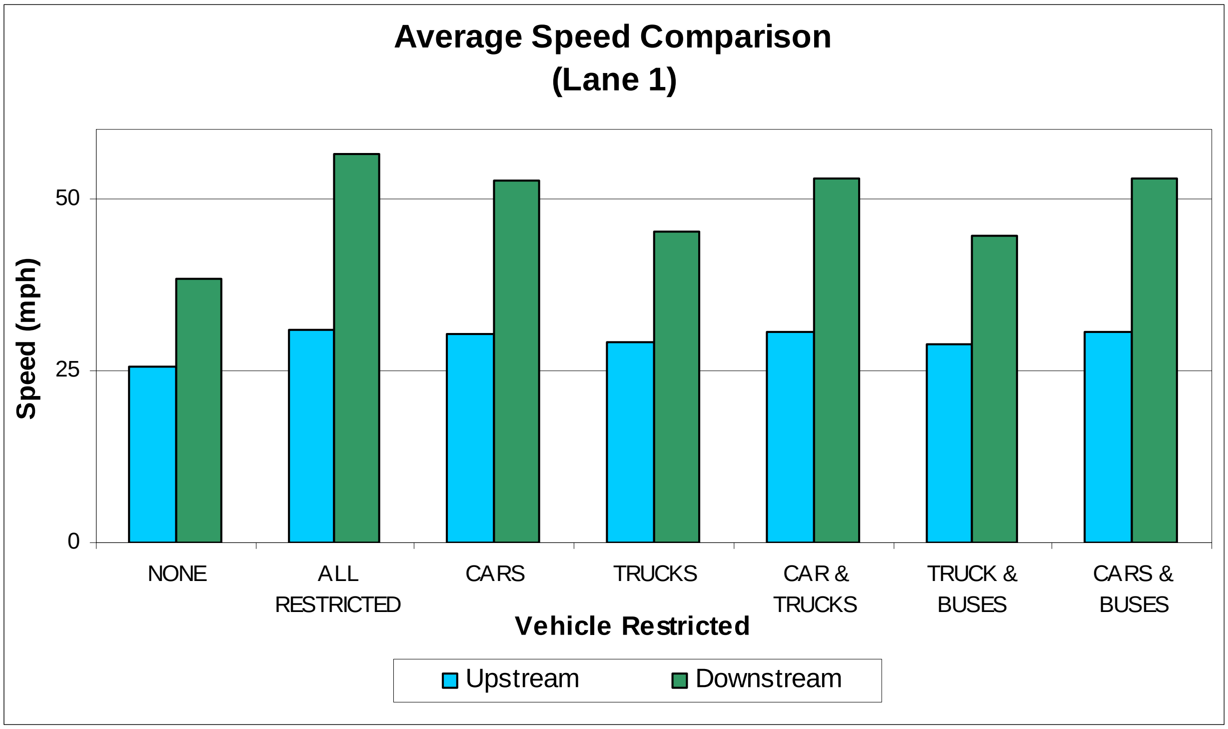


Figure 83. Average Speed Comparison for Lane 1 – Upstream and Downstream.

Average Stopped Delay per Vehicle

The following Figure 84 shows the average stopped delay per vehicle and the respective type of restriction on the Paisano Drive on-ramp. The base case scenario is also shown for comparison purposes. In addition, the average delay accounts for the whole network performance. When no vehicles are restricted into the on-ramp the average stopped delay is higher; however, when restricting certain vehicle types, the stopped delay decreases. Aside from the base case scenario, the highest stopped delay per vehicle shows when only trucks are restricted. However, when cars and buses are restricted the stopped delay reduces considerably (16.93 seconds) when compared to the base case scenario (24.64 seconds). Since buses have a slower acceleration rate, restricting such vehicle type improves the safety and congestion conditions on the IH-10 corridor.

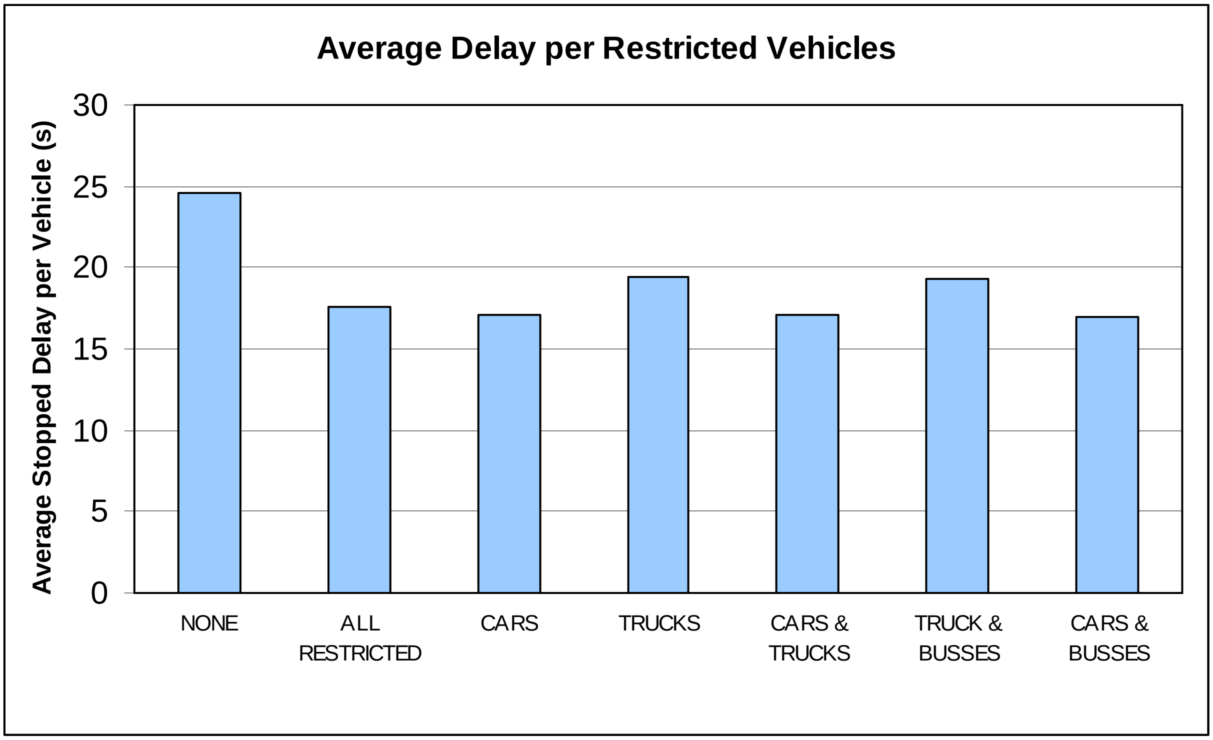


Figure 84. Average Stopped Delay per Vehicle in Seconds.

CHAPTER 6: FOCUS GROUPS

Public acceptance plays a critical role in the success of any project, especially a managed lanes operational strategy applied to ramps that restrict access to certain freeway facilities. Thus, the research team conducted two focus group sessions to obtain input from Texas drivers regarding key issues related to managed ramp operations. The initial focus group was hosted in College Station to gain public input from a community that currently does not have managed lanes in operation. The second focus group was hosted in Houston to gain public input from a community that has familiarity with managed lanes operational strategies. The intent of the focus group was to assess the public's comprehension and acceptance of managed ramps and identify any potential obstacles to implementation.

The focus group discussions were primarily an assessment of the concept of managed ramps, their opinion of the purpose and acceptability of managed ramp strategies, and an assessment of traffic signs that might provide information regarding managed ramp strategies to users.

PARTICIPANTS

A total of 16 Texas drivers participated in the two focus groups, 9 women and 7 men, ranging from age 20 to 73. Researchers conducted the focus group in Texas Transportation Institute (TTI) offices in College Station and Houston. Table 46 shows a complete breakdown of the demographics of the drivers. Participants were asked to indicate the frequency with which they drove a motor vehicle, used toll facilities, or drove on an HOV lane. Participants received $50 for their attendance at the two-hour sessions.

Table 46. Demographics of Focus Group Participants.

City	Total Number	Number of Men	Number of Women	Age Range
College Station	8	4	4	20-73
Houston	8	3	5	24-58

DISCUSSION TOPICS AND COMMENT SUMMARY

The focus group relied on a PowerPoint presentation that consisted of typical photographs illustrating freeway operational techniques and those that had been digitally edited to include new signs indicating ramp operations. The facilitator worked from the same script for each group. In this section of the technical memorandum, each group of slides on a particular topic is presented, along with a summary of the comments on that topic. Appendix D presents the full transcripts of the focus groups.

Discussion topics for the focus groups were identified based on the four operational scenarios that have the most potential to meet various needs of TxDOT districts across the state:

- #1 – flow balance scenario,
- #2 – incident/special management scenario,
- #3 – managed lanes facility preference scenario, and
- #4 – ramp safety scenario.

The focus group facilitator presented images of freeway ramps depicting these scenarios to prompt discussion on the particular operational components. A projector displayed the images via computer on a screen in the conference rooms where the focus groups took place. The images were created by a variety of means. In some case, the photos were not enhanced in any way. In others, researchers digitally edited photographs or sign images in order to present signs in a roadway context and to present different operating conditions of the ramps.

The first focus group in College Station saw the original set of slides. Based on those discussions, two slides were modified to alter some of the text on the depicted signs. Each focus group saw a total of 19 slides. Six of the slides showed welcome messages, procedure details, text questions, and thank you messages. The topics and slides are presented below.

General Discussion on Managing Traffic

The first question asked the focus group participants to identify ways in which transportation agencies could manage traffic on urban freeways. Many of the responses from the participants were related to geometric design improvements or signing at freeway access points. Suggestions included extending entrance ramps, using more auxiliary lanes between entrance and exit ramps, using more dynamic message signs, improving signage at exit ramps – particularly in work zones, and improving striping and retroreflectivity of pavement markings. Other comments included completing construction and increasing speed limits to reduce the high speed differentials on freeways.

Overall, these responses indicated that the participants understood the general impacts of ramp design on operations based on personal experience. However, it is interesting to note that none of the participants mentioned any of the management techniques that were to be discussed in the sessions.

Ramp Metering

The first ramp management discussed was ramp metering, as illustrated in Figure 85. The purpose was to assess participants' understanding of ramp metering. All of the participants in both College Station and Houston had seen a ramp meter on an urban freeway. All of the Houston participants had entered a freeway with an active meter, while several of the College Station participants had not. All of the participants understood what they were supposed to do when they approached an operational meter, indicating that this application of a traffic signal is unambiguous, even to an unfamiliar user.

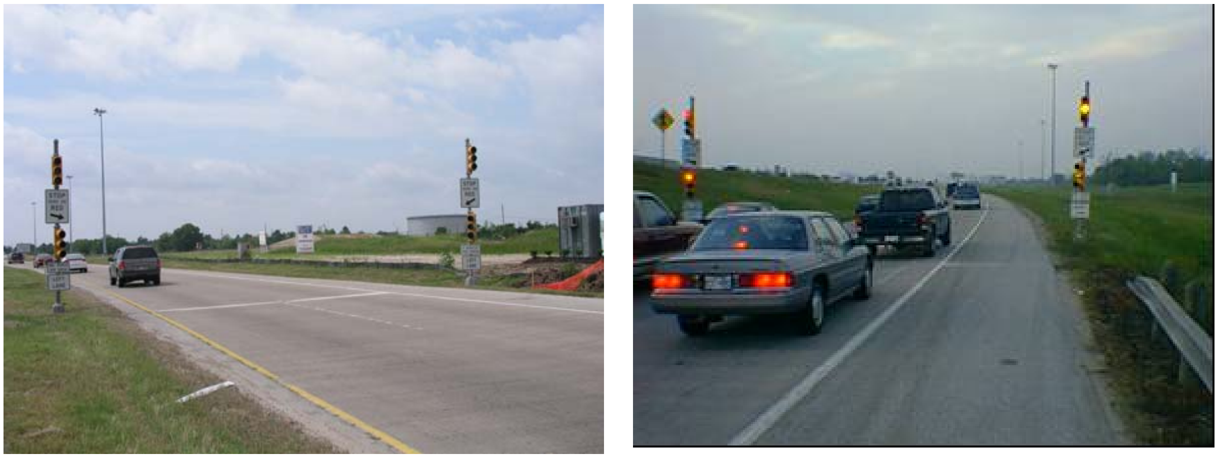


Figure 85. Focus Group Slides 5 and 6 Showing Ramp Metering.

When asked to describe the purpose of a ramp meter, most people indicated that it was supposed to control the volume of vehicles entering the freeway and to reduce traffic. They understood that the meter is designed to create gaps in the ramp traffic to make merging onto the general-purpose lanes smoother. When asked if they believe that a ramp meter accomplishes its intended objectives, responses were mixed. Half of the College Station participants said that ramp meters work, while others said that it has no impact on the freeway and may cause bottlenecks entering the freeway. Houston responses were mixed as well. Some felt that ramp meters work during peak traffic times and at some locations. Others felt that a stop light might be more effective and that a ramp meter only shifts the congestion from the merge point to the ramp itself upstream of the meter. Houston participants did not have a favorable opinion of the ramp meters, but the College Station participants did.

After discussing the ramp meter strategy, the facilitator then asked the participants if they had other ideas of how traffic could be managed in place of ramp meters. College Station participants suggested toll roads as an alternative along with blinking lights and some treatment that would keep traffic flowing at a steady rate. Tolling could be used to keep traffic flowing and the rates would change depending on the time of day. When asked what the drawbacks were to these methods, participants stated that drivers might still spend the same amount of time on their trip and that tolling would not necessarily save them time. Also, alternate routes are not always available and drivers may not be able to make a choice about using the tolled facility. Benefits of tolling a facility might be time savings or the ability to control traffic.

Houston participants suggested longer ramps, adding lanes, and eliminating lane drops as other methods for managing traffic. Another suggestion was to encourage or require traffic in the rightmost lane to slow down or move over to accommodate merging traffic. One participant also suggested using arms with the ramp meters, similar to the arms that raise and lower at toll booths. Participants felt that these strategies could be used in high traffic situations, and some thought they should be used all of the time so that drivers become accustomed to their operation and would be more apt to obey the ramp meter. The benefits of managing access were seen as improving traffic jams, keeping the freeway flowing, and providing gaps for entering traffic. Causing a backup on the ramp as a result of having to stop was seen as the one drawback to ramp management.

Managed Lanes Facility Preference

The second series of slides shown to participants were designed to assess participants' understanding of managed lanes and the management of ramps to provide managed lanes facility preference. The slide shown in Figure 86 was intended to assess whether participants were familiar with HOV lanes and their purpose in a freeway corridor. All of the College Station and Houston participants indicated that they had been on a freeway with an HOV or carpool lane. Only three of the College Station participants had used an HOV lane, while all of the Houston participants had used one (one accidentally, however). All of the participants understood that HOV lanes are intended to encourage carpooling and to decrease the number of vehicles on the roadway. One Houston participant said that HOV lanes make travel times faster and trips safer, and another said that they help decrease air pollution.

Figure 86. Focus Group Slide 8 Showing HOV Lane.

The photos in Figure 87 were shown to assess participants' understanding and acceptance of providing preferential treatment to managed lanes users at specific ramps. Participants from both Houston and College Station understood that there was a restriction on users at the ramp during the hours noted on the sign. When asked if the sign provided any information about the freeway mainlanes, responses were mixed. Some believed that it indicated the entire roadway was only for HOV users during the posted hours, one thought that it could mean there was an HOV lane on the freeway, and several said it provided no information about the mainlanes.

Nearly all of the participants in both cities knew that they could not use the ramp if they didn't have the specified number of occupants. They also indicated that they would have to use either a different ramp to access the freeway, form a carpool if they wanted to use the ramp on a regular basis, or adjust their commute time if they didn't have a passenger in the vehicle with them. When asked to suggest a purpose for this ramp treatment, participants noted that it offers an incentive to drivers between the operating hours to get a faster trip by using the HOV facility.

Figure 87. Focus Group Slide 9 (Two Versions) Showing HOV Only Ramp Access.

The facilitator then showed the slides depicted in Figure 88 and Figure 89 and explained to the participants that a managed lanes facility was located in the center of the freeway. Opinions of the value of providing preferential ramp access to managed lanes users so that they can access the managed lanes facility were mixed. Some felt that it would encourage more carpooling. Others thought that it was unfair to provide special treatment to HOVs when they already have their own lane on the freeway. One suggested that the idea would be improved with a direct connect ramp to the managed lane that could operate all the time. One person thought the access was not convenient to users while another thought that it would be convenient for drivers living in the vicinity of the ramp. Still another participant suggested doing away with carpool lanes and emphasizing transit and rail because individuals are still driving their vehicles.

Figure 88. Focus Group Slide 10 Showing Center Managed Lane.

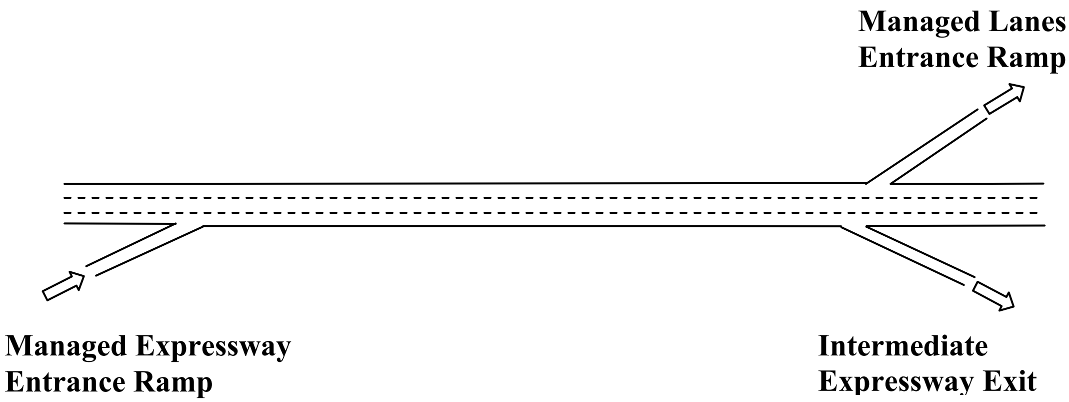


Figure 89. Focus Group Slide 11 Illustrating Managed Lane Ramp Preference Concept.

Focus group participants were also shown the slides in Figure 90 where priority access is provided to bus and taxis during specified hours. All of the participants understood that only the designated vehicles could use the ramp during the posted hours, but none really had a favorable opinion of the treatment. They did not see the inherent value providing this priority access.

Figure 90. Focus Group Slide 12 (Two Versions) Showing Bus- and Taxi-Only Ramp Access.

Balanced Flow

The facilitator presented the next series of slides to assess participants' comprehension and acceptance of tolling ramp access to improve flow on a freeway facility. The slide shown in Figure 91 was intended to assess their general understanding of and experience with toll roads. All of the participants in both College Station and Houston had been on a toll road in the past.

When asked what they thought users were paying for when utilizing a toll road, most felt that users were expecting to get a faster trip for their money, a trip that would be even quicker if they had a toll tag.

Figure 91. Focus Group Slide 13 Showing Toll Facility.

The image in Figure 92 was used to determine how participants felt about tolling access to a freeway. All of the participants understood that users would have to pay the $1.25 toll to access this roadway, but it was not clear to them if only the ramp was tolled or if the entire facility was tolled. Several participants in both cities thought that drivers should expect less traffic on the mainlanes given that not all drivers would be willing to pay the toll. When asked how they would behave if they frequently used this facility, participant responses were somewhat mixed, though most were unfavorable toward this ramp treatment. Some indicated they would never pay the toll and would find a free alternate route. Others stated they would pay the toll – regardless of what it was – if they knew traffic was moving freely and they could reach their destination quicker. One Houston participant said the highest toll rate she would be willing to pay at this ramp was $0.25.

Figure 92. Focus Group Slide 14 Showing Tolled Ramp Access.

One final question the facilitator asked the participants was whether they would be willing to use this ramp if they knew there were non-tolled ramps upstream and downstream of this ramp. Nearly all participants said they would not pay the toll and would use an alternate ramp that was free. One College Station participant said they would pay the toll if they could be sure they would have a faster trip. Overall, the Houston participants did not favor this ramp treatment since they felt users would be paying to sit in traffic rather than accessing a congested roadway for free. Several College Station participants felt that this treatment had some merit, particularly in the event of an incident, in a work zone area, or where an agency would want to decrease traffic upstream of a major interchange.

The slide illustrated in Figure 93 was used by the facilitator to determine whether participants felt that a truck restriction at a ramp was a beneficial and acceptable ramp management treatment. All participants understood that no trucks were allowed to use this ramp during the posted hours. However, it was unclear if the sign meant all trucks or only large tractor-trailer trucks. All College Station participants said that this sign did not reveal any specific information about allowing trucks on the general-purpose lanes. All but one of the Houston participants had the same opinion, with the exception of one participant who thought the trucks could not use the entire facility during the posted hours. All participants believed that this ramp treatment was intended to keep trucks off of the facility in this particular area.

Figure 93. Focus Group Slide 15 Showing Truck-Restricted Ramp Access.

When asked what drivers would hope to gain with such a ramp treatment, participants provided several answers, including:

- a lower number of trucks on the facility during the peak period,
- a reduction in traffic in this area,
- an increase in travel speeds, and
- drivers not having to worry about trucks on this particular facility.

However, not everyone felt that this ramp treatment would necessarily provide benefits to the facility. One Houston participant suggested that increasing ramp lengths to accommodate heavy trucks would also be helpful.

Incident and Special Management

The slide shown in Figure 94 was used to assess whether participants felt that ramps would be effectively managed as part of a larger incident management operation. In both cities, all respondents believed that ramps could be managed to help with incident response. The overwhelming suggestion for management was total closure for the duration of the incident and until traffic was moving again. Many of the participants suggested providing alternate route information to drivers would also be beneficial. They all believed that the intent of the ramp strategy would be to prevent the backup from the incident from growing. Other suggestions included allowing only emergency services and police to use the ramps to facilitate responder access, proving drivers with information about the incident ahead, possibly keeping one lane of the freeway open to help keep some traffic moving, and improving the traffic management activities undertaken by the police during incidents. Overall, all participants in both cities had a favorable opinion of this ramp treatment.

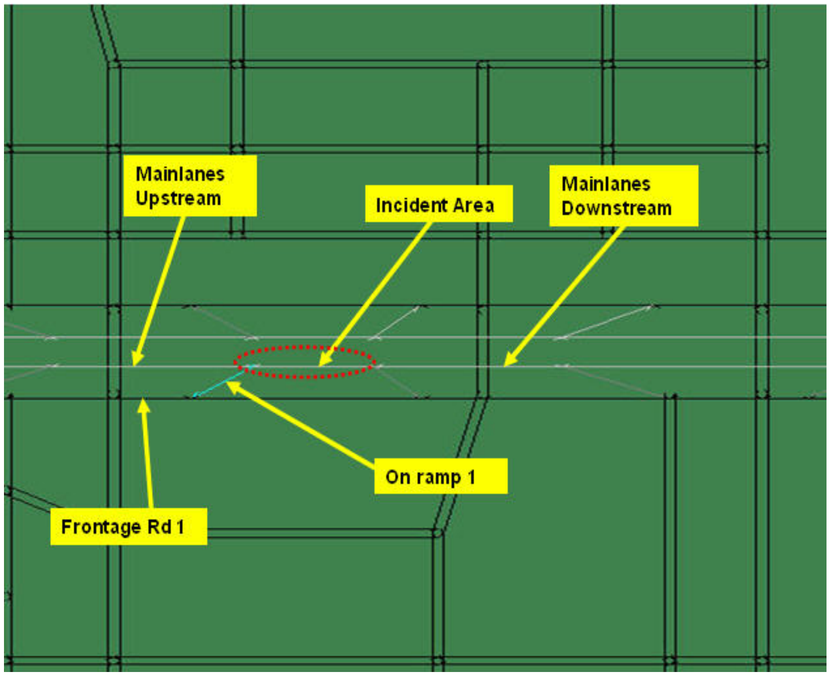


Figure 94. Focus Group Slide 16 Showing Incident Location.

Ramp Safety

The facilitator showed respondents the final slide pictured in Figure 95 to assess their comprehension and acceptance of complete ramp closure. The intent of this closure, as discussed in a previous section, is to reduce traffic at a location that has geometric limitations. All participants identified this slide as a photo of a gate to be used for ramp closure. When asked when this ramp treatment might be used, participants gave a variety of responses, including evacuation, weather, emergencies, traffic congestion, or to regulate entrance to an HOV lane. They felt that possible benefits include a reduction in traffic, a reduction in accidents, and improved emergency response. Overall, participants had a favorable opinion of this treatment.

Figure 95. Focus Group Slide 17 Showing Ramp Gate.

CHAPTER 7: MANAGED RAMP DECISION MATRIX

Applying managed lanes strategies to ramps could meet *community* goals by reducing the environmental impacts of congestion. If pricing is applied to ramp management, then it may help meet the *financial* goals of the region by generating revenue to help improve the benefit-cost ratio of a project. Finally, ramp management implementation can support *homeland security* goals if specific strategies are applied during incidents to support emergency management and/or disaster management operations.

As described previously, these operational options are categorized by lane management strategy or a combination of multiple lane management strategies. All of these strategies have potential application to ramps and ramp management. However, the overall effectiveness of these strategies may vary depending on a number of factors. These factors may include, but are not limited to, the existing conditions of the general-purpose lanes, the specific problems and issues impacting performance at ramp locations, the willingness of travelers to accept managed ramps, the preexistence of managed lanes in the region, and the overall goals and objectives of TxDOT and partner agencies regarding mobility, congestion, and transportation project finance.

The same goals and related objectives generally applied to managed lanes strategies could also apply to strategies for managing ramps. Furthermore, the application of managed lane strategies at ramps can help address operational problems at a specific location or can be applied at a series of ramps to achieve corridor level benefits. Once again, the potential for meeting these goals lies with the specific lane management strategy implemented at either isolated ramps or along an entire corridor. Four operational scenarios that have the most potential to meet various needs of TxDOT districts across the state include:

- flow balance,
- incident/special event management,
- managed lanes facility preference, and
- ramp safety.

Based on detailed modeling analysis of the aforementioned managed ramp scenarios, specific applications of these strategies have the potential to improve freeway operations. These managed ramp strategies can be matched to managed ramp goals to help a transportation agency clearly identify which managed ramp operational strategies are best suited for a region, corridor, or facility.

Table 47 presents the managed ramp strategies and the related managed ramp goals to be achieved. The intent of the table is to provide guidance in selecting a managed ramp operational strategy that can address specific managed ramp goals identified by the transportation agency as critical components of an overall managed lanes planning process.

Table 47. Managed Ramp Goals and Related Strategies.

		Flow Balance	Incident Management			Special Event Management		Managed Lane Facility Preference			Ramp Safety	
Goal Category	**Managed Ramp Goals**		**Ramp Closure**	**HOV**	**Pricing**	**Select User Restriction**	**Ramp Closure**	**Forced Merge**	**Acceleration Lane**	**Full Auxiliary Lane**	**Automobile Restriction**	**Total Closure**
Operational / Mobility	**Prevent freeway from breaking down in bottleneck location**	**X**				**X**	**X**	**X**			**X**	**X**
	Provide priority access to special class of user to general-purpose facility	**X**				**X**		**X**	**X**	**X**		
	Overcome geometry deficiency to particular class of vehicles										**X**	**X**
	Overcome ramp storage problems		**X**	**X**	**X**	**X**	**X**				**X**	**X**
	Provide priority access to special class of user destined for managed lanes facility							**X**	**X**	**X**		
	Promote balanced flow in corridor	**X**	**X**			**X**	**X**				**X**	**X**
	Enhance and support incident management		**X**	**X**	**X**	**X**	**X**					
	Delay the onset of congestion on the freeway corridor	**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**
Safety	**Reduce vehicle crashes in merge and weaving areas**	**X**	**X**			**X**	**X**	**X**	**X**	**X**	**X**	**X**
	Reduce vehicle conflicts in merge and weaving areas	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
	Channelize vehicles with different operating characteristics to ramps which can better accommodate them			**X**				**X**	**X**	**X**	**X**	**X**

	Reduce the potential of rear-end collisions at ramps where congestion frequently occurs	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Community	**Balance perception of penalizing short vs. long trips**	**X**						**X**	**X**	**X**		
	Promote the use or discourage the use of certain facilities, ramps, or adjacent roadway(s) by certain vehicle users (i.e., trucks)	**X**		**X**		**X**	**X**					**X**
	Serve as an alternative to installing ramp meter signals at a specific location	**X**		**X**	**X**						**X**	
	Enhance TxDOT's ability to operate the corridor in an integrated fashion with other transportation providers in the community	**X**						**X**	**X**	**X**		
Financial	**Generate revenue for particular ramp or facility**	**X**			**X**							
	Delay the need to widen a freeway facility by maximizing the use of all the available capacity in the corridor through better operations	**X**						**X**	**X**	**X**	**X**	**X**
Homeland Security	**Enhance and support emergency management operations**		**X**	**X**	**X**	**X**	**X**					
	Ensure access to a managed lane facility to aid in the rapid deployment of emergency vehicle and disaster relief resources in an emergency event		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		

CHAPTER 8: RELATED ISSUES

A number of related issues are important when considering managed ramp operational strategies for implementation. These include, but are not limited to,

- public and agency input,
- pricing as an option,
- decision-making needs and traffic control devices,
- enforcement,
- environmental justice,
- evaluation and monitoring,
- interoperability, and
- outreach and marketing.

The following sections highlight these issues within the managed ramps context, thereby illustrating the need for transportation agencies to carefully consider them throughout the project development process.

PUBLIC AND AGENCY INPUT

It goes without saying that public and agency input is critical to the development of any project involving managed ramps. This input should be part of every step in the project development process. Without it, the project may not necessarily reflect the goals and objectives of the region and its residents, increasing the risk of opposition to efforts to improve the transportation system. The metropolitan planning organization and transportation agency should engage the public and other stakeholder groups by establishing communication, sharing information, gathering feedback, and enhancing their participation in the planning and project development process.

Through consensus building, project managers can realize project delivery in a more timely fashion. Generally speaking, the public may not fully understand the true costs of transportation, or the current state of transportation finance. Therefore, it is useful to educate the public regarding the financial constraints of the potential transportation investments. Scenario planning and visualization tools can also be useful to work with the public to raise awareness and reach consensus.

The managed ramps concept complicates this involvement process by generating a need for public education. The MPO must thoroughly communicate the concept and the various potential strategies it might include. Also, the MPO should include such aspects of managed ramps as goals, objectives, operations, and potential revenue use, when considering them for the transportation plan. Public involvement can help ensure that an MPO considers all of the social, economic, and environmental consequences of their transportation investment decisions as they relate to managed ramps. It gains buy-in from the public and develops an environment of cooperation and collaboration with participating stakeholders that can smooth the way for project development in the future.

PRICING AS AN OPTION

Pricing is one of the methods in which an agency may be able to achieve ramp management within the region. Whether implemented alone (value-priced or toll ramps) or with an occupancy component (HOT lanes), pricing can be a tool for preserving the operational integrity of a freeway. However, pricing is not without its challenges. In addition to the overall operational strategies, agencies must face such issues as identifying and selecting pricing alternatives, assessing the level and use of revenues, and determining public and political acceptance (*61*). With all of these challenges and their far-reaching ramifications, agencies and stakeholders need to determine whether ramp pricing will be an option at the regional level. While ramp pricing may not be appropriate for every corridor, having pricing in the toolbox of feasible alternatives increases the potential viability of projects and can serve as a means to manage ramp demand as well as make them feasible financially (*61*).

DECISION-MAKING NEEDS AND TRAFFIC CONTROL DEVICES

An implied goal of the managed ramps concept is to manage freeway access based on designated user groups or operational limitations at ramps. These choices can vary by time of day or possibly in response to changing traffic conditions on the general-purpose lanes in the corridor or region. The extent to which travelers can and will accommodate such operational flexibility hinges on their getting the right information at the right time and in the right format so that they can make effective decisions pertaining to their trip. Figure 96 illustrates the types of managed ramps-centered knowledge a driver needs and how it varies by familiarity with a facility.

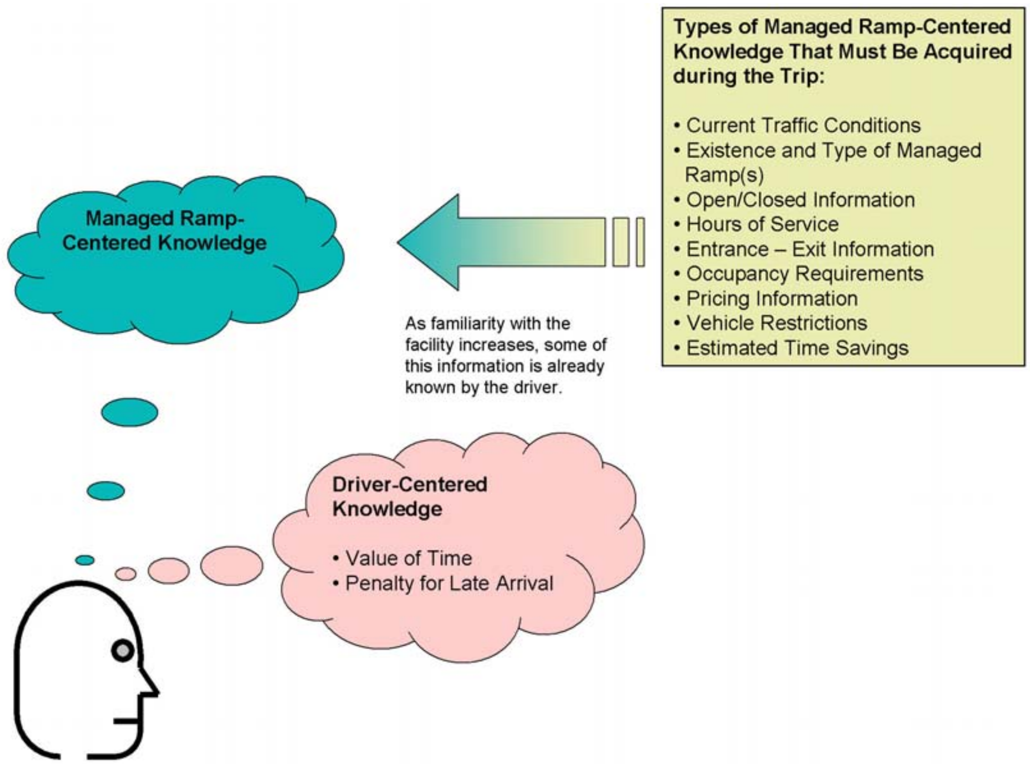


Figure 96. Driver Information Needs (Adapted from 62).

Determination of who the target audience really is (familiar, semi-familiar, or unfamiliar) can help determine how much information must be presented within a corridor regarding the managed ramps and/or a managed lanes facility. This step needs to happen early in the design process so that designers can make rational decisions about what levels of information they need to present.

Designers and operators of managed ramps must consider traffic control device needs early in the planning process as well. The initial costs of communicating with drivers includes:

- the right-of-way for signing and supporting structures,
- the cost of the structures,
- the cost of dynamic message signs and accompanying power and communications,

- the cost of designing, fabricating and installing static signs including any lane closures required, and
- the cost of pavement markings including standard lane striping plus any horizontal signs and symbols required or desired to augment guide or warning information contained in the signs *(63)*.

The ongoing costs of communication include maintenance of signs and markings, communications fees such as monthly cell phone charges for wireless networks, and maintenance of power supplies and other electronic components of dynamic message signs.

Beyond the cost of traffic control, early consideration of driver information needs in the planning process will assure that an operating scheme is not implemented that requires overly complex signs *(63)*. Variable tolls based on occupancy or time of day with dynamic pricing based on current conditions can result in complex toll schedules. Conventional toll roads often have a full menu of prices posted at toll plazas. With vehicles moving at slow speeds, and in most cases stopping completely, it is safe to present this large amount of information. But with electronic toll collection at high speed, it becomes dangerous to overload drivers with complex toll rules. For such complex operations, planners may have to accept that “one big sign” is not appropriate.

If the managed ramps will have a subscription-based pricing system, communication with subscribers through the mail or other means can allow agencies to provide the full toll schedule off-road. If a wider audience is anticipated, other methods of presenting the information must be considered such as the use of multiple, sequential signs. Another strategy might be to present a small amount of information that applies to the largest number of users, such as the minimum toll for a passenger vehicle. Other mechanisms, such as two-way transponders, which would present information in-vehicle are on the horizon and may lessen the need for numerous traffic control devices in the future.

In addition to operating strategies, planners need to consider traffic control devices in the geometric design as well. Considering traffic control early in the process can ensure that the necessary infrastructure is in place to meet the information needs of a facility to maximize driver comprehensive and utilization of the system.

ENFORCEMENT

A freeway facility with managed ramps requires effective enforcement policies and programs to operate successfully. Agencies employ strategies on managed ramps to regulate demand, and those actions require enforcement to maintain the integrity of the facility. The enforcement strategy chosen for managed ramps may be similar to those of managed lanes: routine enforcement, special enforcement, selected enforcement, or self-enforcement *(64)*. Routine enforcement would use existing freeway patrols to monitor managed ramps while special enforcement would use dedicated equipment and manpower specifically to monitor the managed ramps. Selective enforcement is a combination of the two strategies and may be used for specific events or concerns, such as the opening of new managed ramps or to combat high violation rates. The last enforcement strategy relies on the concept of self-enforcement, which involves promoting citizen monitoring and self-regulation by users of the managed ramps and the motorists in adjacent general-purpose lanes. Experience has shown that the best compliance rates yield from routine and special enforcement led by dedicated or semi-dedicated law enforcement personnel combined with automated enforcement techniques *(65)*.

Enforcement of vehicle-occupancy requirements, use by authorized vehicles, or proper toll collection is critical to protecting eligible vehicles' travel-time savings and safety. As these operating strategies are combined, enforcement becomes even more difficult. Visible and effective enforcement promotes fairness and maintains the integrity of the managed lanes facility to help gain acceptance among users and non-users. Furthermore, fines for violating managed ramps operational conditions should be high enough to discourage willful violation and minimize the need for dedicated enforcement *(66)*. Currently, penalties for HOV and HOT lane projects in the United States can range from $45 for a first offense to over $1000 for repeat offenders and/or license points *(66)*. Development of enforcement policies and programs ensures that all appropriate agencies are involved in the process and have a common understanding of a project and the need for enforcement *(64)*. Participation from enforcement agencies, the courts and legal system, state departments of transportation, and transit agencies is critical for enforcement success.

Enforcement also impacts the design of managed ramps. For example, traditional enforcement on managed ramps often requires dedicated enforcement areas, which would most likely be located immediately adjacent to the managed ramp and allow enforcement personnel to monitor the facility, pursue violators, and apprehend violators to issue appropriate citations. They also serve as a safe environment for enforcement personnel to perform their duties. However, recent advances in automated enforcement technology may lower the number of dedicated enforcement areas needed in the future, thereby shifting the focus of design to proper placement of electronic equipment *(64)*. Planning for enforcement from the beginning can ensure that the facility is designed properly to accommodate it and preserve the integrity of the system and the fairness to users.

ENVIRONMENTAL JUSTICE

Environmental justice is an increasingly important element of policymaking in transportation. It is fundamentally about fairness toward the disadvantaged and the concept of environmental justice requires that transportation plans be fully inclusive. This concept means that plans may not disproportionately impact minority and low-income communities or areas, and must allow these groups to fully share in the benefits of transportation infrastructure implementation *(67)*. These strategies that are intended to expand access for low-income and minority populations to transportation programs are mandated by the Civil Rights Act of 1964, Executive Order 12898 issued in 1994, and U.S. DOT Order 5680.2 issued in 1997 *(68)*.

Environmental justice is closely intertwined with the planning and project development processes. As agencies develop their regional plan and identify projects that could incorporate managed ramps, they should consider the impacts they may have on these groups. Examples of planning to meet environmental justice standards include placement of highways, providing access to transit for transportationally disadvantaged people, emphasizing pedestrian plans, and enhancing streetscapes and sidewalks. Involving the impacted groups in the planning process through meaningful public involvement, as discussed previously, is critical to ensuring environmental justice *(69)*.

EVALUATION AND MONITORING

Successful monitoring and evaluation programs generally consist of six indistinct and overlapping steps:

- setting goals and objectives that reflect the program or system’s desired performance and are consistent with agency or regional priorities;

- identifying appropriate performance metrics to accurately evaluate attainment of the goals and objectives;
- identifying required data and sources to support calculation of the performance measures;
- defining appropriate evaluation methods within the constraints of data availability and staff training;
- defining an appropriate schedule for on-going, periodic monitoring of the system; and
- reporting the results in a usable and easily understood format (*70*).

The performance of managed ramps, documented through a comprehensive evaluation and monitoring program, should play a central role in the traditional long-range, short-range, and operations level transportation planning process.

Performance measures, derived from goals and objectives set earlier in the planning and project development processes and related to mobility and congestion, reliability, accessibility, safety, environmental impact, system preservation, or organizational efficiency, help gage progress toward performance "targets" for managed ramps. Subsequently, these performance measures, and their relation to the performance targets, are used to direct resources and activities (i.e., projects, programs, and policies) and focus public discussions around alternative investment strategies. Because of their potential to influence resource allocations and the subsequent success of managed ramps, it is important for the performance measures to address all aspects of managed ramps activities. A primary function of managed ramps may be to reduce congestion through improvements in vehicle throughput or effective capacity. To maintain this primary functionality, the planning process must also consider activities such as facility maintenance and incident management. Adequately monitoring and evaluating these "support" functions, in terms of both product or outcome and process, will help to ensure appropriate resource allocations in these areas. Incident management activities, in particular, may require additional resources not traditionally or immediately available within departments of transportation (i.e., properly equipped incident response vehicles, specialized training, etc.).

The continued deployment of intelligent transportation systems technologies has the potential to make a vast amount of data available to support planning and operational efforts at all levels. Planning for managed ramp evaluation and monitoring can ensure an agency has the appropriate infrastructure, policies, and procedures in place, prior to implementation, to ensure the effective operation of managed ramps within the region.

INTEROPERABILITY

Bringing managed ramps to completion is a complex process of planning, design, and daily operation. These ongoing operations include, at a minimum, management, enforcement, incident detection, revenue collection, and enforcement. Often, managed ramps may be cross-cutting, not only in the use of multiple operating concepts to achieve goals, but also because it can involve multiple agencies and vehicle user groups.

These types of interactions all point to a level of interoperability that creates operational challenges. As a definition, interoperability can best be expressed as "the ability of a system to use the parts, information, or equipment of another system." The complex nature of a managed lanes facility calls for a complete understanding of major relationships within managed lanes, their scope, and the critical issues associated with each relationship or area of interoperability (*71*). In general, interoperability within the context of managed ramps can exist at three levels: at the agency level, at the facility level, and/or at the equipment level. The level at which interoperability exists helps determine the interactions agencies should consider in the planning and project development processes. For example, agency level interactions are typically going to consist of long-term planning or design coordination, as well as broad-scale agreements for creating similar policies and procedures for operating managed ramps. Agency level interactions will also typically examine the use of managed ramps in more of a regional context, as one method of accomplishing regional transportation goals. In sharp contrast to that high-level planning and interaction, coordination at the equipment level is meant to ensure that data elements from one system can be transmitted, received, and understood by another system, regardless of their eventual use in both systems. In the middle of the two endpoints are the facility level interactions, which typically would occur in areas such as geometric design, traffic control devices, enforcement, and more (*71*). While facility level interactions can certainly be planning oriented, they are typically more corridor specific, focusing on the components or operations of an individual facility, rather than the focus of regional goals performed at the agency level. The development of any crosscutting facility, like managed ramps, must be supported by all of the involved agencies and must support the broad-based transportation goals of the region.

OUTREACH AND MARKETING

Public acceptance plays a critical role in the success of any project. Marketing a new product or concept can be challenging. Effective marketing campaigns must consider the goals of the managed ramps project and tailor the message to meet those goals. Several different techniques can be used to communicate with the public depending on the message that is to be delivered and the objectives. Likewise, a message may be tailored to particular audiences. It is important that the public, or the audience, be correctly defined. Audiences will depend on the nature or scope of the managed ramps project and may change throughout the different phases of the project. Additionally, once the managed ramps project is operational, conveying information to the users should continue to ensure they are fully aware of potential changes in operational conditions and to maintain their trust in the project and compliance with regulations governing its use.

CHAPTER 9: RECOMMENDATIONS

Managed lanes operational strategies can maximize existing capacity, manage demand, offer choices, improve safety, and generate revenue. The key to successfully operating managed lanes is the ability to alter the operations of the lanes in ways that keep traffic flowing. This strategy provides flexibility, not only in the day-to-day operations of the lanes, but in situations where isolated incidents such as a major accident call for the lanes to be open to more or different user groups.

Historically, ramp management strategies refer to ramp metering and ramp closures. These strategies with special use treatments and ramp terminal treatment are the most commonly accepted methods of ramp management strategies. Ramp metering is the most extensively used strategy. One of the areas for potentially improving freeway performance is at ramp locations. The currently used ramp treatments only address point demand. Simply put, ramp management is the application of control devices, such as traffic signals, signing, and gates, to regulate the number of, and rate by which, vehicles enter or leave the freeway. The concept of managed ramps would be to apply any of the myriad of managed lanes operational strategies along a corridor to optimize the use of the overall freeway facility. As discussed previously, such operational strategies discussed throughout this report could help maximize existing capacity, manage demand, offer choices, enhance mobility, improve safety, and generate revenue within the freeway corridor itself.

VIABLE MANAGED RAMP STRATEGIES

Based on the results of this research effort, the research team recommends that specific managed ramp scenarios have the potential to enhance ramp and freeway operations. The following sections highlight which ramp management scenarios have the most potential as well as their limitations within the context of the research project.

Viable Strategies for Flow Balance

The results of simulation analysis clearly show that metering the demand on higher volume ramps allows operators to maintain a higher level of operating speed and throughput on freeways. Thus, limiting ramp access to select user groups to enhance flow balance is a feasible ramp management strategy. However, the operating agency must first assess how much traffic needs to be diverted away from a ramp through the application of a managed lane strategy to achieve the same level of operation on a freeway if ramp metering was deployed. To do this, one must identify at what level of ramp demand when no ramp meter is present produces the same level of operation on the freeway (i.e., average running speed) that occurs when ramp metering is used on a ramp. Furthermore, the operating agency must then determine what user group and/or pricing scheme would generate the appropriate ramp demand. Identifying specific user group combinations and pricing thresholds was beyond the scope of this project. Additional research is needed to determine which managed lane strategies would be most effective at achieving this level of demand reduction.

Viable Strategies for Special Event Management

Two managed ramp strategies for special event management have the most potential to improve freeway operations: venue-destined vehicle restrictions and total closure. Both of these strategies have the potential to alleviate problems when too many vehicles utilize a single exit ramp to access a special event venue.

Venue-Destined Vehicle Restrictions

The first ramp management strategy is to dynamically restrict venue-destined vehicles from entering the venue from the closest freeway exit that creates problems. When queuing reaches the midpoint of the exit ramp, the venue-destined vehicles are automatically rerouted and forced to continue on the freeway facility to the next available exit. The goal is to prevent the queued vehicles from spilling back onto the freeway mainlanes. As the queue dissipates, venue-destined vehicles are allowed to utilize the exit ramp again. Output performance measures are compared to a base case (do nothing) model and consist of ramp queue length, average freeway travel time on a predefined section, average speed upstream of the exit ramp, and average delay measured at the terminal intersection.

Ramp Closure

The second strategy is to restrict all vehicles from exiting at the problem exit ramp when spillback onto freeway mainlanes starts to occur. As with the venue-destined vehicle restriction strategy, all vehicles are automatically rerouted and forced to continue on the freeway facility and bypass the exit ramp. Performance measures for all vehicles restricted are identical to the venue-destined vehicle restriction.

Special Event Management Strategy Comparison

When both scenarios are compared to a base case model, significant impacts are noticeable. A comparative analysis of average freeway speed drops below 15 mph when no ramp management strategies are implemented. Restricting venue-destined vehicles and restricting all vehicles considerably increases freeway speeds to approximately 50 mph.

If ramp storage from the stop bar at a terminal intersection is approximately 900 ft to the loop detector, queue length exceeds the storage capacity in the base model and continues to spill back for the duration of the special event. Both ramp management scenarios drastically reduce the queue length. The length of the queue fluctuates but stays relatively short and does not surpass the storage capacity of the off-ramp.

Modeling shows that ramp closure performs the best when compared to venue-destined vehicle restrictions. Significant improvements to speed, queue length, delay, and travel time are apparent in simulation models. This brings forth the question of how dynamic restrictions and closures can be implemented. It must be noted that in reality, all traffic does not obey messages placed on DMS, which can be a useful tool to implementing these strategies. Therefore, it is important to consider the optimal upstream placement of DMS to maximize traffic flow or minimize traffic disruption caused by off-ramp queue spillback resulting from congestion from special events.

Viability of Managed Facility Preference

Only those conditions with speed differentials of less than 10 mph are considered desirable and viable for providing managed ramp preference for vehicle destined for a managed lanes facility. The following sections discuss the overall impacts of various factors on the ability to maintain speed differentials of less than 10 mph for this purpose. Each discussion presents information related to the three merging conditions noted previously.

Proportion of Trucks on the Expressway

The vehicle mix on the expressway mainlanes can be divided into three categories: no trucks (90 percent auto and 10 percent bus); normal mix (90 percent auto, 5 percent bus, and 5 percent truck); and high truck volume (80 percent auto, 5 percent bus, and 15 percent trucks). As the expressway truck percentage increases, expressway through lane speeds and ramp weaving speeds decrease for all ramp merge conditions. Expressway mainlane speeds and ramp weaving speeds are higher where the ramp merge features an auxiliary lane.

Space between Managed Ramp and Managed Lanes Access Point

Different ramp spacings of 500 ft, 1000 ft, and 1500 ft per expressway lane also impact the operations of the freeway when managing ramps for managed lanes facility preference. As discussed previously, mainlane speeds are observed to increase with spacing increases between the managed ramp and the managed lane access ramp. Ramp weaving speeds also increase with an increase in spacing entry ramp to expressway and entry ramp to the managed lane.

Proportion of Automobiles on the Ramp

Four managed ramp vehicle mixes provide insight into the impact of these vehicle mixes on freeway operations when managed at the ramp. These vehicle mixes include: all automobiles (100 percent auto); normal mix (90 percent auto, 5 percent bus, and 5 percent truck), HOV/HOT/SOV/buses only (85 percent auto and 15 percent bus); and trucks only (100 percent truck). Expressway mainlane speeds are observed to increase with an increase in the proportion of automobiles found in the ramp traffic mix. Similarly, ramp weaving speeds increase with an increase in the ramp auto proportion. Expressway speeds and ramp weaving speeds both increase with increases in weaving distance and increase in the proportion of automobiles found on the ramp.

The “truck-only” ramp vehicle mix performs better with full auxiliary lane than the other two types of ramp merge conditions. The speed difference is approximately 7 mph between full auxiliary lane and acceleration lane ramp merge conditions for a ramp composition of 100 percent trucks. The speed difference reduced to approximately 1 mph for a ramp featuring only automobiles in the vehicle mix. Expressway mainlane speed was approximately 52 mph with 100 percent trucks on the ramp and the speed increased to approximately 64 mph with 100 percent automobiles on the ramp for a ramp with an acceleration lane. The differential of ramp weaving speed between two ramp conditions, full auxiliary lane and acceleration lane, is approximately 17 mph for 100 percent trucks on the entrance ramp. The speed differential of ramp weaving speed for these two ramp merge conditions is approximately 1 mph if 100 percent autos are found on the ramp.

Full auxiliary lanes yield higher ramp weaving speeds for both 100 percent truck and 100 percent auto vehicle mixes on the entrance ramp. The difference in the ramp weaving speed between the acceleration lane and forced merge ramp condition is greater when the ramp serves 100 percent truck traffic. Ramp weaving speed differentials are observed to decrease as the truck proportion on the ramp traffic decreases. The difference is marginal when truck proportion in traffic mix reaches zero, e.g., 100 percent automobiles on the ramp.

Expressway Volume Level

Two typical volume expectations for expressway traffic conditions are either nominal (1000 vehicles per hour per lane [vphpl]) or higher (1400 vehicles per hour per lane) volume flow levels. As expected, expressway mainlane and ramp weaving speeds are greater when the volume level is less demanding in terms of volume-to-capacity ratio.

Presence of an Intermediate Ramp

The presence of an intermediate ramp between the expressway's managed entrance ramp and the entrance ramp to the managed lanes decreases the expressway mainlane and ramp weaving speed. Both expressway mainlane and ramp weaving speeds are lower for all ramp merge conditions in the presence of intermediate ramps.

Entry Ramp Flow Level

Two typical levels of managed ramp flow can impact operations, those levels being 375 and 750 vehicles per hour per lane. Figure 65 shows the extent to which higher ramp flows have an impact on freeway and ramp weaving speed performance. The output is also organized to demonstrate the differences ramp merge conditions have under the different ramp flow scenarios.

Proportion of Ramp Traffic Weaving to Reach the Managed Lane

To ascertain the impact that different quantities of weaving traffic from the managed ramp to the managed lanes access point had on overall operations, cases are designed with 25 percent and 50 percent of ramp traffic weaving to reach the managed lane. Essentially, the higher the volume of ramp traffic weaving to reach the managed lane, the lower the speeds for mainlane traffic and weaving ramp traffic.

Viable Strategies for Ramp Safety

As a result, various combinations of vehicle restriction scenarios can be modeled to determine which ones performed the best when assessing optimal safety conditions on a freeway corridor. Two managed ramp strategies for ramp safety have the most potential to improve freeway operations: automobile restrictions and total closure.

Automobile Restrictions

The first ramp management strategy with the potential to improve operations as they relate to ramp safety is restricting automobiles from using a designated entrance ramp. All the vehicles traveling on the freeway mainlanes upstream of an entrance ramp targeted for ramp management decelerate to provide adequate gaps for vehicles entering the freeway. This behavior can be a safety issue because it interrupts the mainlane flow of the freeway with vehicles entering at the entrance ramp. The flow of mainlane traffic is dependent upon the inflow rate of vehicles entering the freeway. As various vehicle classes are restricted from the entrance ramp, speed increases upstream of the entry point.

Speed is most influenced when no restriction is placed on the entrance ramp since all vehicles are allowed access to the freeway. As various vehicle classes are restricted, freeway mainlane speed increases. With a typical vehicle mix composed of 90 percent automobiles, their restriction from an entrance ramp has the most influence on mainlane speed other than total ramp closure. Restricting only cars from entering a facility also causes the least amount of speed acceleration and deceleration fluctuation for vehicles traveling upstream of the managed entrance ramp.

Safety issues more frequently occur in the right lane since vehicles using the entrance ramp affect the flow on the freeway. Thus, it is important to analyze in depth the right lane traffic because this is where entering vehicles have the greatest effect on the freeway traffic flow. The traffic flow on the far rightmost lane is influenced the greatest when no vehicles are restricted. Allowing all vehicles to enter the freeway facility greatly impacts speed on the far right freeway merge lane. Only allowing trucks and/or buses access shows to have the highest travel speeds on the far right lane upstream of the managed ramp. As congestion builds on the model network, speeds for trucks and buses using the ramp level out at 32 mph. Allowing cars to enter the freeway decreases the average speed on the far right lane upstream of the managed entrance ramp to approximately 27 mph.

When no vehicles are restricted from entering the freeway, overall mainlane speed downstream of the weave/merge area created by the managed ramp dropped to approximately 50 mph. When cars are restricted independently or in juxtaposition with other vehicle classes, average speed on all mainlanes ranges from 60 to 62 mph, an occurrence that is more apparent when analyzing average acceleration downstream of the managed entrance ramp. The car-restricted management strategy shows the acceleration to level off at approximately 1 ft/sec^2. This means that there is less fluctuation of the overall traffic speeds and vehicles are flowing smoother when compared to other scenarios. When restrictions of large traffic compositions are regulated from entering the freeway, there is less fluctuation in speeds. Hence, restricting the highest number of vehicles (i.e., automobiles) creates less disruption of freeway mainlanes.

The right lane can be analyzed independently since this lane has the greatest amount of turbulence caused by the merging and weaving of vehicles. Since cars compose the highest volume (90 percent), freeway access poses the greatest variability of speed. Vehicle restrictions that include automobiles have better performance than other scenarios with speed distributions ranging from 53 to 60 mph. The same pattern emerges when analyzing the average acceleration and deceleration. Restricting cars from entering the freeway allows the downstream vehicles traveling in the far right lane to maintain a more constant speed. Having a constant speed in a merge area provides for smoother transition and flow of vehicles and ultimately provides a safer environment for motorists.

Ramp Closure

The second and more restrictive ramp management strategy with the potential to improve ramp safety is total ramp closure. In terms of speed performance, closing the entire entrance ramp proves to be the most optimal. However, total ramp closure does show to have a greater range of acceleration variability. Acceleration in the far right lane also has the greatest range of variability when all vehicles were restricted from entering the freeway facility because mainlane traffic speeds up when passing the on-ramp without disruption.

Ramp Safety Strategy Comparison

When comparing all vehicle restrictions at a managed entrance versus the base case "do nothing" scenario, density decreases by 17 percent in the rightmost lane. This decrease represents the highest density reduction compared to other possible scenarios. This lane also has the highest increase in speed of 21 percent when compared to all other scenarios.

When ramp closure is not an option, the most ideal ramp management strategy consists of car and truck restrictions with a 15.4 percent decrease in density followed by car and bus restrictions with a 15.3 percent density reduction. Restricting only cars reduces density by 14.7 percent when compared to the base case scenario. Restricting only cars also increases speed in the far right lane by almost 20 percent. All scenarios that restrict cars independently or in conjunction with other vehicle classes show a 20 percent increase in upstream mainlane speed and approximately 15 percent decrease in density. Ramp management scenarios that do not restrict cars from entering the freeway show significantly poorer performance measures when compared to no vehicles restricted. Truck-only restrictions decrease density in the far right lane by 11 percent.

For the downstream analyses, there was a considerable difference in density compared to the upstream lanes due to the spillback created by vehicles entering the facility. The performance measures followed the same general patterns as the upstream mainlanes. Total ramp closure decreased density on the far right lane by 35 percent when compared to "do nothing." Speed also increased significantly on the far right lane. Speed is consistently similar for restriction of cars, cars and trucks, and cars and buses, each with an average speed increase of 37 percent when compared to no vehicle restrictions.

The main improvement in density and speed is observed in lane one. The subsequent lanes—lanes two, three, and four—have less significant change as compared to lane one, but follow the same pattern as lane one. Lane four has some variation since it is the farthest lane from the effect from the managed entrance ramp.

When no vehicles are restricted from the on-ramp the average stopped delay is higher. However, when restricting certain vehicle types, the stopped delay decreases. Aside from the base case scenario, the highest stopped delay per vehicle shows when only trucks are restricted. However, when cars and buses are restricted the stopped delay reduces considerably (16.93 seconds) when compared to the base case scenario (24.64 seconds). Since buses have a slower acceleration rate, restricting such vehicle types improves the safety and congestion conditions on the IH-10 corridor.

RELATED ISSUES

A number of related issues are important when considering managed ramp operational strategies for implementation. These issues include but are not limited to public and agency input, pricing as an option, decision-making needs and traffic control devices, enforcement, environmental justice, evaluation and monitoring, interoperability, and outreach and marketing. As discussed previously, each of these issues has the potential to impact the viability and overall success of ramp management strategies discussed herein. It is critical that an agency considering these strategies thoroughly assess and address these issues through the decision-making process to maximize the potential for success.

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APPENDIX A. SIMULATION OUTPUT FOR FACILITY FLOW BALANCE

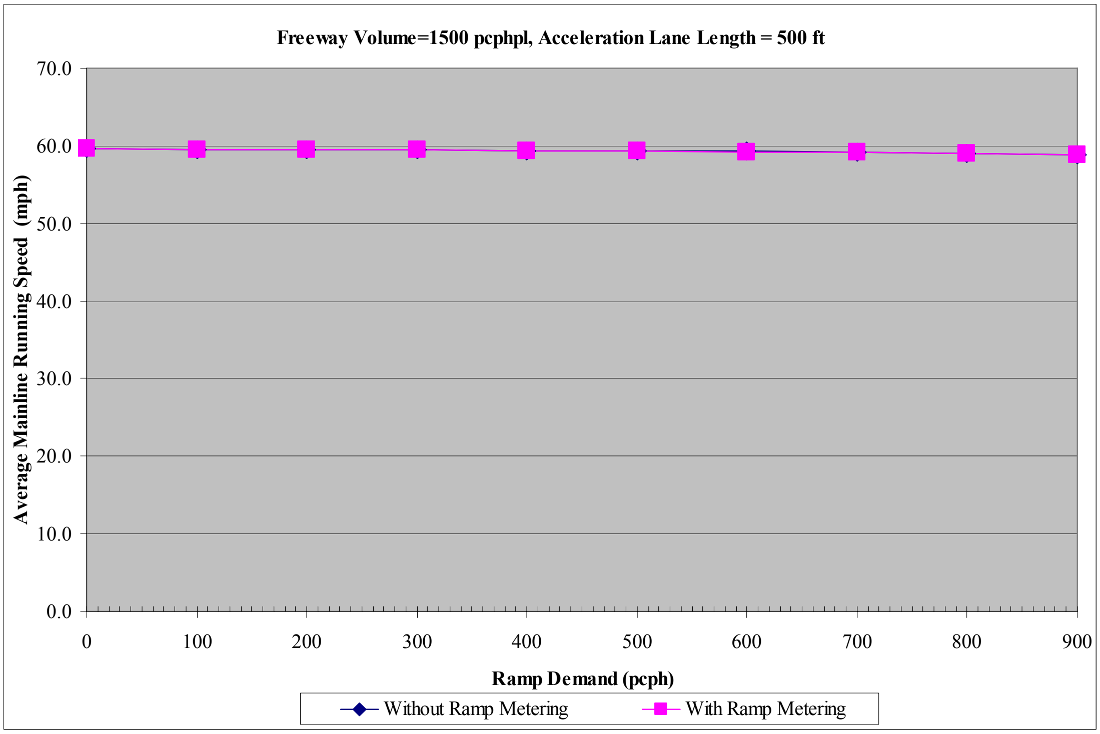

Figure A-1. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 500 ft.

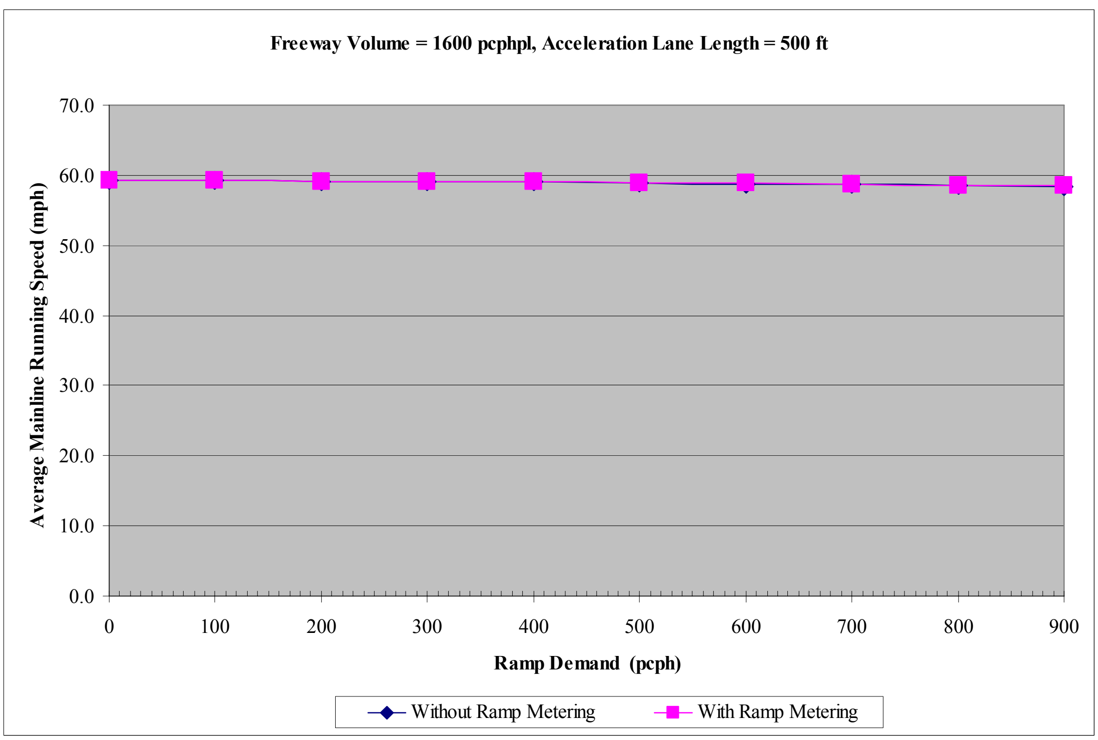

Figure A-2. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1600 pcphpl, Ramp Acceleration Lane Length = 500 ft.

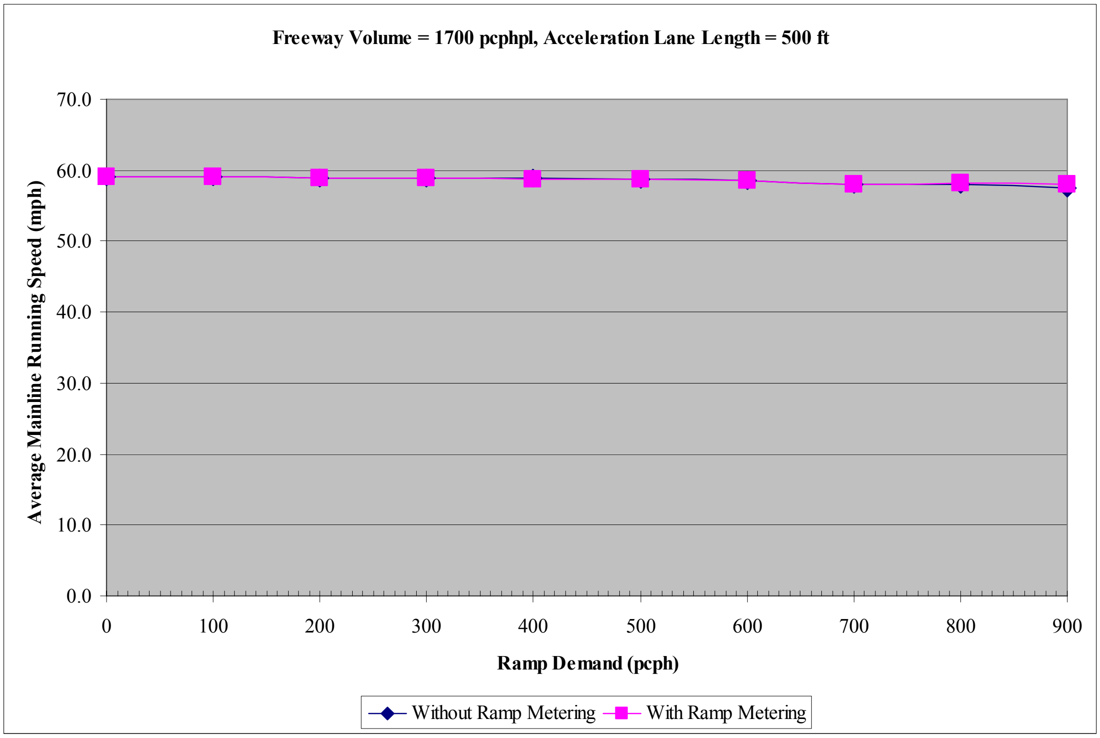

Figure A-3. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1700 pcphpl, Ramp Acceleration Lane Length = 500 ft.

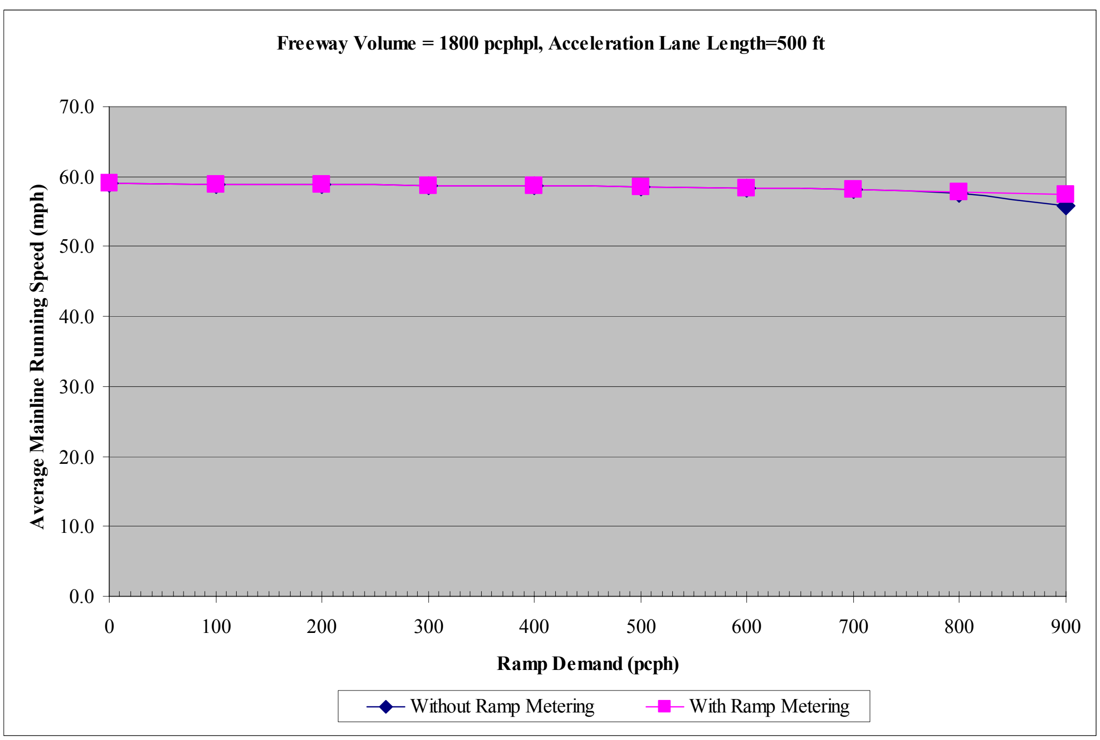

Figure A-4. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1800 pcphpl, Ramp Acceleration Lane Length = 500 ft.

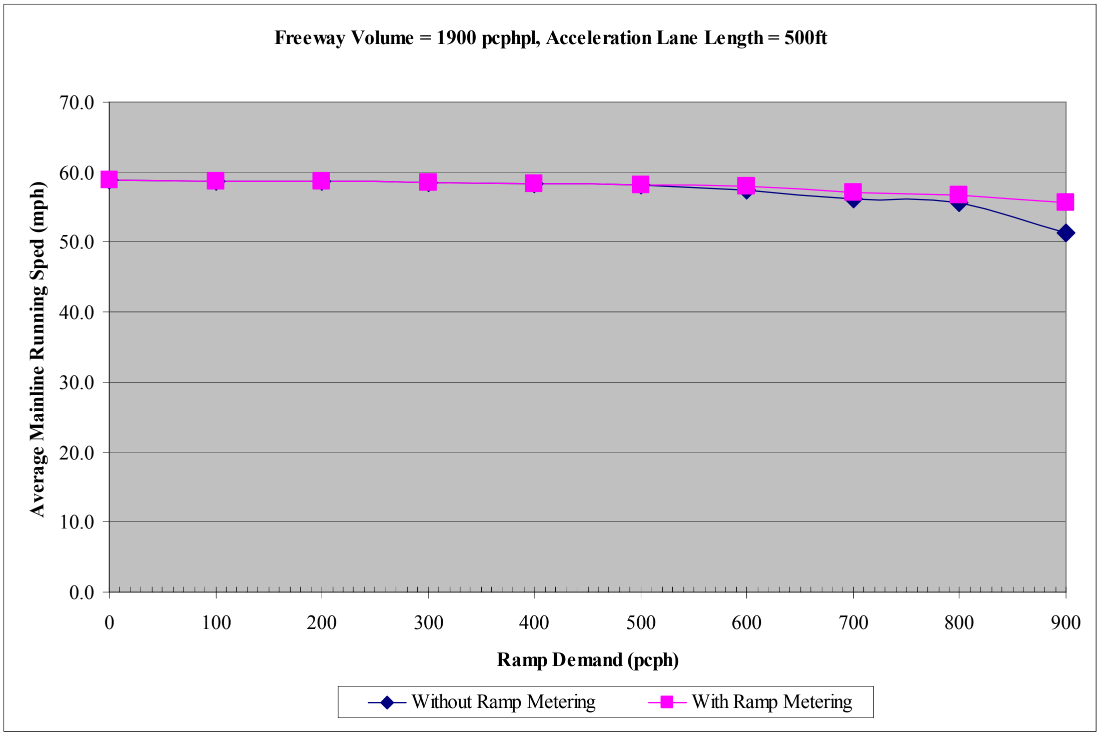

Figure A-5. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1900 pcphpl, Ramp Acceleration Lane Length = 500 ft.

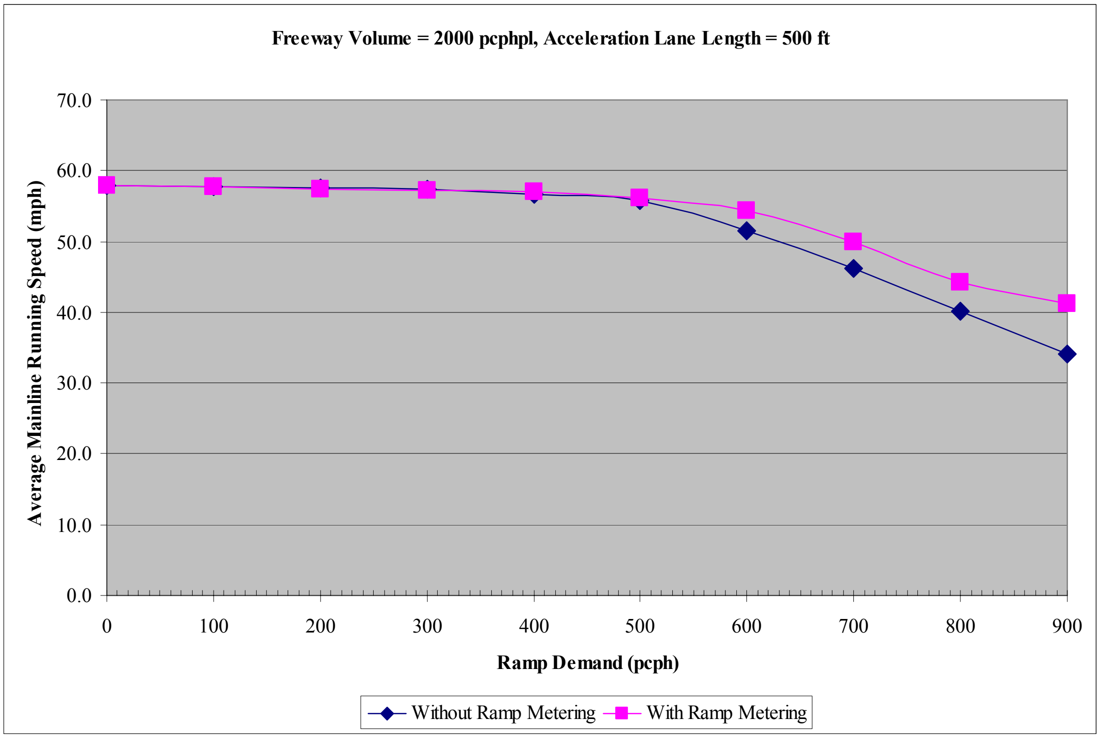

Figure A-6. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2000 pcphpl, Ramp Acceleration Lane Length = 500 ft.

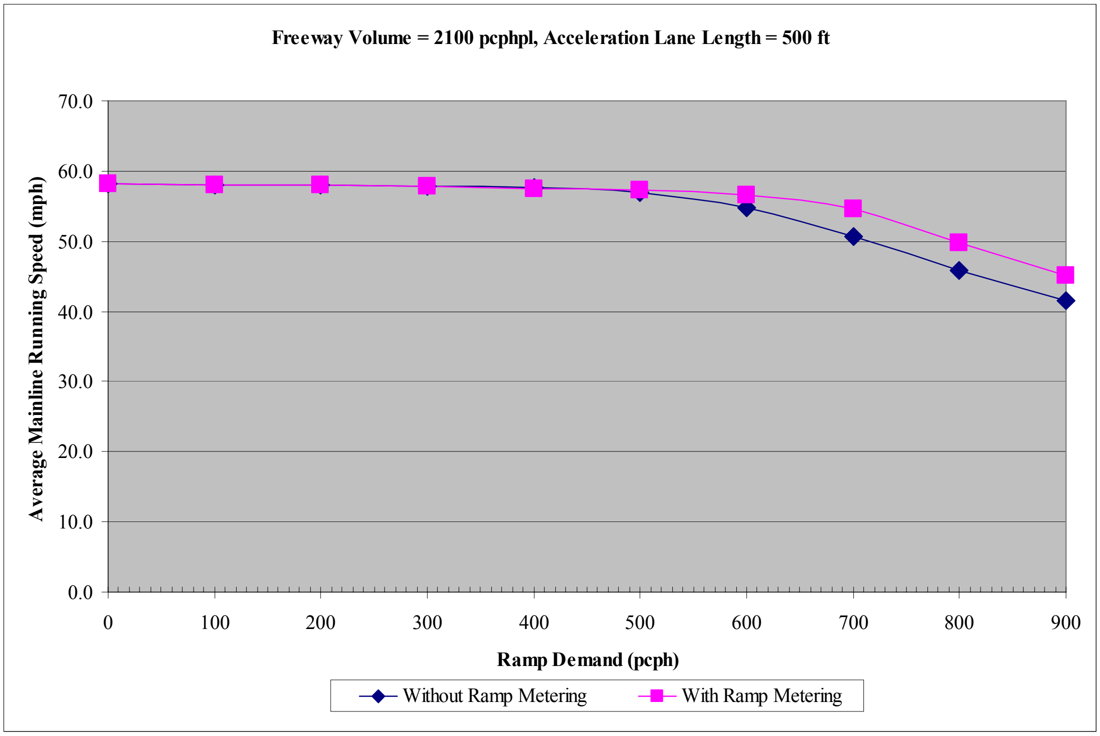

Figure A-7. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2100 pcphpl, Ramp Acceleration Lane Length = 500 ft.

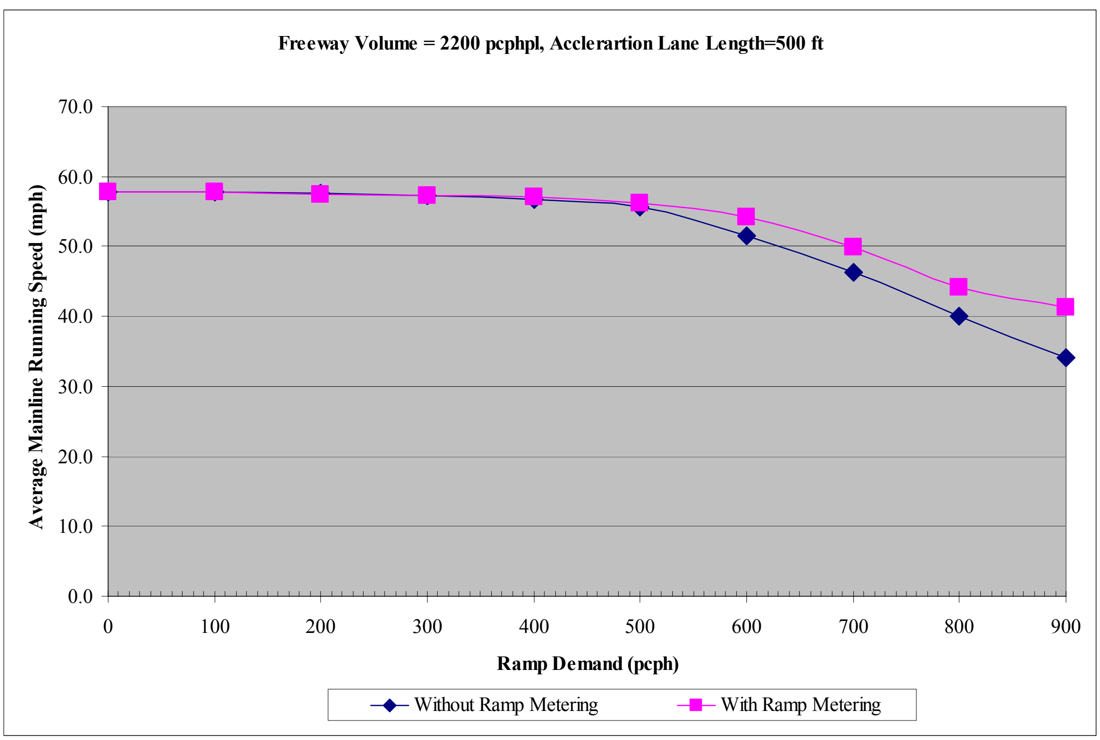

Figure A-8. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2200 pcphpl, Ramp Acceleration Lane Length = 500 ft.

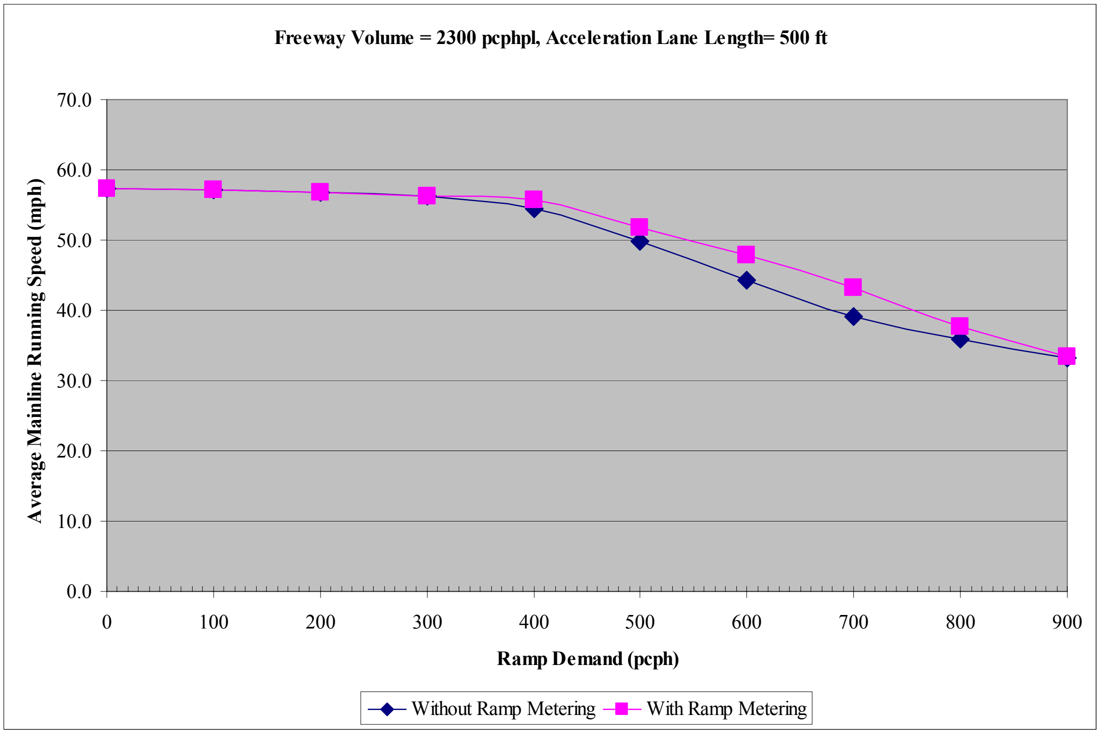

Figure A-9. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2300 pcphpl, Ramp Acceleration Lane Length = 500 ft.

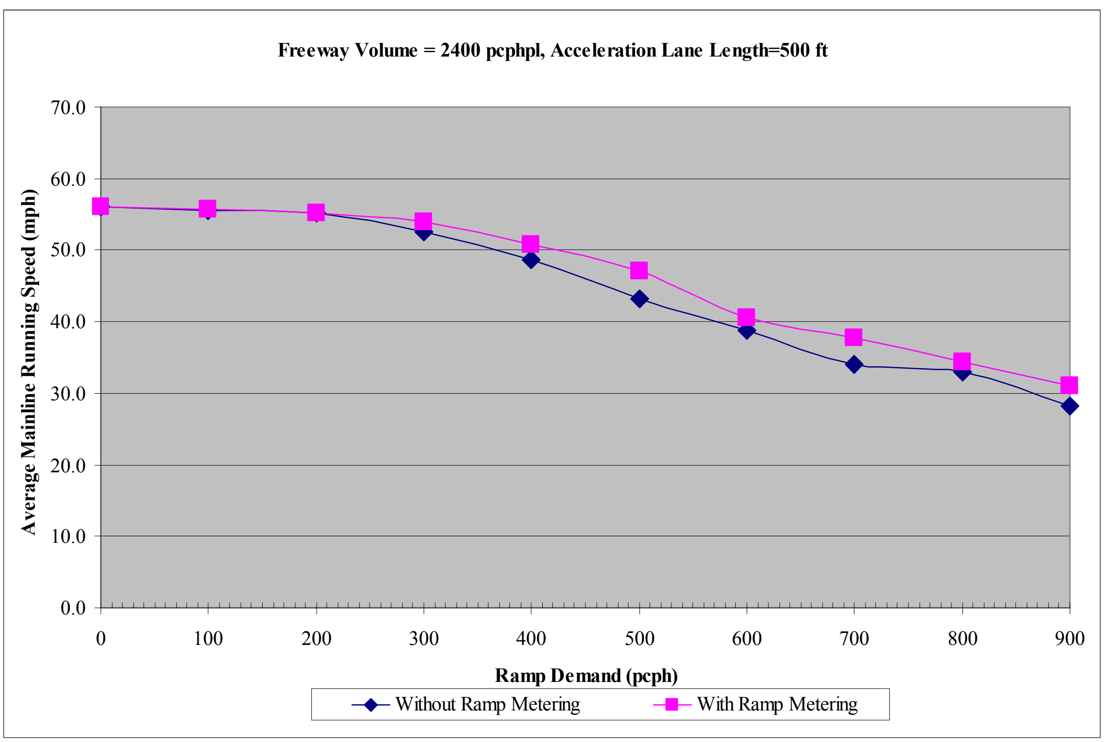

Figure A-10. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2400 pcphpl, Ramp Acceleration Lane Length = 500 ft.

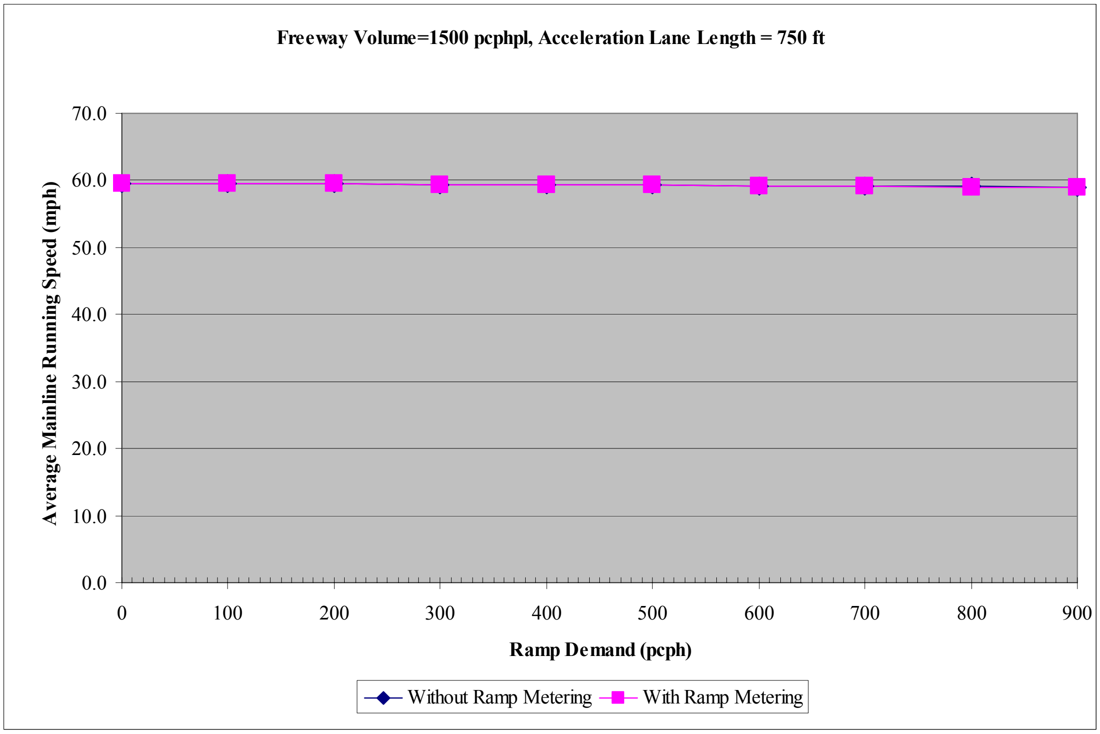

Figure A-11. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 750 ft.

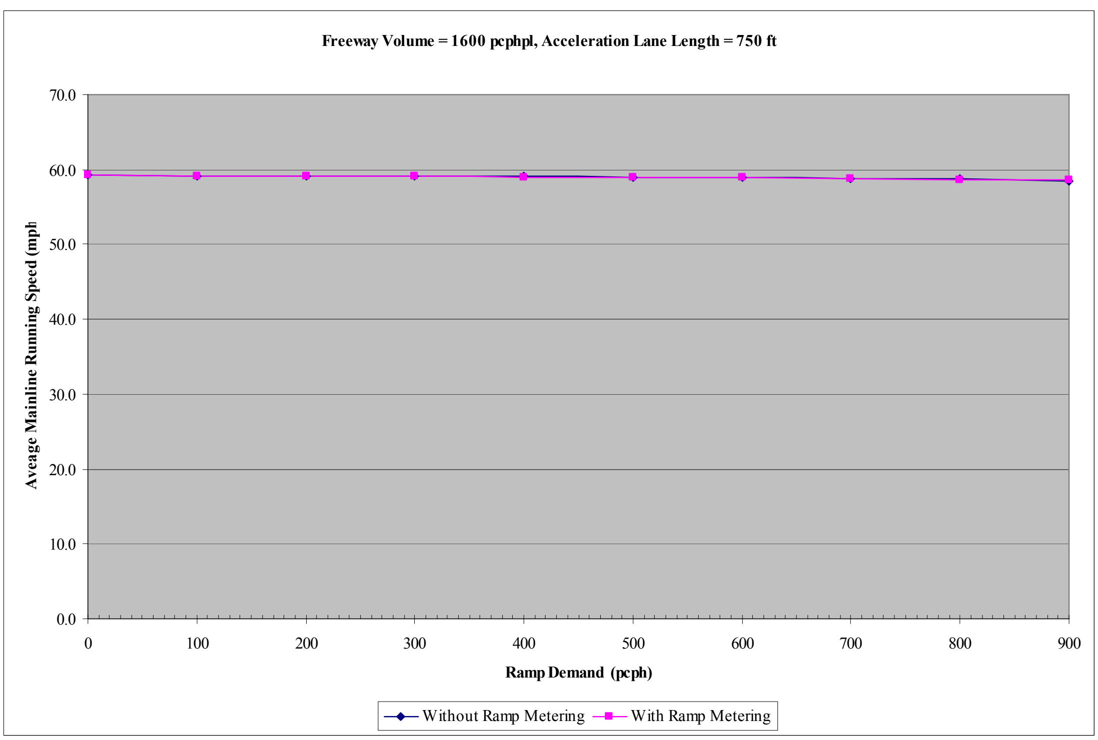

Figure A-12. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1600 pcphpl, Ramp Acceleration Lane Length = 750 ft.

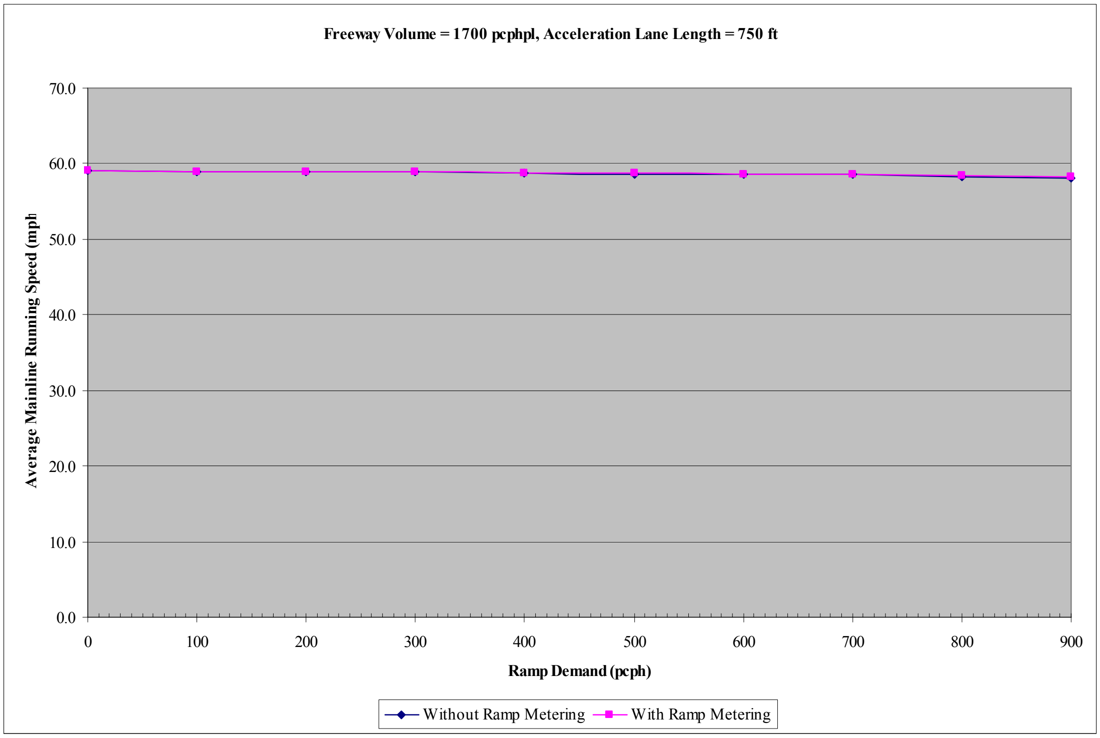

Figure A-13. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1700 pcphpl, Ramp Acceleration Lane Length = 750 ft.

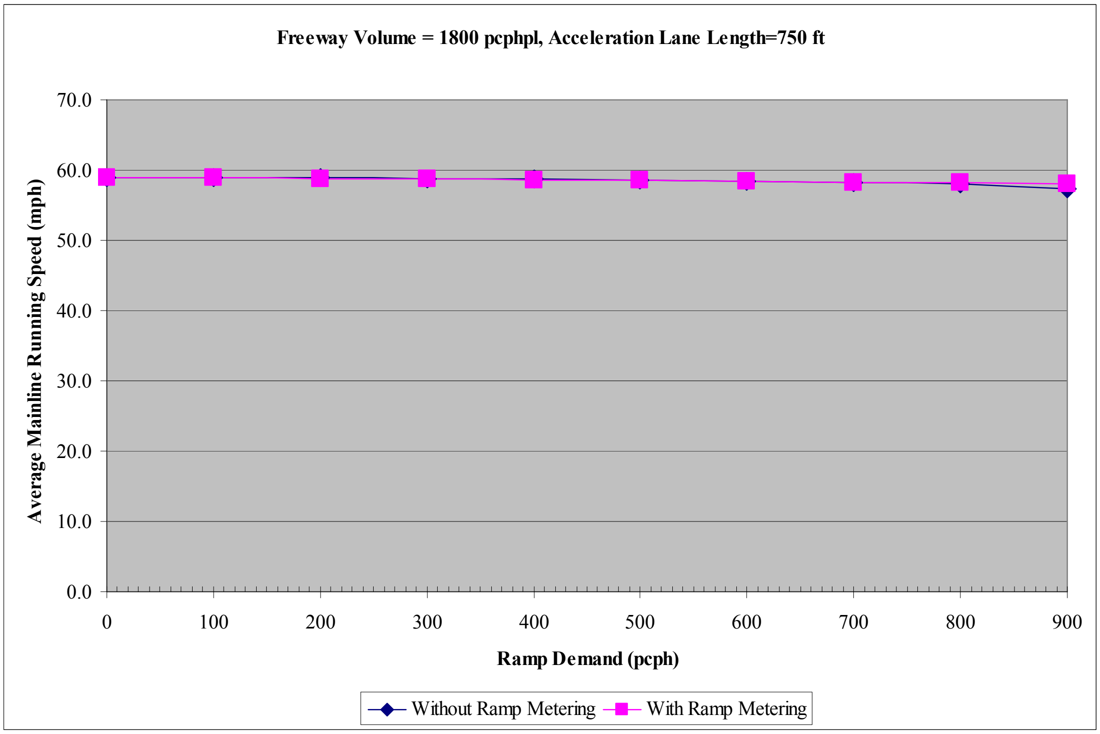

Figure A-14. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1800 pcphpl, Ramp Acceleration Lane Length = 750 ft.

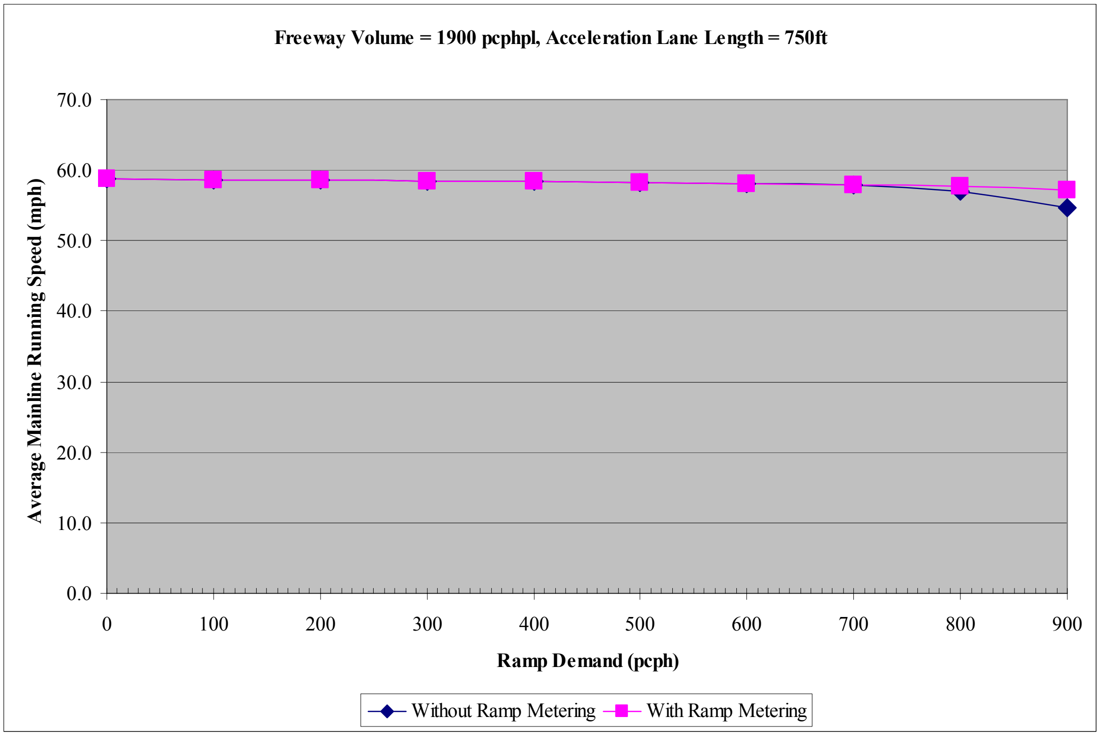

Figure A-15. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1900 pcphpl, Ramp Acceleration Lane Length = 750 ft.

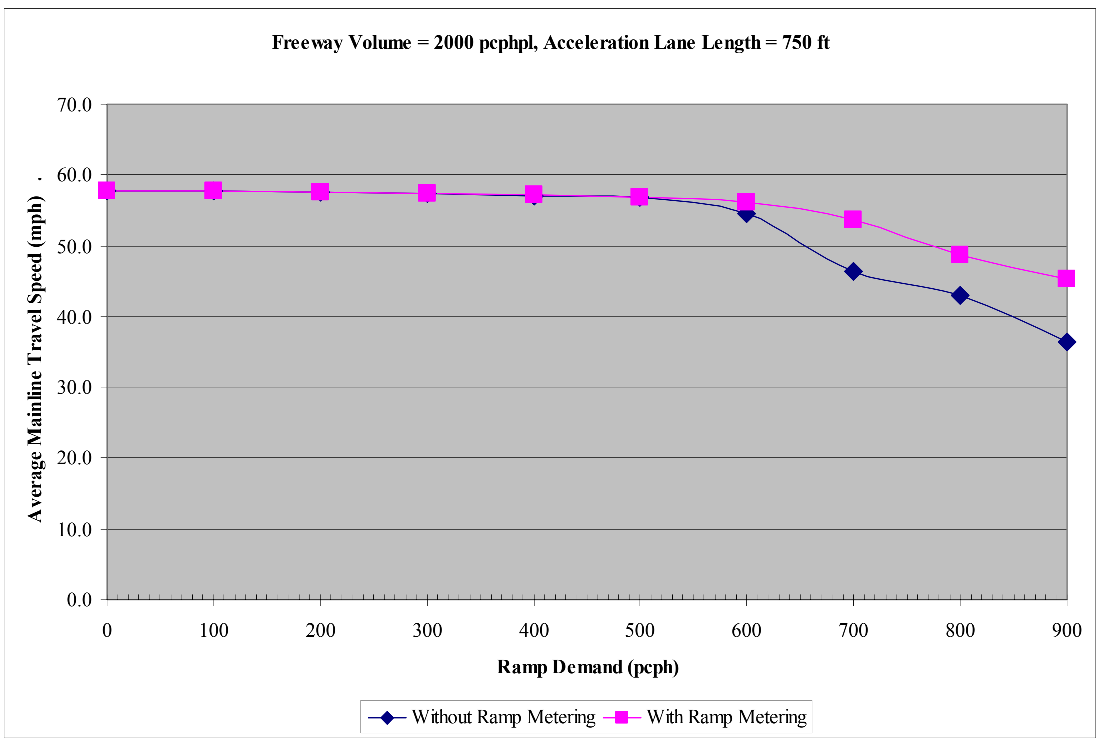

Figure A-16. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2000 pcphpl, Ramp Acceleration Lane Length = 750 ft.

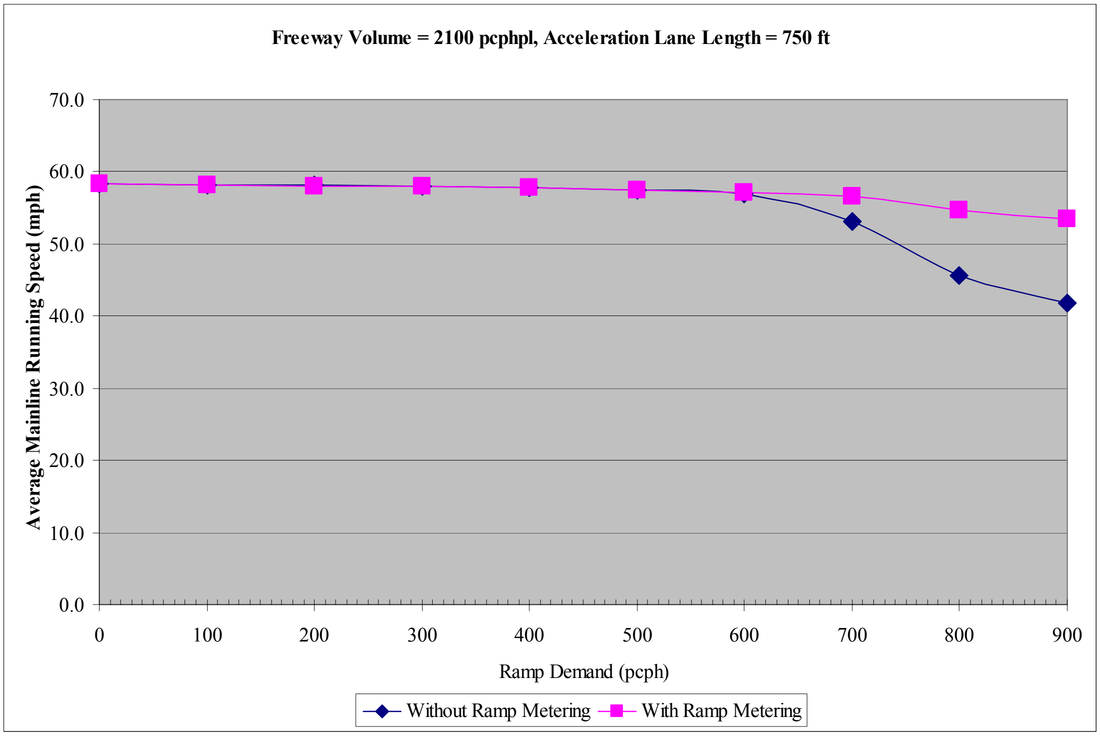

Figure A-17. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2100 pcphpl, Ramp Acceleration Lane Length = 750 ft.

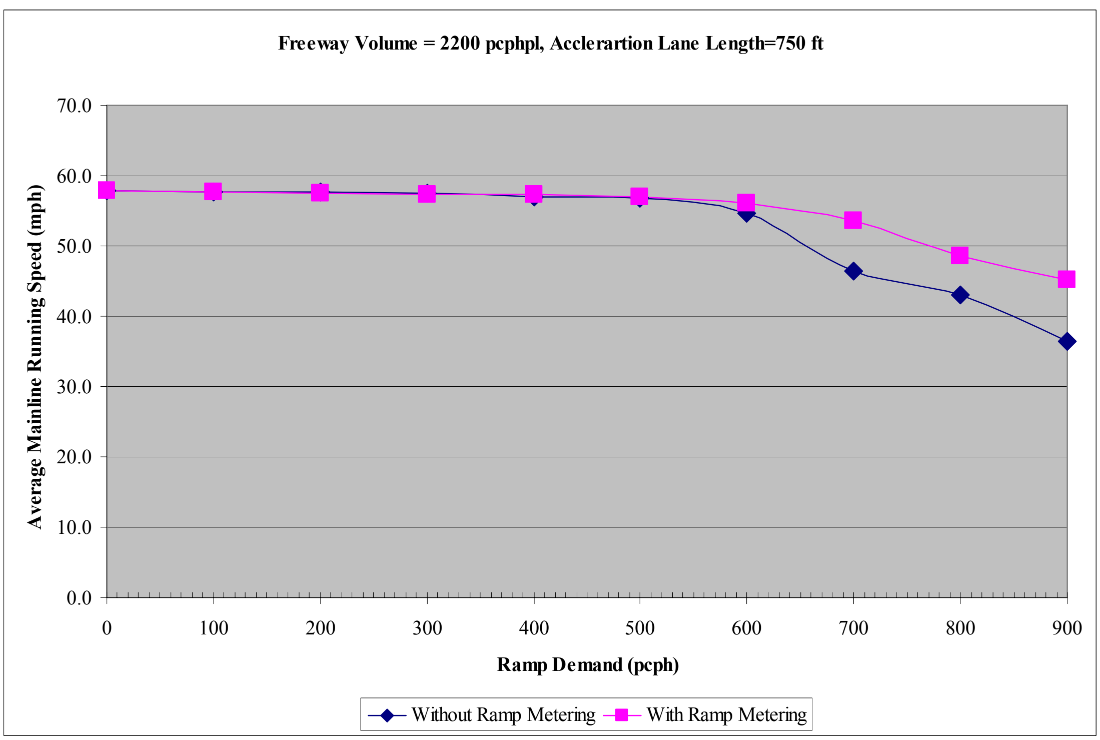

Figure A-18. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2200 pcphpl, Ramp Acceleration Lane Length = 750 ft.

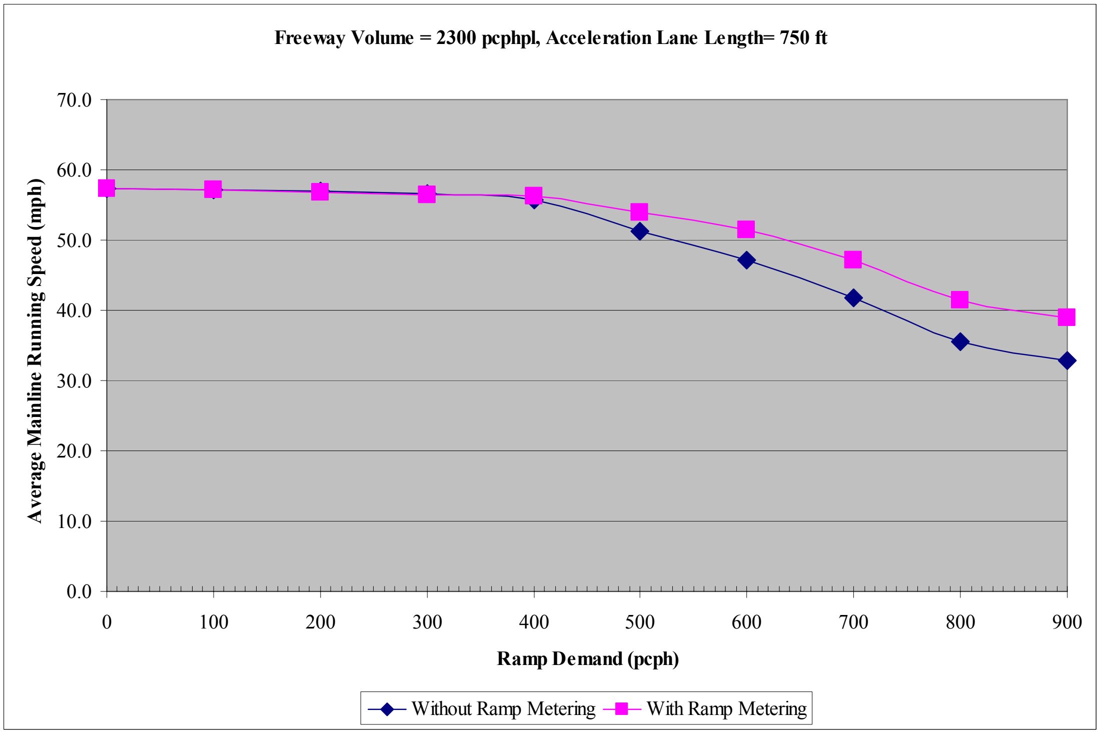

Figure A-19, Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2300 pcphpl, Ramp Acceleration Lane Length = 750 ft.

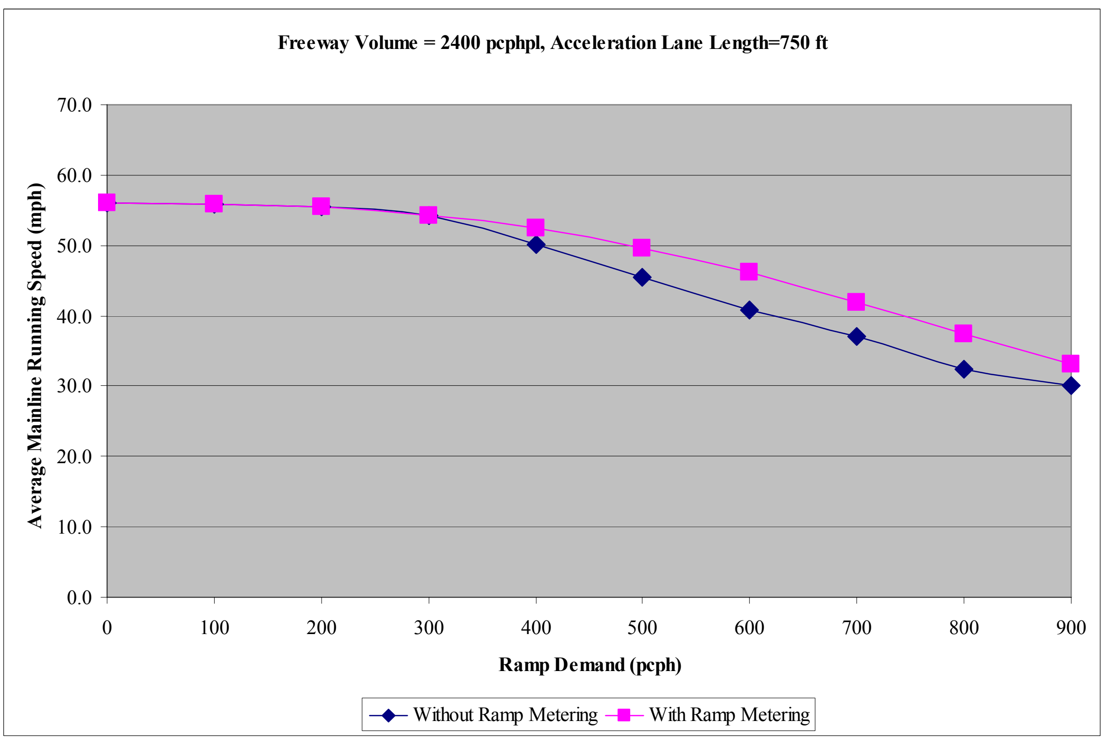

Figure A-20. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2400 pcphpl, Ramp Acceleration Lane Length = 750 ft.

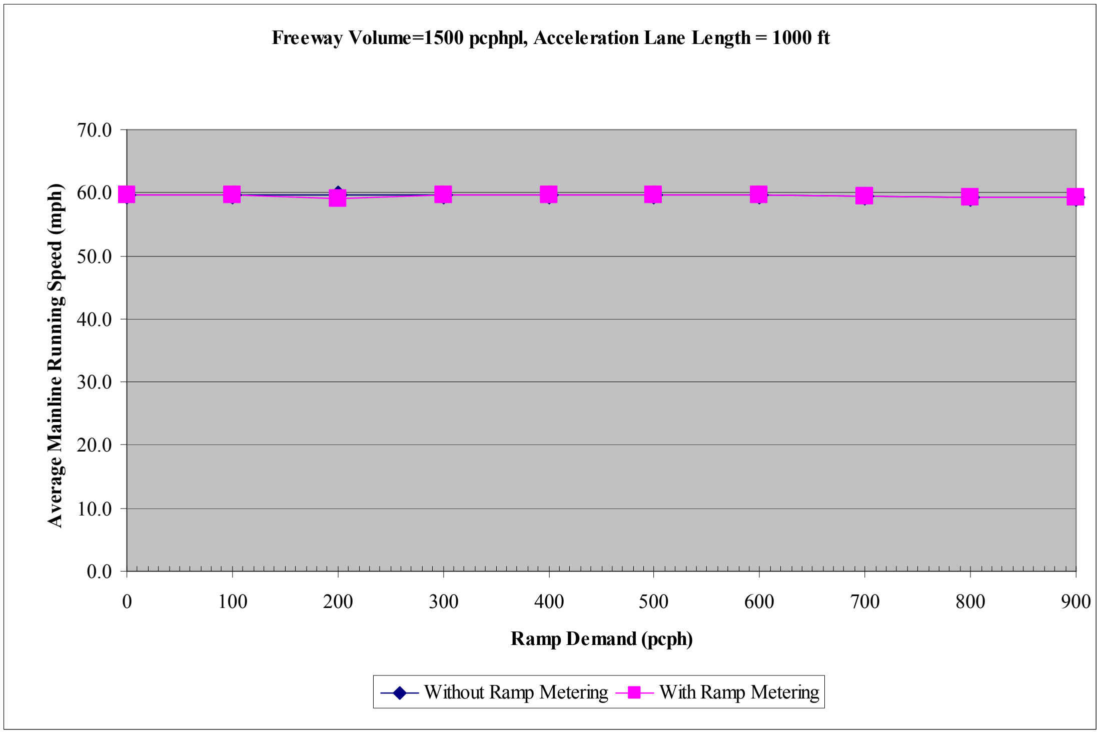

Figure A-21. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

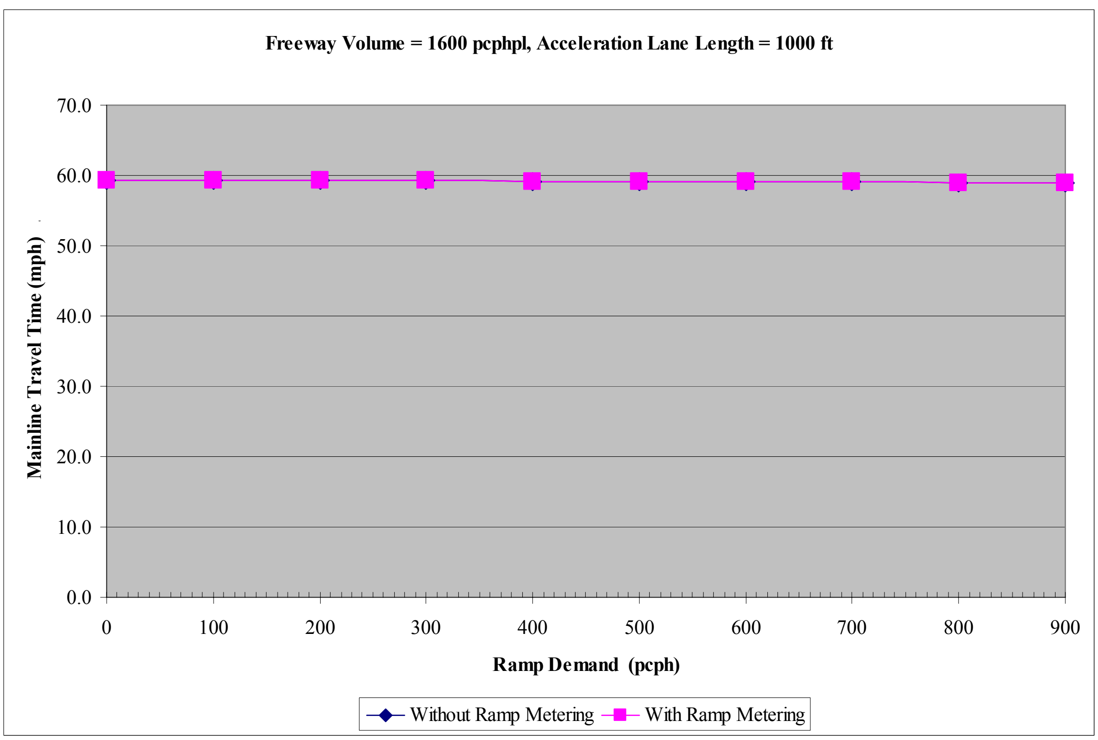

Figure A-22. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1600 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

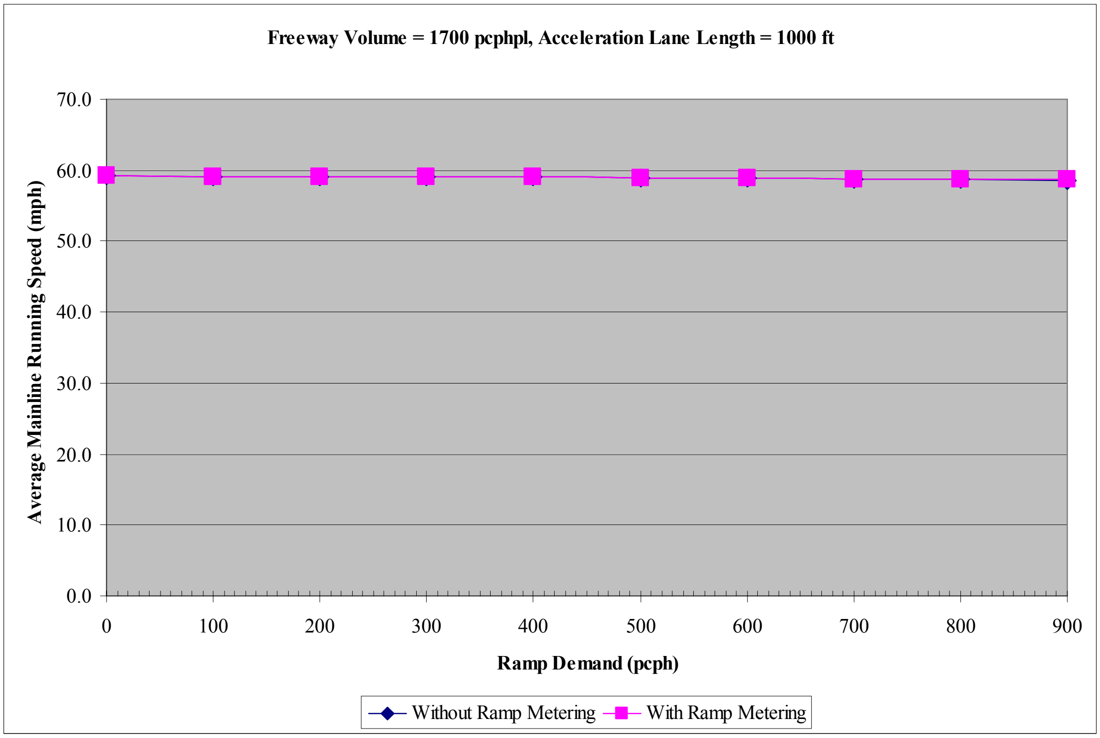

Figure A-23. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1700 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

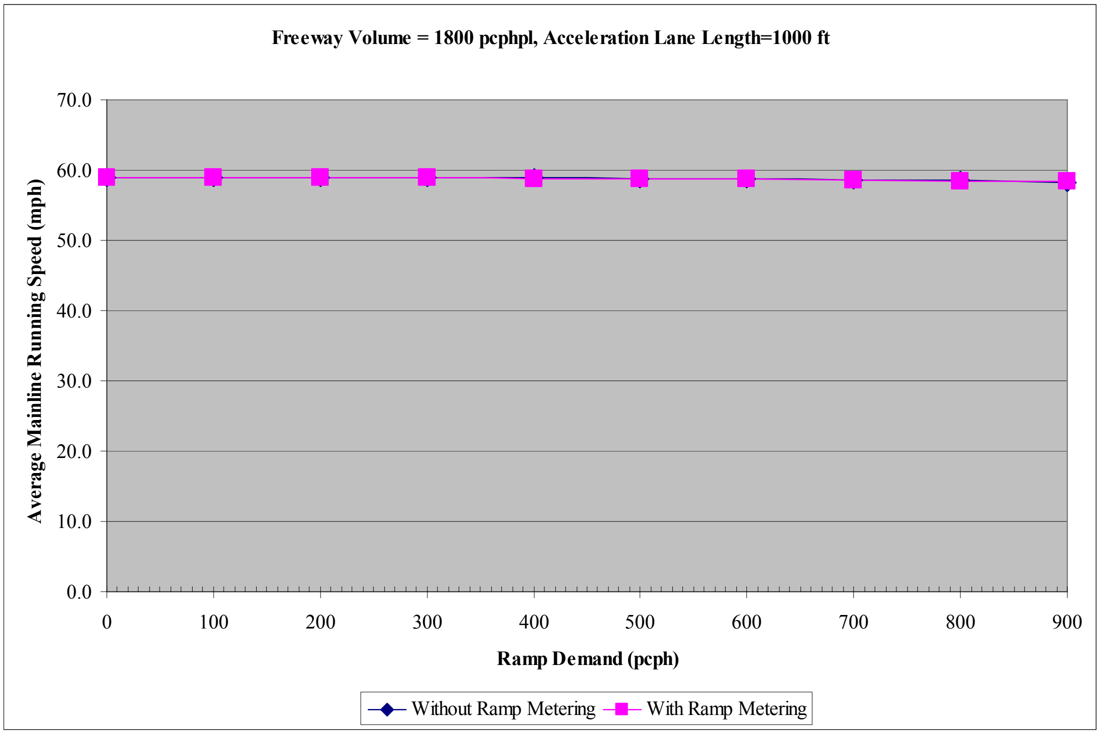

Figure A-24. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1800 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

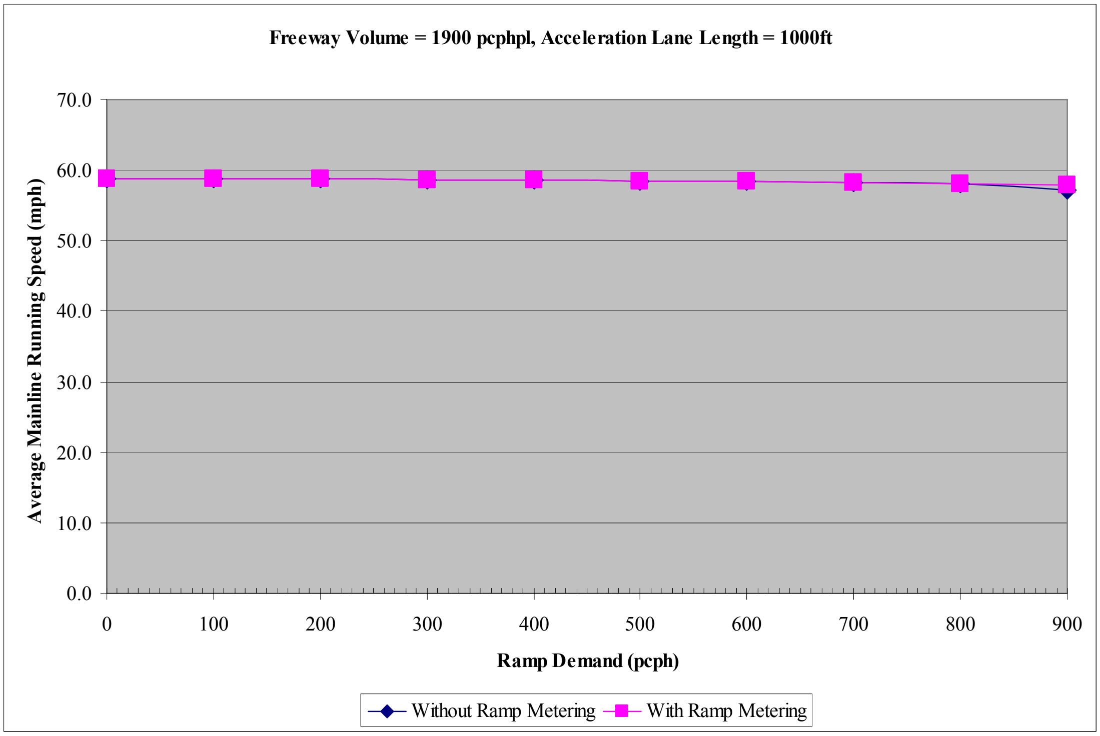

Figure A-25. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1900 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

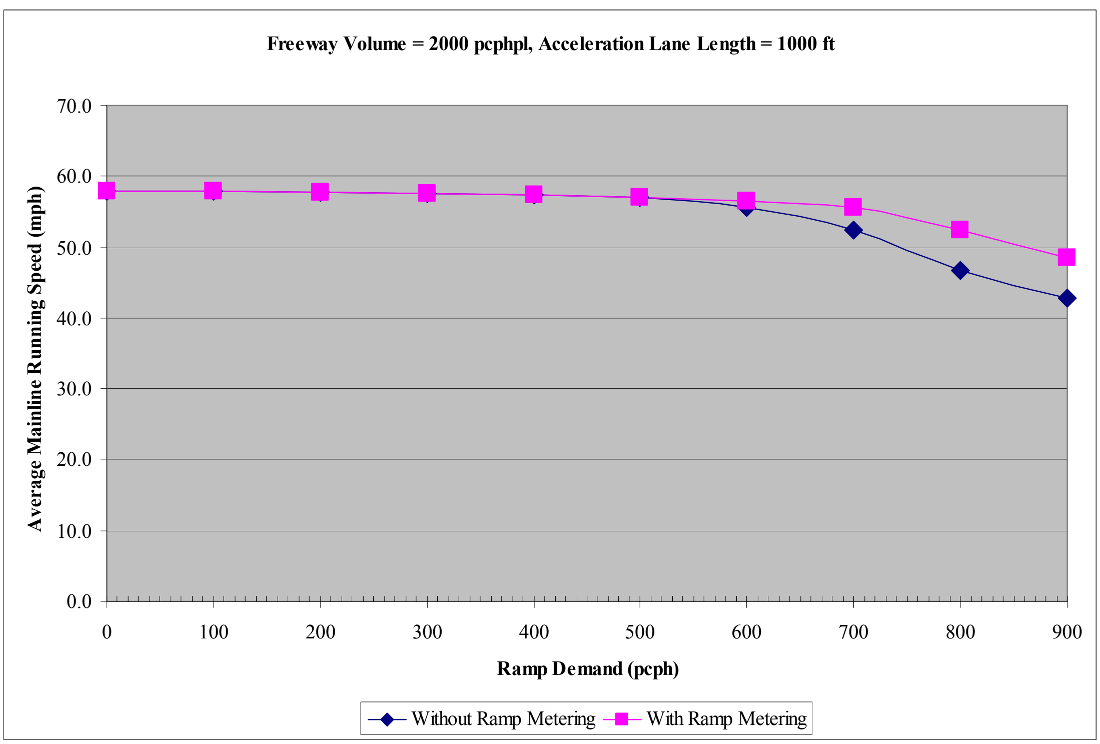

Figure A-26. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2000 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

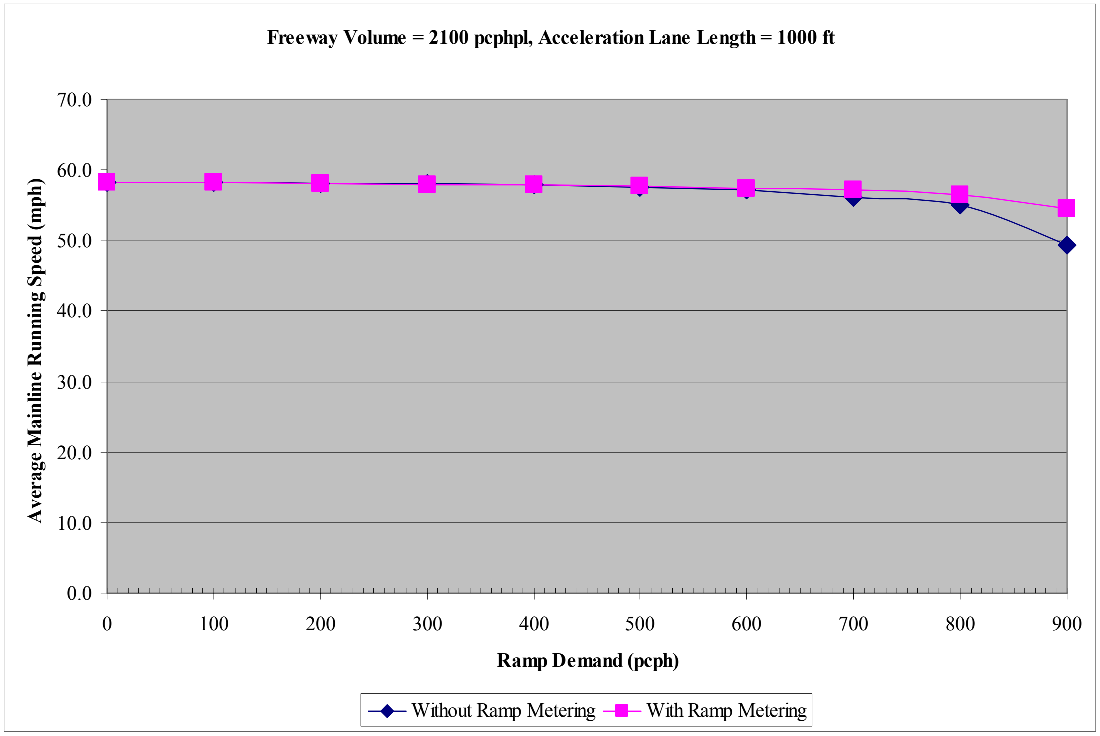

Figure A-27. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2100 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

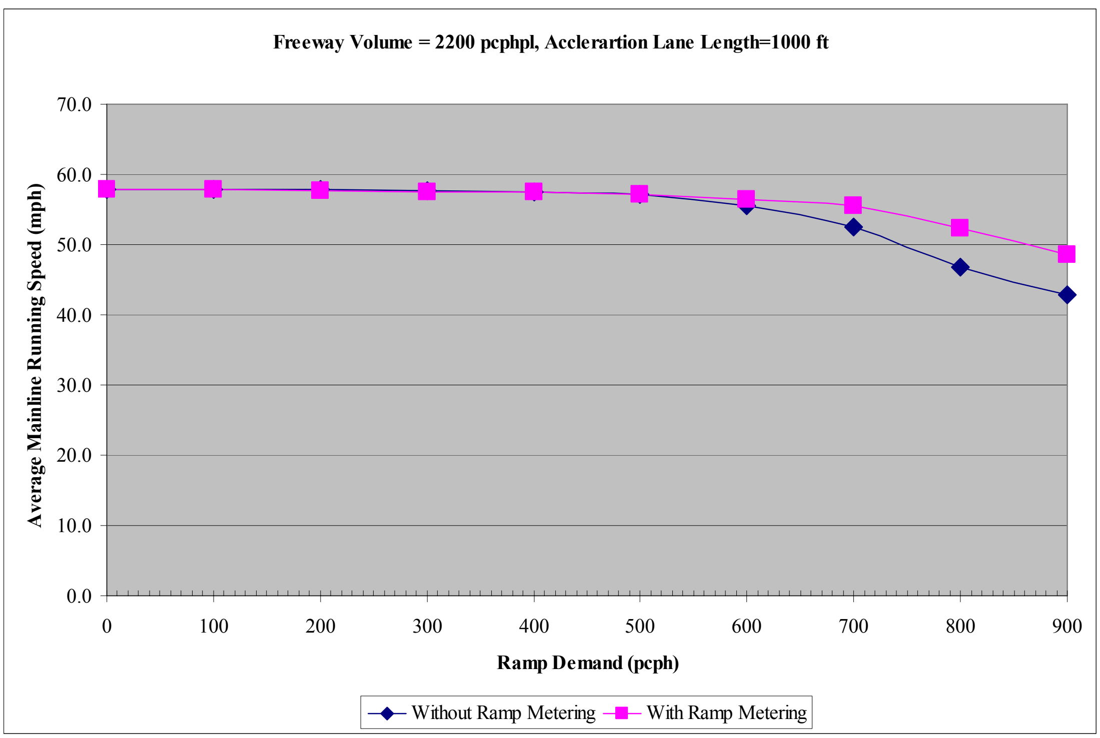

Figure A-28. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2200 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

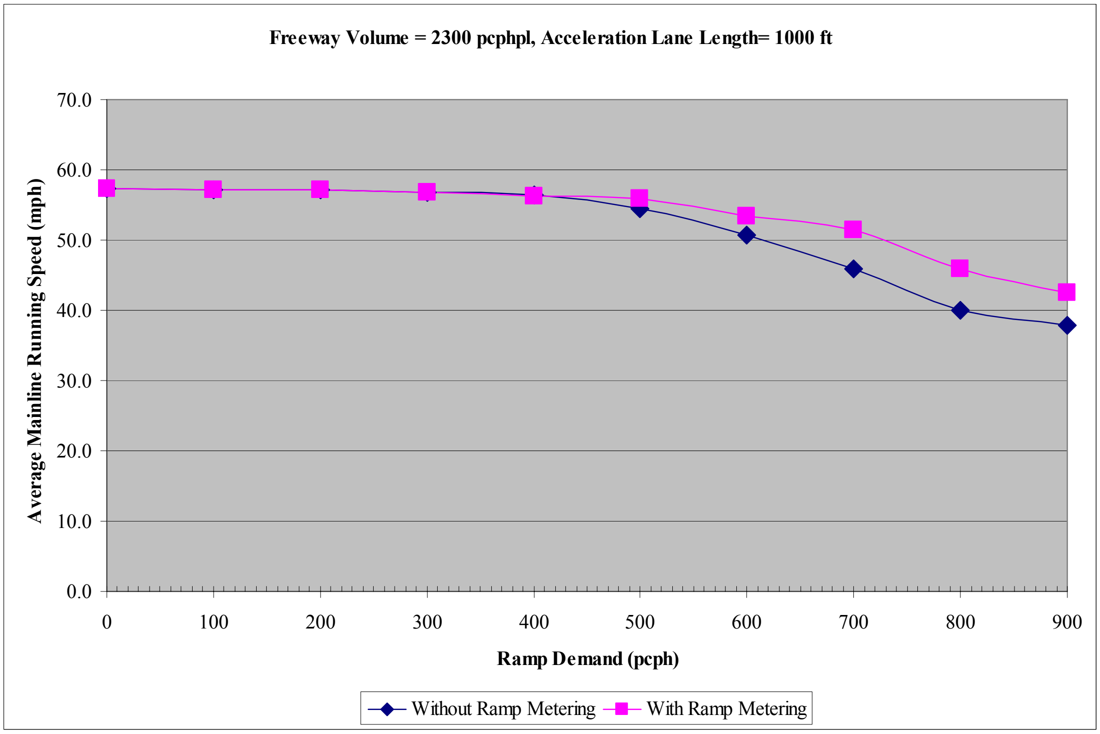

Figure A-29. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2300 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

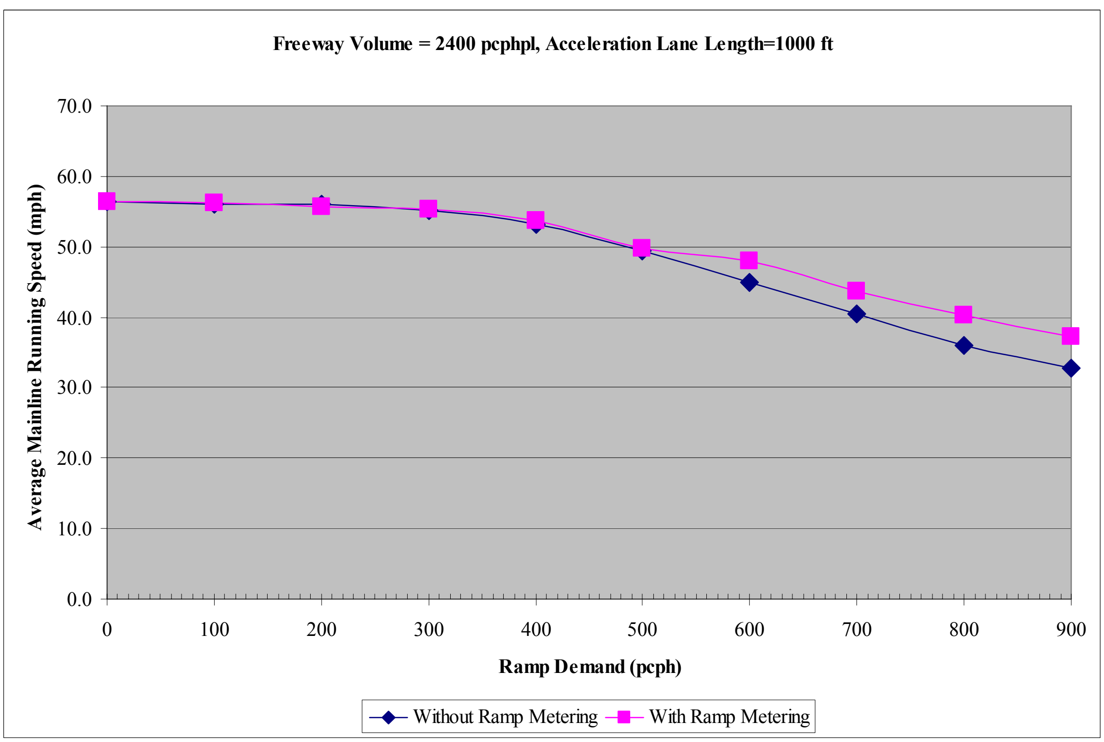

Figure A-30. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2400 pcphpl, Ramp Acceleration Lane Length = 1000 ft.

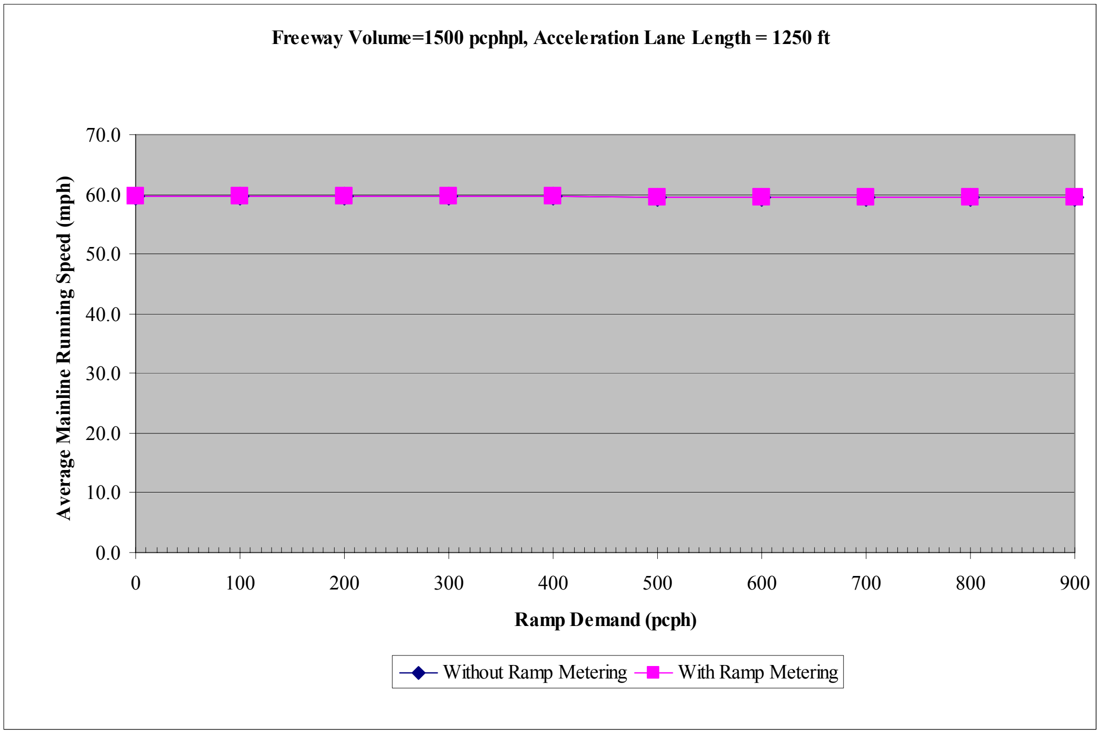

Figure A-31. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

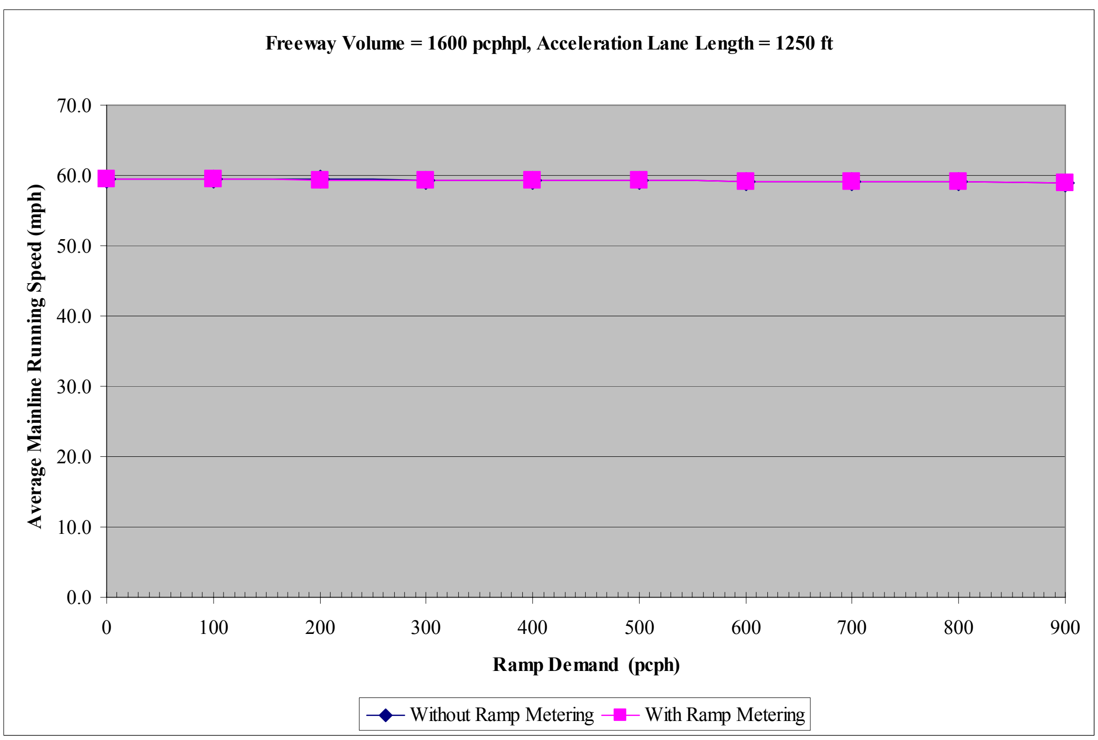

Figure A-32. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1600 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

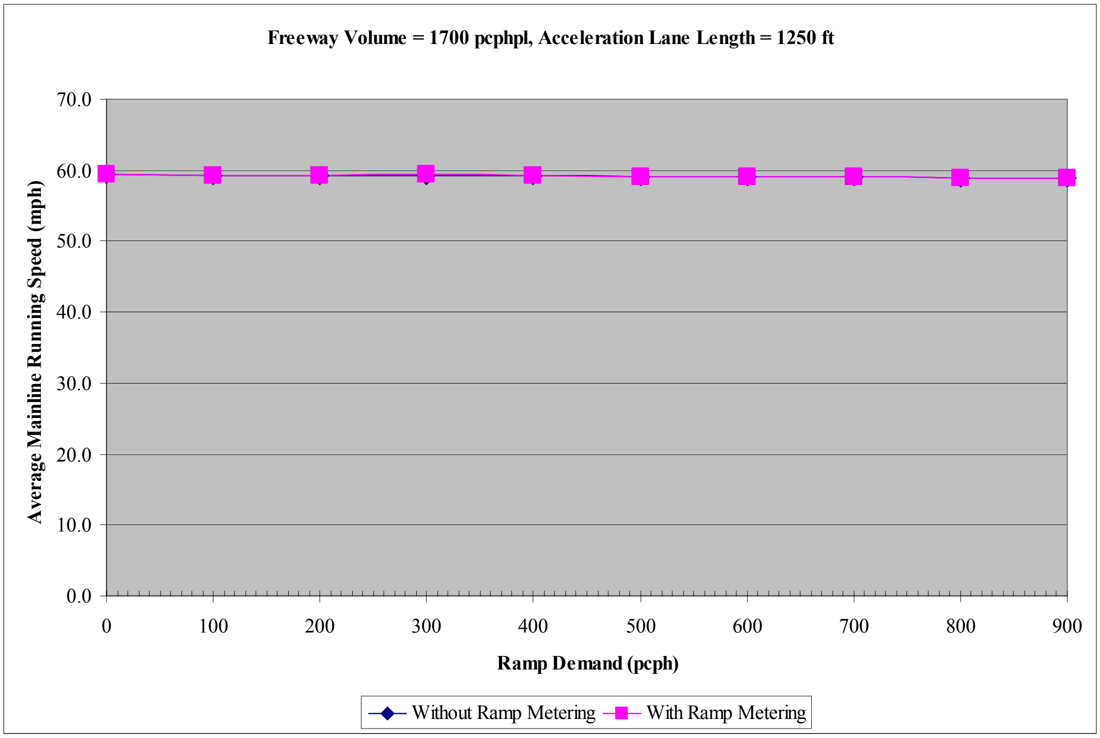

Figure A-33. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1700 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

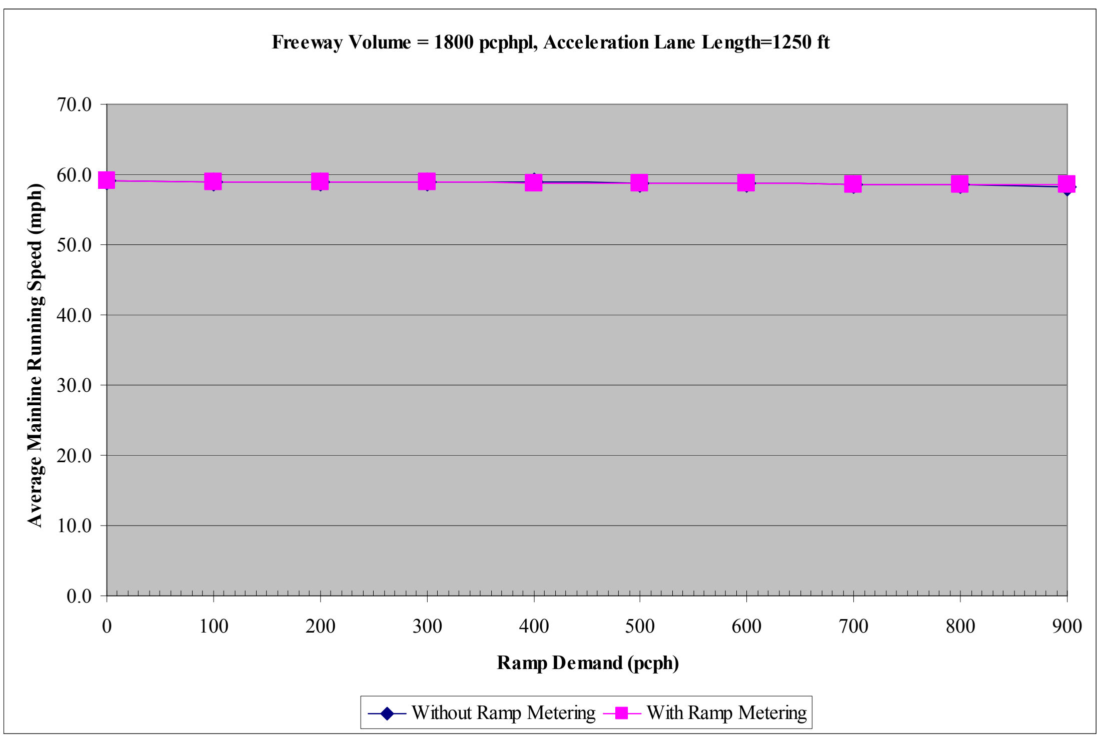

Figure A-34. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1800 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

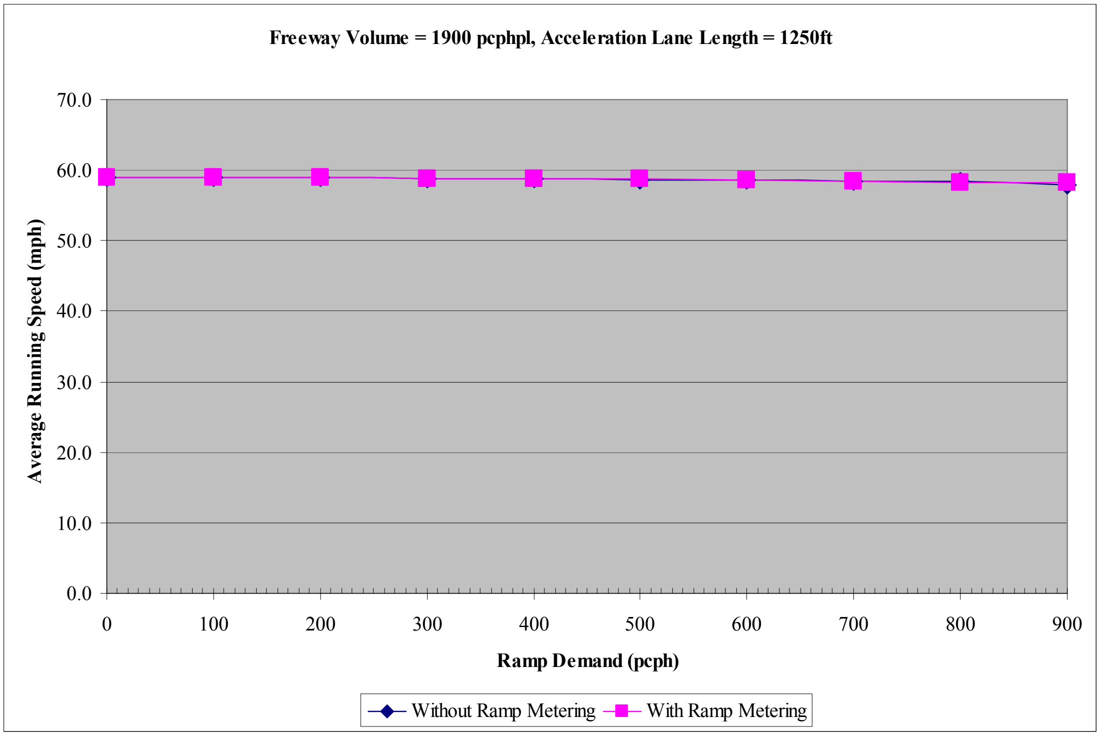

Figure A-35. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1900 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

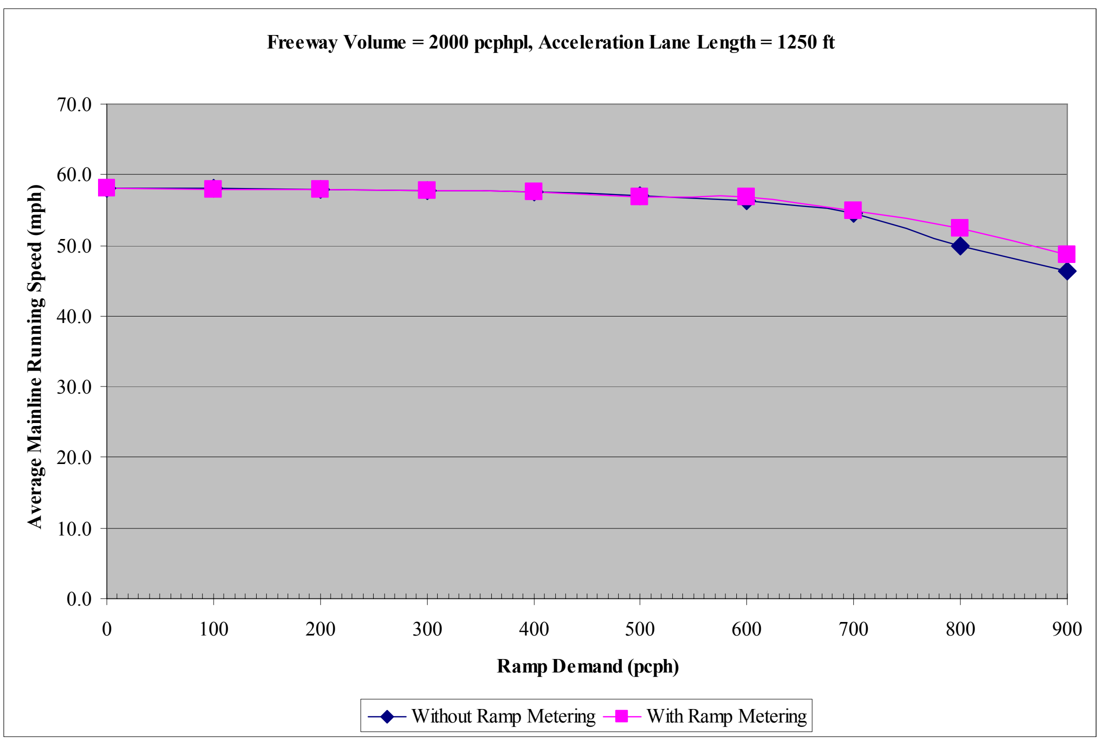

Figure A-36. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2000 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

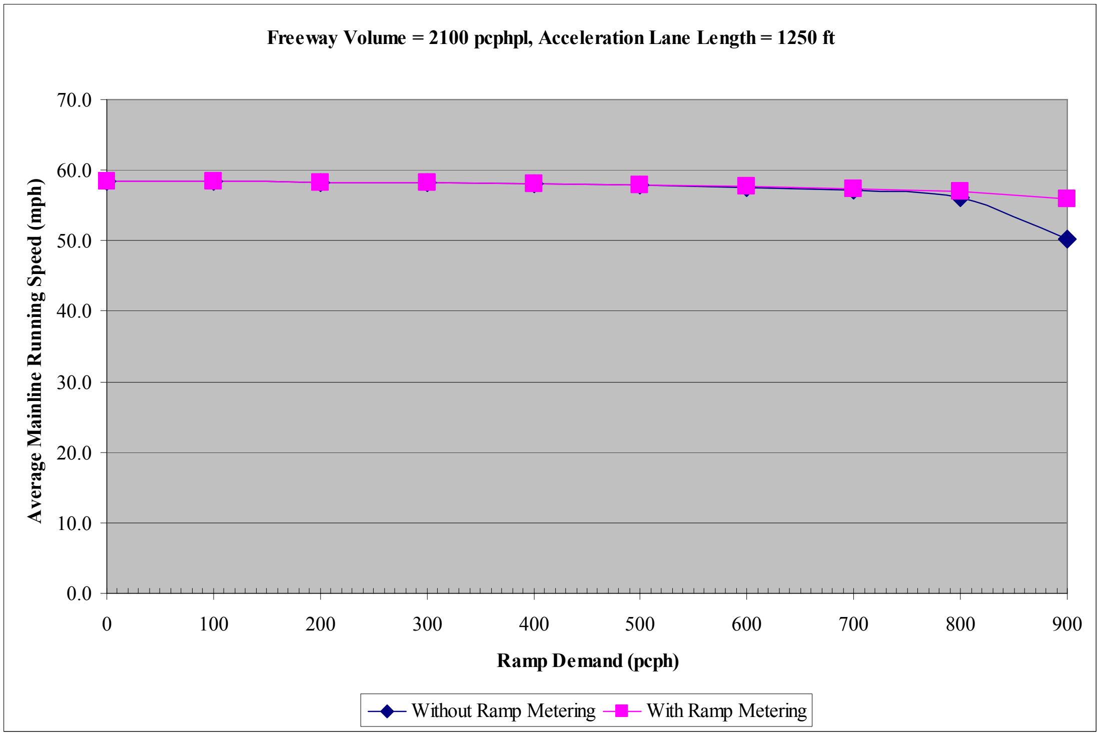

Figure A-37. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2100 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

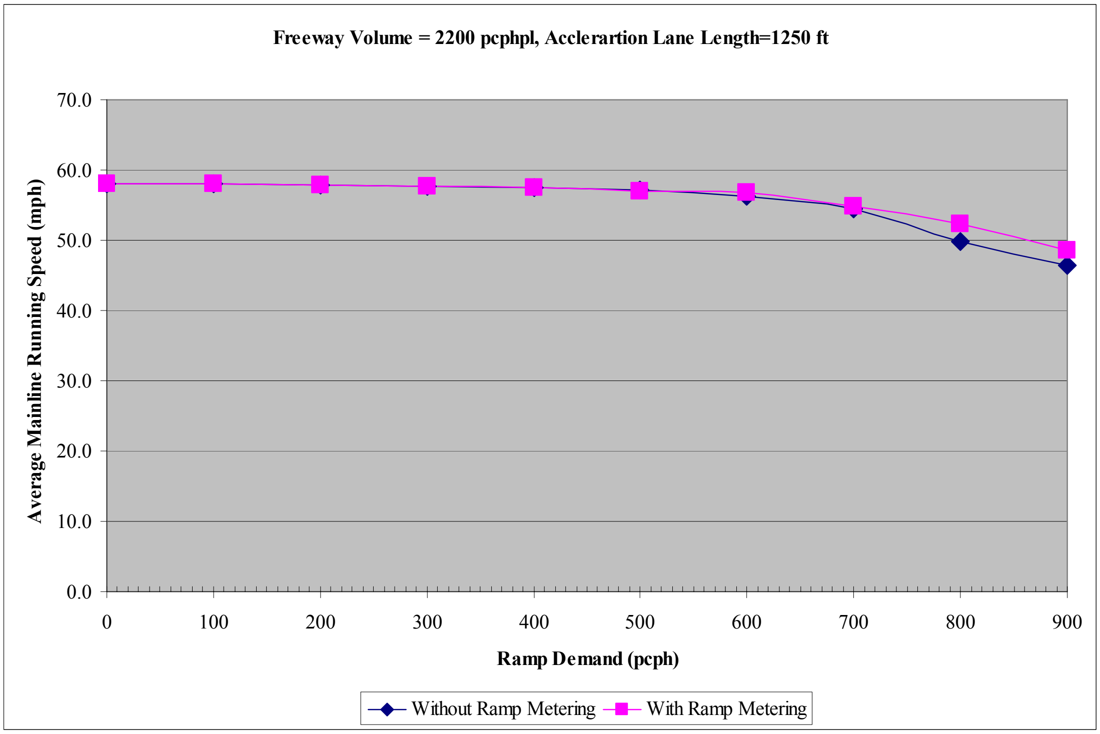

Figure A-38. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2200 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

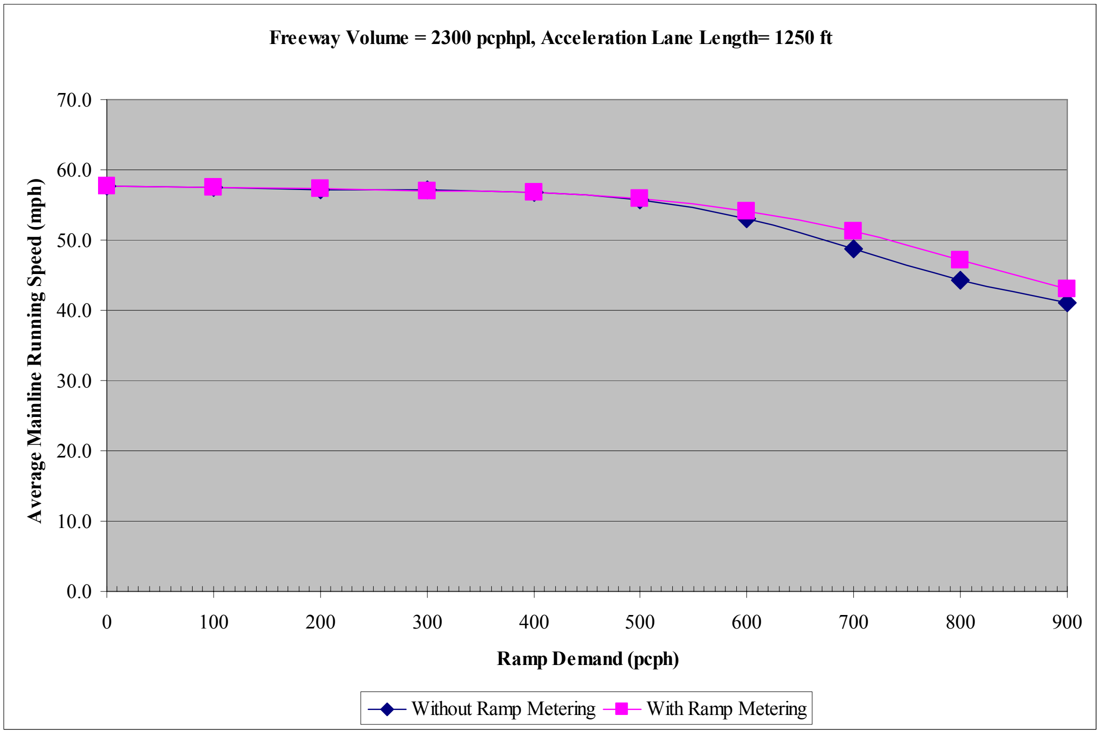

Figure A-39. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2300 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

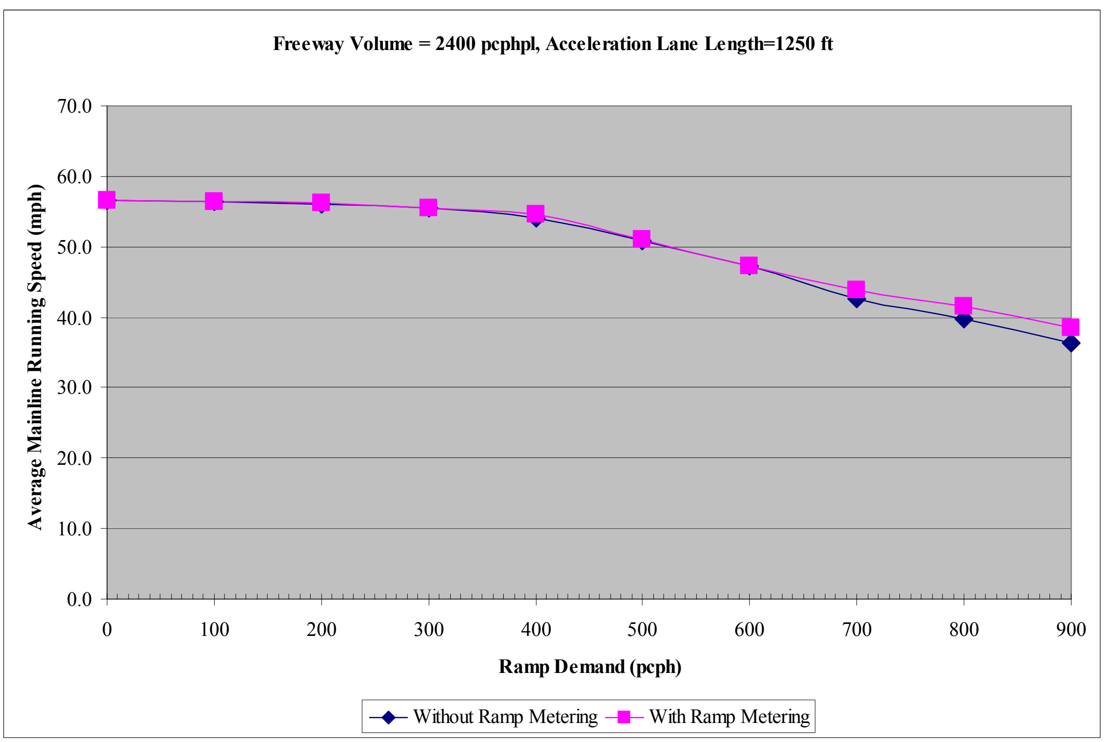

Figure A-40. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2400 pcphpl, Ramp Acceleration Lane Length = 1250 ft.

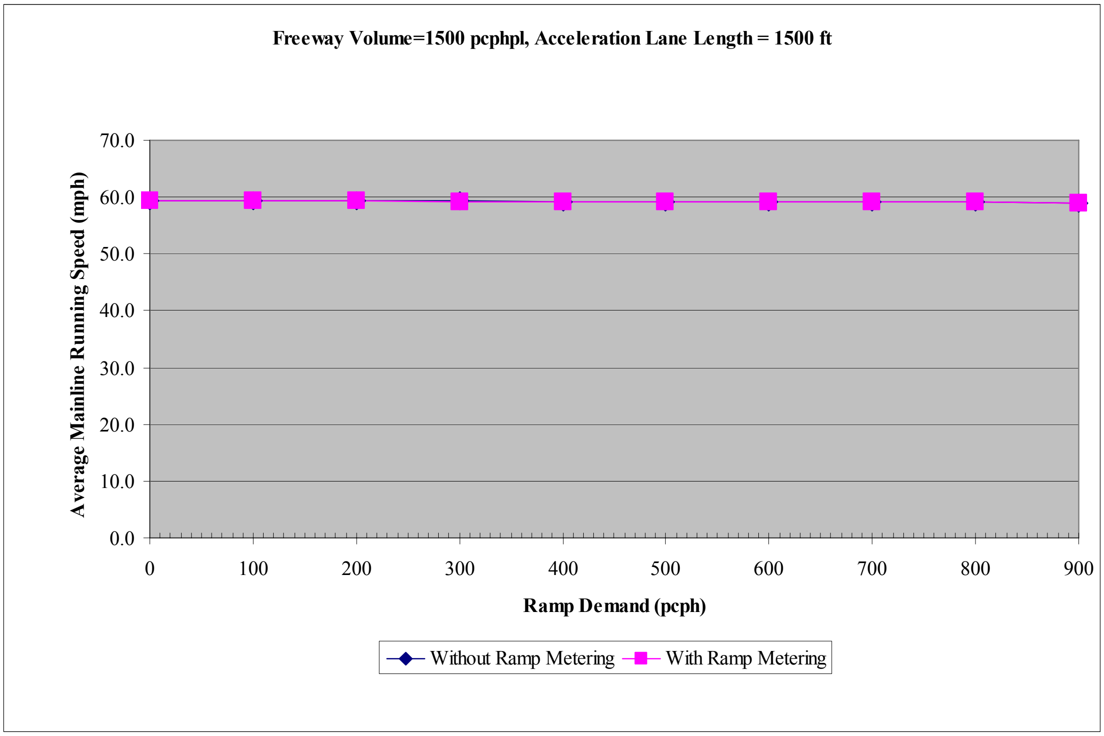

Figure A-41. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

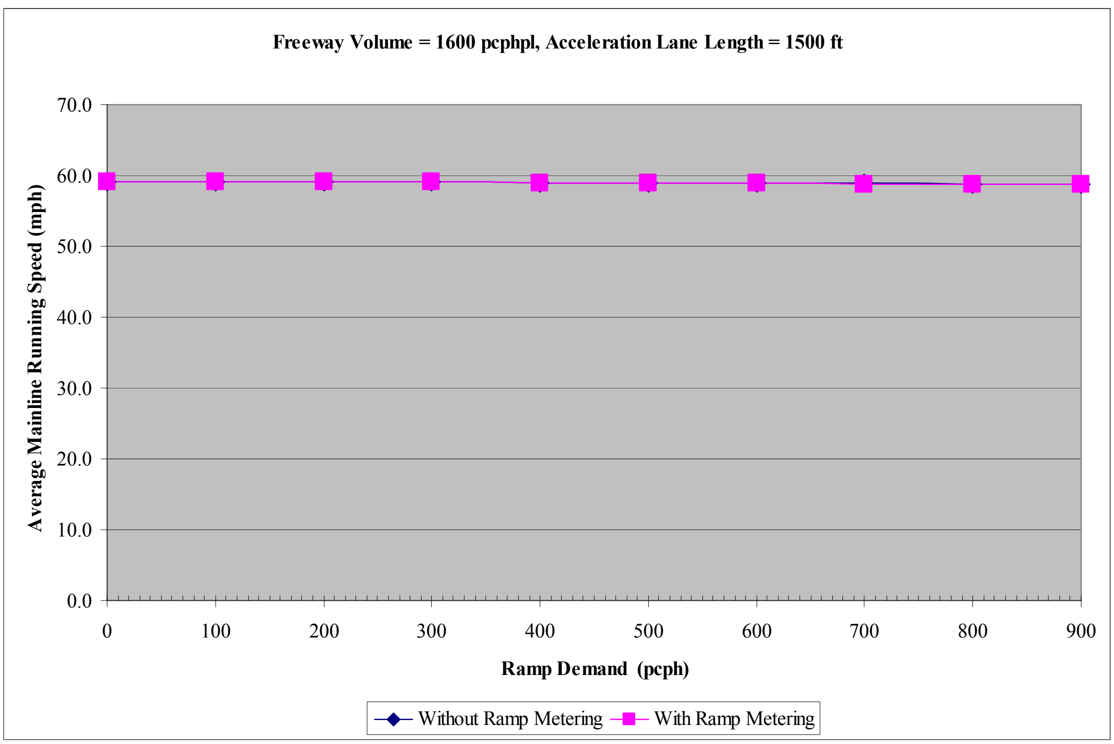

Figure A-42. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1600 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

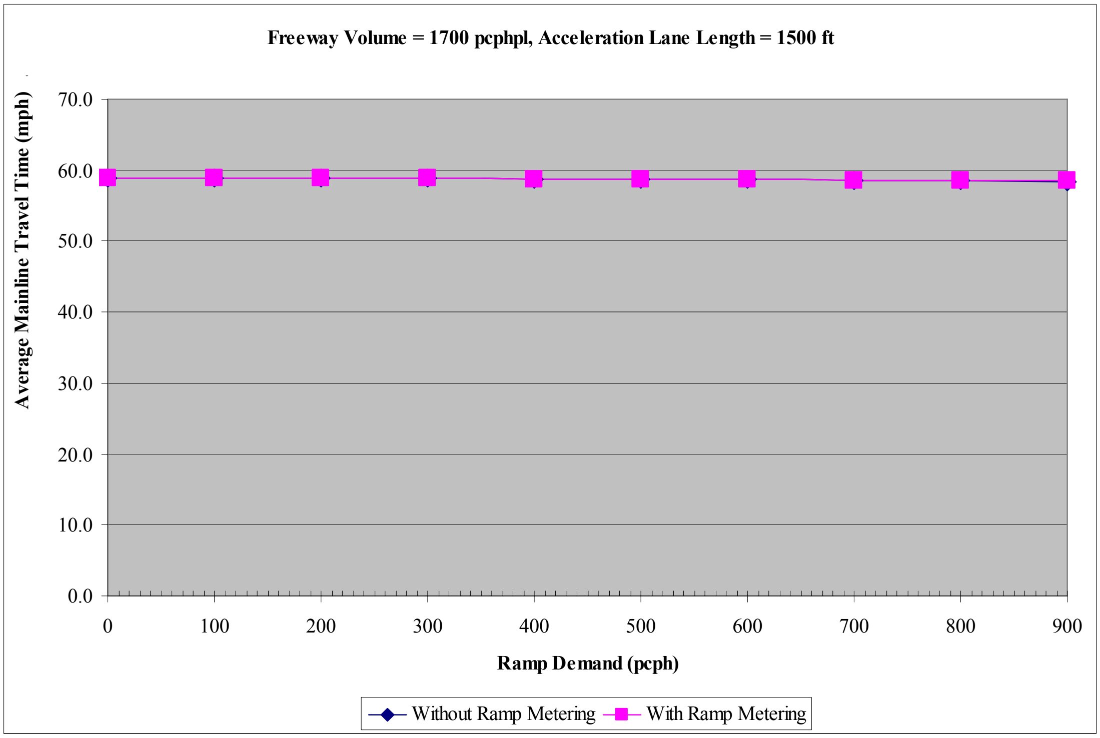

Figure A-43. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1700 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

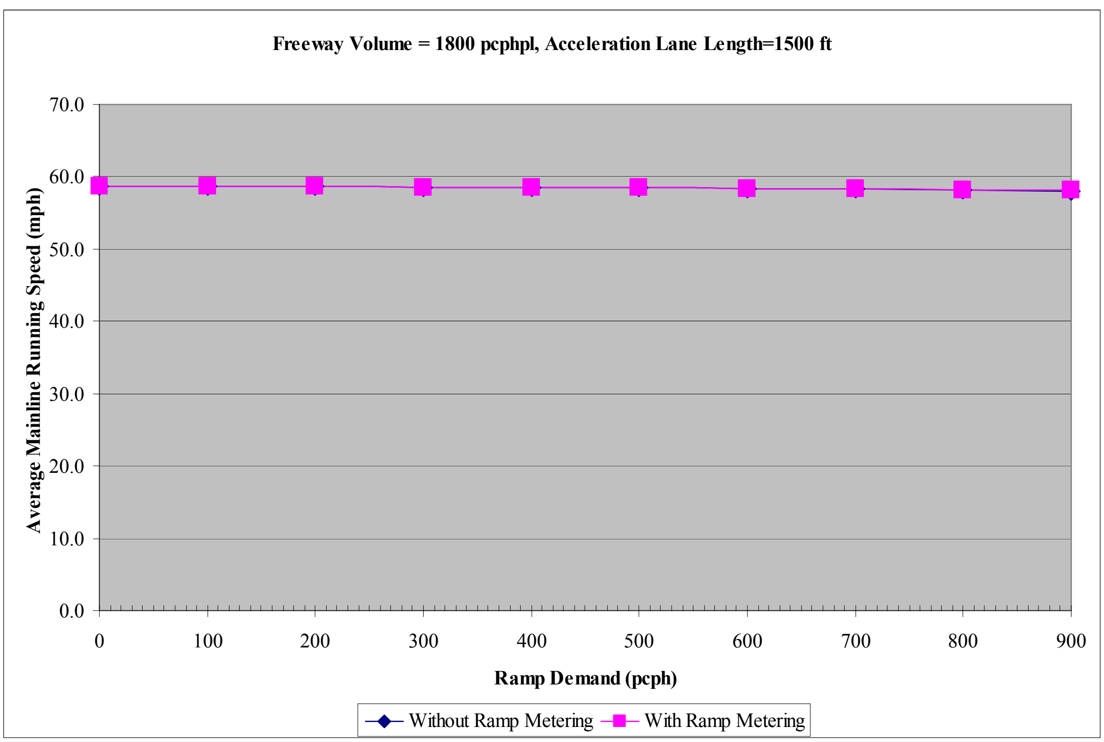

Figure A-44. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1800 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

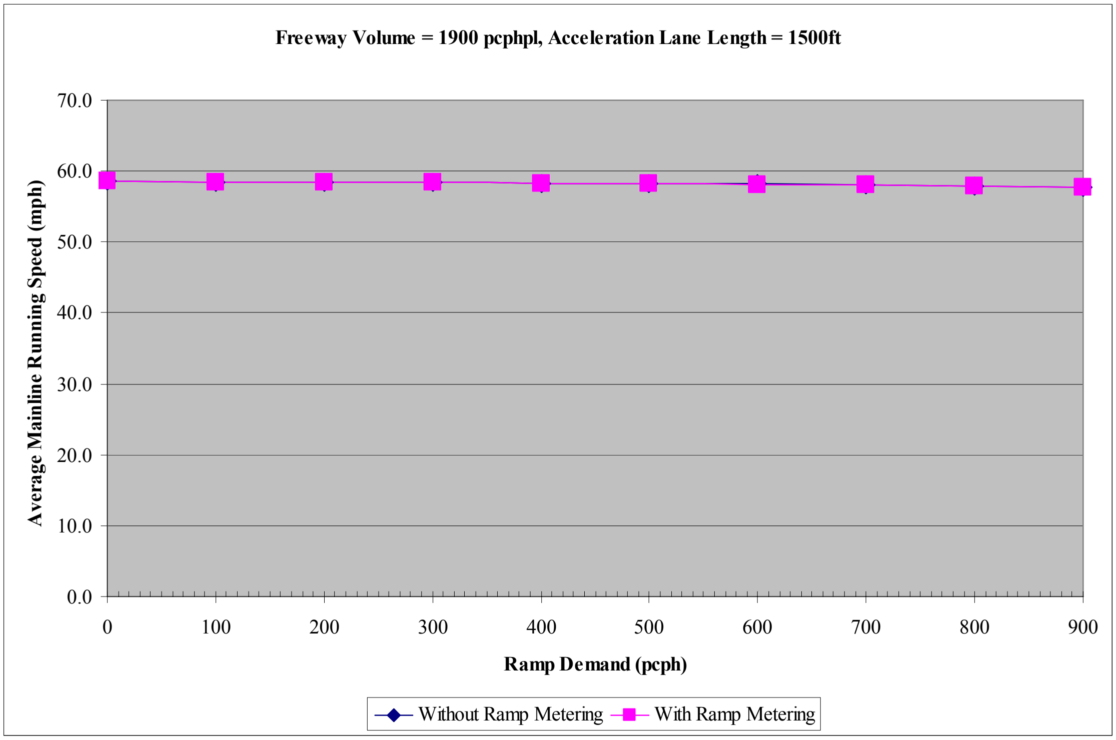

Figure A-45. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1900 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

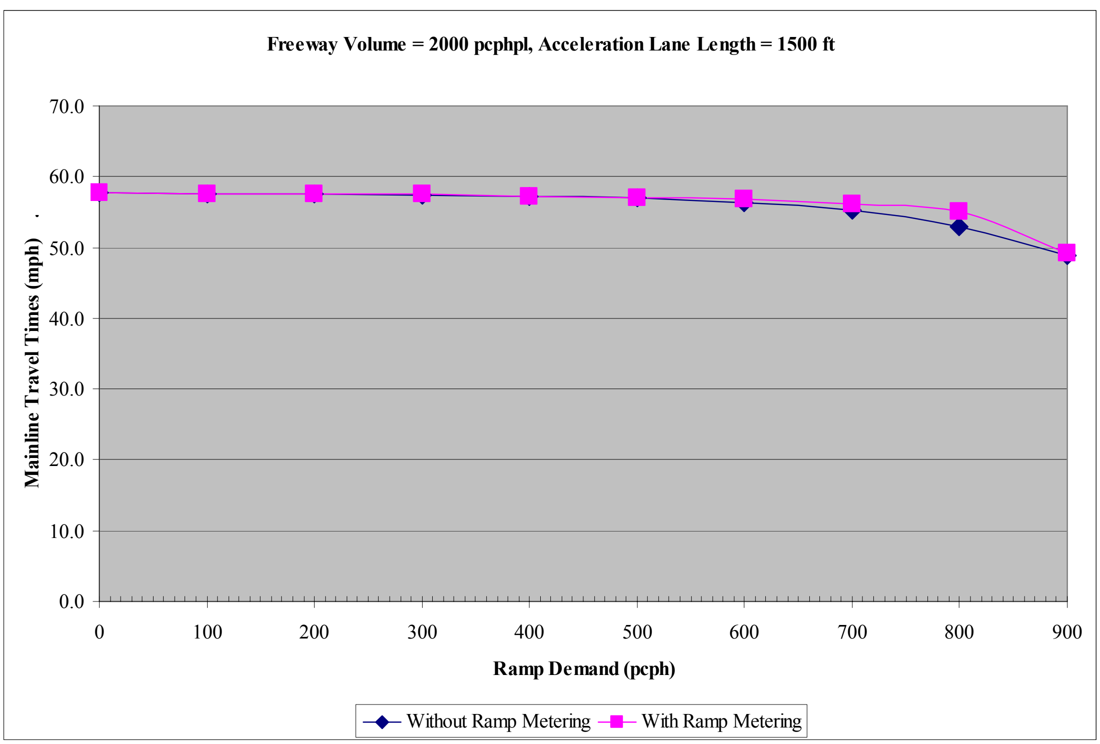

Figure A-46. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 1500 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

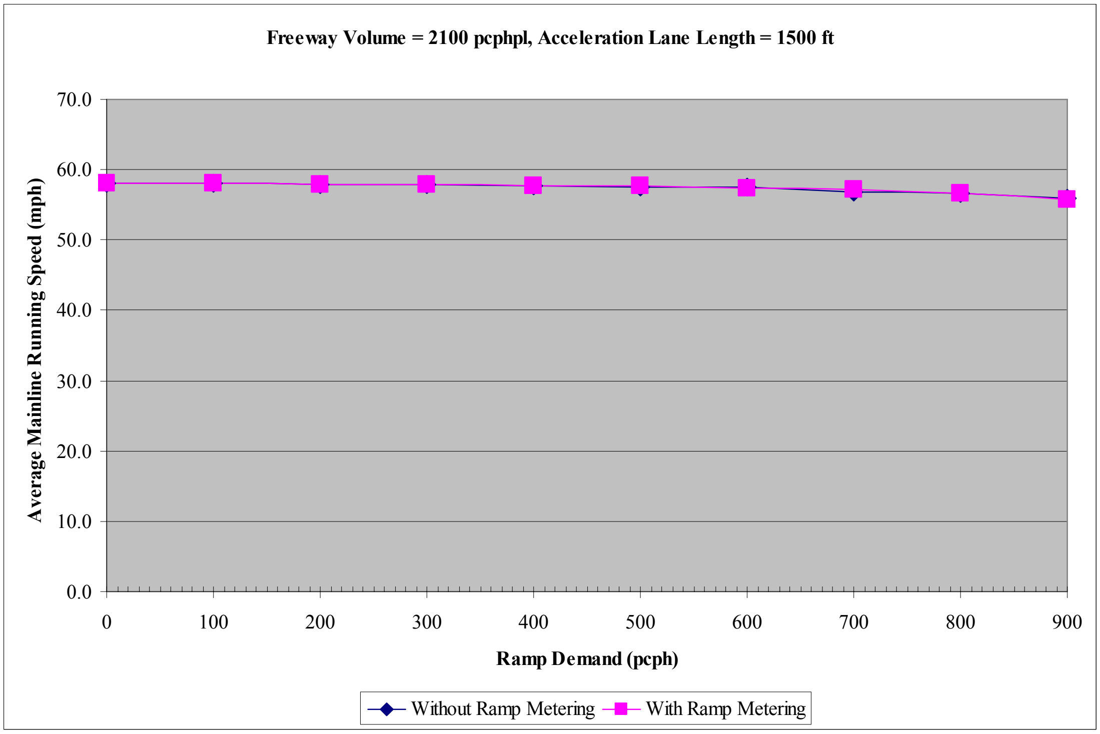

Figure A-47. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2100 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

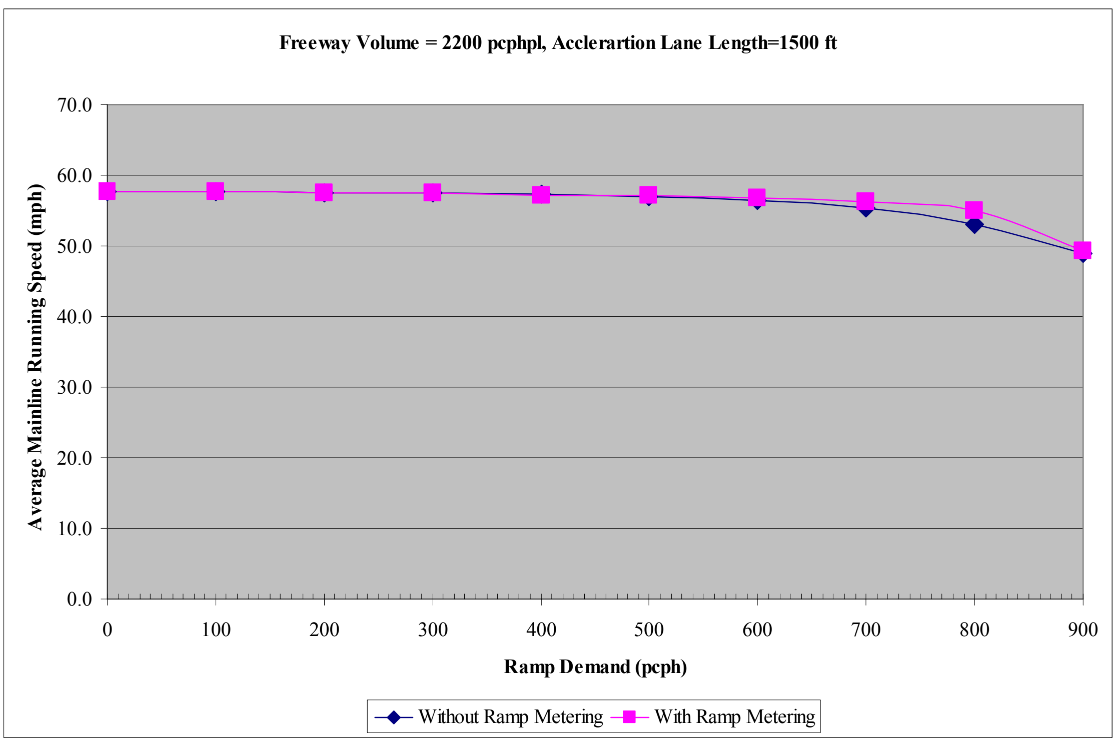

Figure A-48. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2200 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

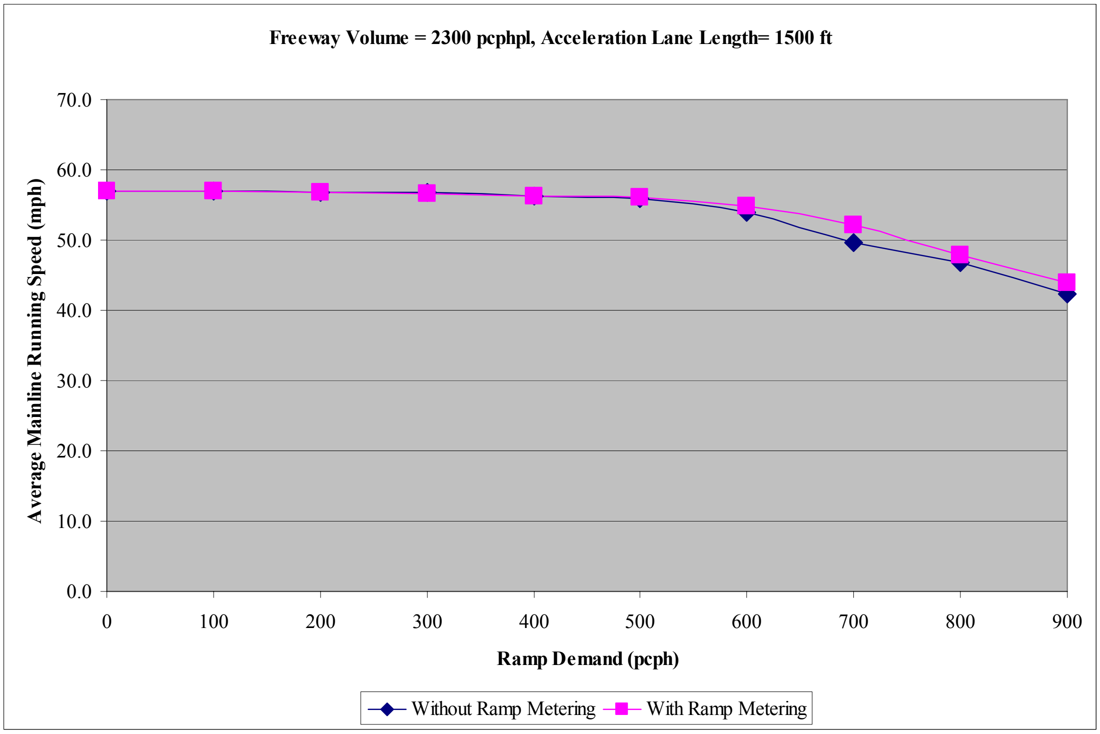

Figure A-49. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2300 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

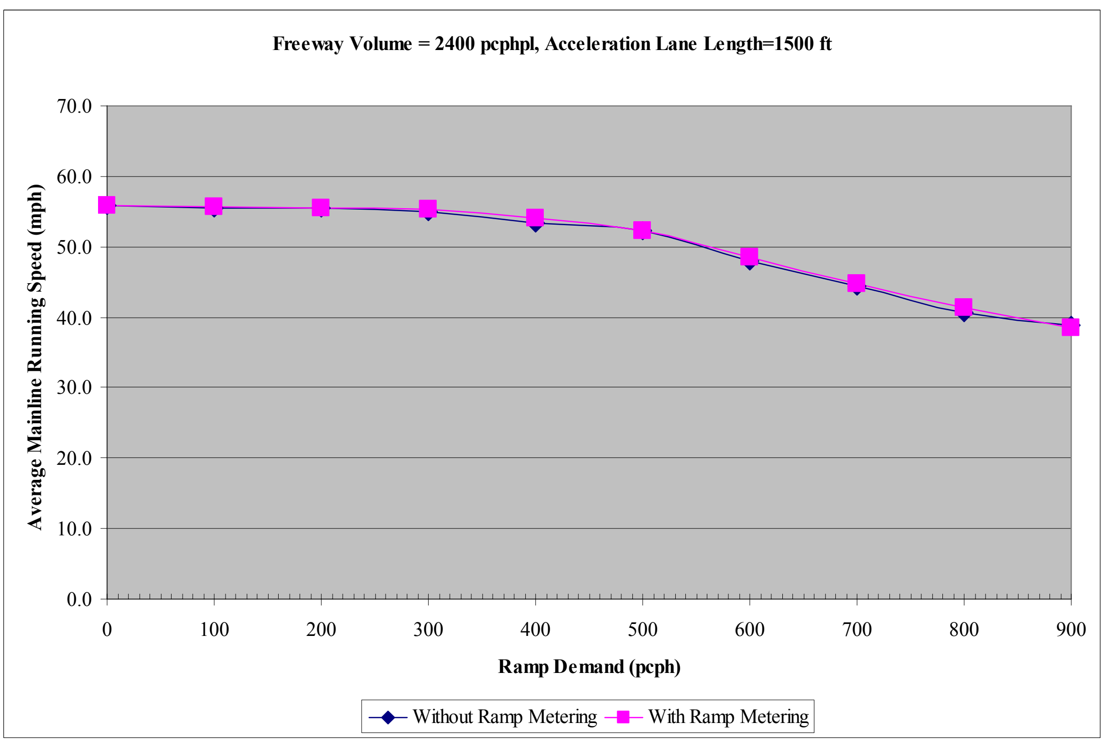

Figure A-50. Comparison of Average Mainlane Running Speed with and without Ramp Meter Active – Freeway Volume = 2400 pcphpl, Ramp Acceleration Lane Length = 1500 ft.

APPENDIX B: SIMULATION OUTPUT FOR MANAGED LANES FACILITY PREFERENCE

Table B-1. Ramp Merge Conditions – Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(63)	66(64)	64(61)	66(63)	65(61)	66(63)	65(62)	65(62)	63(59)
		188 vph	66(64)	65(63)	66(64)	65(62)	65(63)	63(61)	66(63)	65(62)	66(62)	63(60)	65(61)	59(55)
	750 vph	188 vph	66(64)	63(60)	65(63)	62(59)	65(63)	55(49)	65(62)	64(60)	65(63)	63(59)	65(62)	56(52)
		375 vph	65(63)	62(59)	65(62)	58(56)	63(60)	43(38)	64(61)	60(56)	64(60)	57(52)	63(59)	40(33)
90% Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(62)	66(63)	63(60)	66(62)	65(61)	66(63)	64(61)	65(62)	63(59)
		188 vph	66(64)	65(62)	66(63)	64(62)	66(63)	62(59)	66(62)	64(60)	65(62)	63(59)	65(61)	60(56)
	750 vph	188 vph	65(63)	62(59)	65(63)	60(57)	65(62)	40(34)	65(62)	62(57)	65(62)	62(58)	64(61)	49(43)
		375 vph	64(62)	60(57)	63(61)	53(49)	62(59)	40(35)	64(60)	57(52)	64(60)	55(50)	61(57)	40(33)
85% Auto	375 vph	94 vph	66(64)	65(62)	66(64)	65(62)	66(63)	64(62)	66(63)	65(62)	66(63)	65(62)	65(62)	63(59)
		188 vph	66(64)	65(62)	66(64)	64(62)	65(63)	62(60)	66(63)	64(60)	65(62)	62(57)	65(62)	60(56)
	750 vph	188 vph	65(63)	62(59)	65(63)	63(60)	65(63)	44(40)	65(62)	63(59)	65(62)	62(59)	64(61)	46(40)
		375 vph	65(62)	59(56)	64(62)	56(54)	63(60)	37(32)	64(60)	59(55)	64(60)	55(51)	62(58)	39(33)
No Auto	375 vph	94 vph	65(59)	60(55)	65(60)	60(51)	64(58)	50(43)	64(58)	61(54)	65(59)	59(51)	64(58)	53(45)
		188 vph	62(56)	53(45)	62(58)	49(41)	60(53)	36(29)	62(57)	53(45)	62(55)	47(37)	62(56)	38(29)
	750 vph	188 vph	42(31)	39(26)	46(36)	36(26)	43(34)	35(25)	59(49)	46(31)	57(45)	43(29)	54(47)	38(27)
		375 vph	37(28)	39(26)	36(27)	32(25)	33(25)	31(25)	44(35)	38(26)	40(31)	36(26)	37(28)	36(26)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-2. Ramp Merge Conditions – Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	65(62)	66(64)	64(61)	66(63)	61(58)	66(62)	64(61)	65(63)	63(59)	65(62)	54(51)
		188 vph	66(64)	65(62)	66(63)	63(60)	65(62)	59(57)	65(62)	63(59)	65(62)	61(58)	65(61)	51(47)
	750 vph	188 vph	65(63)	60(56)	64(62)	55(51)	64(61)	41(34)	65(62)	61(56)	65(61)	60(56)	64(60)	44(35)
		375 vph	65(62)	58(55)	64(61)	55(52)	62(60)	39(32)	64(60)	58(52)	64(60)	52(45)	62(58)	41(33)
90% Auto	375 vph	94 vph	66(64)	65(62)	66(64)	63(59)	65(63)	61(58)	65(63)	64(60)	65(62)	62(58)	65(61)	53(48)
		188 vph	66(64)	64(61)	65(63)	63(59)	65(62)	59(56)	65(62)	63(60)	65(62)	61(56)	64(61)	51(45)
	750 vph	188 vph	65(63)	59(54)	65(62)	51(44)	63(60)	40(32)	65(61)	61(56)	64(60)	55(50)	64(60)	43(34)
		375 vph	64(61)	55(51)	63(60)	63(60)	60(57)	38(31)	63(59)	57(52)	63(58)	48(40)	60(55)	41(32)
85% Auto	375 vph	94 vph	66(64)	64(61)	66(64)	63(59)	65(63)	62(59)	66(63)	64(60)	65(62)	62(58)	65(62)	58(54)
		188 vph	66(64)	64(62)	65(63)	63(60)	65(63)	57(55)	65(61)	63(59)	65(61)	62(58)	64(60)	50(46)
	750 vph	188 vph	65(62)	60(57)	65(62)	53(47)	64(62)	41(34)	65(61)	61(57)	65(61)	58(53)	64(60)	44(36)
		375 vph	64(62)	55(49)	64(60)	45(39)	61(58)	40(33)	64(59)	57(52)	63(59)	51(45)	60(56)	41(34)
No Auto	375 vph	94 vph	64(58)	60(52)	64(58)	49(38)	62(56)	40(30)	64(58)	59(49)	64(58)	53(42)	63(55)	43(31)
		188 vph	62(56)	51(42)	61(55)	41(32)	58(52)	36(28)	61(54)	52(42)	62(54)	42(30)	59(50)	38(28)
	750 vph	188 vph	45(32)	40(25)	43(31)	38(25)	37(27)	37(26)	55(43)	46(28)	54(41)	44(28)	47(34)	41(27)
		375 vph	38(27)	37(25)	36(26)	35(25)	34(25)	33(24)	46(35)	41(27)	42(30)	40(27)	41(30)	38(26)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-3. Ramp Merge Conditions – Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(63)	63(60)	66(63)	62(60)	65(63)	58(54)	66(65)	66(65)	66(65)	66(65)	66(65)	65(63)
		188 vph	65(62)	61(58)	65(62)	59(56)	64(61)	54(51)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	65(62)	61(58)	64(61)	58(56)	63(60)	45(43)	66(65)	65(63)	66(65)	65(63)	66(65)	63(60)
		375 vph	62(59)	54(51)	61(58)	48(46)	59(57)	30(29)	66(64)	64(61)	66(64)	62(60)	65(63)	56(54)
90% Auto	375 vph	94 vph	65(62)	63(60)	65(62)	62(59)	65(63)	60(56)	66(65)	66(64)	66(65)	66(64)	66(65)	65(62)
		188 vph	65(61)	61(58)	65(61)	59(56)	64(60)	51(49)	66(65)	65(64)	66(65)	65(64)	66(65)	63(61)
	750 vph	188 vph	64(61)	59(56)	64(60)	56(54)	62(59)	43(40)	66(65)	65(63)	66(64)	65(62)	66(64)	60(59)
		375 vph	62(59)	48(45)	60(57)	42(41)	57(55)	29(28)	66(64)	63(61)	66(64)	62(59)	65(63)	53(51)
85% Auto	375 vph	94 vph	66(63)	63(59)	65(62)	62(59)	66(63)	58(54)	66(65)	66(65)	66(65)	66(64)	66(65)	64(62)
		188 vph	65(61)	61(58)	64(62)	60(57)	64(60)	52(50)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	64(61)	59(56)	63(60)	56(52)	62(59)	41(39)	66(65)	65(63)	66(65)	65(63)	66(64)	61(59)
		375 vph	61(58)	52(50)	60(57)	40(40)	58(55)	27(26)	66(64)	64(62)	66(64)	63(60)	65(63)	56(53)
No Auto	375 vph	94 vph	64(58)	57(49)	64(57)	57(48)	63(55)	42(37)	66(63)	65(61)	66(63)	63(58)	66(63)	59(54)
		188 vph	60(53)	43(37)	59(53)	29(26)	59(52)	24(21)	65(62)	62(59)	65(63)	60(55)	64(61)	49(43)
	750 vph	188 vph	53(44)	43(30)	49(39)	38(28)	43(35)	39(30)	64(59)	55(39)	63(59)	51(38)	63(59)	48(36)
		375 vph	24(23)	24(20)	27(24)	23(21)	23(22)	23(21)	58(52)	44(33)	58(53)	42(32)	51(44)	39(32)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-4. Ramp Merge Conditions – Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)	66(65)	65(63)	66(65)	65(63)	66(65)	62(60)
		188 vph	66(65)	66(64)	66(65)	65(63)	66(65)	63(61)	66(65)	65(64)	66(65)	64(63)	66(64)	61(59)
	750 vph	188 vph	66(65)	65(63)	66(65)	63(61)	65(64)	52(47)	66(65)	65(62)	66(64)	63(61)	65(64)	53(48)
		375 vph	66(65)	64(62)	65(64)	62(60)	65(63)	53(49)	66(64)	64(62)	65(64)	63(61)	65(63)	52(46)
90% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	65(63)	66(65)	65(63)	66(65)	65(63)	66(65)	65(63)	66(65)	62(60)
		188 vph	66(65)	65(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(63)	66(65)	65(63)	65(64)	61(59)
	750 vph	188 vph	66(64)	63(59)	66(65)	60(57)	65(64)	48(43)	66(64)	64(62)	66(64)	62(60)	65(64)	52(46)
		375 vph	65(64)	64(61)	65(64)	56(52)	65(63)	49(44)	66(64)	64(61)	65(63)	63(60)	65(63)	52(45)
85% Auto	375 vph	94 vph	66(66)	66(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(63)	66(65)	65(63)	66(64)	62(60)
		188 vph	66(65)	66(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(64)	66(65)	64(63)	66(64)	61(59)
	750 vph	188 vph	66(65)	65(63)	66(64)	61(59)	65(64)	49(45)	66(64)	64(62)	62(59)	63(61)	65(64)	54(49)
		375 vph	66(64)	64(62)	66(64)	59(56)	65(63)	49(44)	66(64)	64(62)	65(64)	63(61)	65(63)	52(47)
No Auto	375 vph	94 vph	66(63)	63(57)	66(63)	64(59)	65(62)	51(42)	66(62)	64(59)	66(62)	62(58)	65(61)	58(50)
		188 vph	66(62)	63(58)	65(62)	62(58)	65(61)	54(46)	65(61)	61(54)	65(60)	60(54)	65(61)	52(45)
	750 vph	188 vph	56(43)	51(35)	52(40)	49(35)	51(40)	46(35)	63(54)	57(39)	60(48)	53(37)	56(44)	51(37)
		375 vph	55(44)	49(35)	57(47)	47(34)	49(40)	44(33)	60(53)	53(36)	57(47)	51(36)	52(41)	49(35)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-5. Ramp Merge Conditions – Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(64)	66(66)	66(64)	66(65)	65(64)	66(65)	64(63)
	750 vph	188 vph	66(66)	66(65)	66(65)	65(64)	66(65)	64(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	62(61)	66(65)	65(63)	66(65)	64(63)	66(65)	59(57)
90% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(64)	66(65)	66(64)	66(65)	65(64)	66(65)	63(62)
	750 vph	188 vph	66(65)	66(64)	66(65)	65(64)	66(65)	59(56)	66(65)	65(64)	66(65)	65(64)	66(65)	62(60)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	60(58)	66(65)	65(63)	66(64)	63(61)	66(65)	56(55)
85% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	65(65)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(66)	66(64)	66(65)	66(64)	66(65)	64(63)
	750 vph	188 vph	66(65)	65(64)	66(65)	65(64)	66(65)	62(60)	66(65)	65(64)	66(65)	65(64)	66(65)	63(62)
		375 vph	66(65)	65(64)	66(65)	64(63)	66(65)	59(57)	66(65)	65(63)	66(65)	65(63)	66(64)	58(57)
No Auto	375 vph	94 vph	66(64)	65(63)	66(64)	66(63)	66(64)	65(63)	66(64)	65(62)	66(64)	65(61)	66(64)	62(59)
		188 vph	66(64)	65(62)	66(64)	64(61)	66(64)	60(57)	66(64)	63(60)	66(64)	60(56)	65(63)	56(52)
	750 vph	188 vph	64(60)	56(41)	60(50)	54(43)	60(52)	51(40)	65(62)	57(43)	65(61)	55(41)	64(60)	52(40)
		375 vph	63(58)	52(39)	59(52)	50(39)	53(44)	48(38)	62(57)	62(57)	60(55)	47(36)	53(49)	44(35)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-6. Ramp Merge Conditions – Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	65(64)	59(58)	65(64)	56(56)	63(63)	43(41)
		188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	65(64)	59(58)	64(64)	54(56)	62(62)	44(42)
	750 vph	188 vph	66(65)	65(64)	66(65)	64(62)	66(65)	57(53)	64(64)	56(55)	63(63)	52(50)	60(60)	44(38)
		375 vph	66(65)	65(64)	66(65)	64(62)	66(65)	55(50)	64(63)	56(54)	63(63)	51(49)	61(61)	44(39)
90% Auto	375 vph	94 vph	66(65)	66(65)	66(66)	65(64)	66(65)	65(64)	65(64)	58(57)	64(64)	55(54)	62(62)	43(40)
		188 vph	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	65(64)	58(56)	64(63)	54(53)	62(62)	43(41)
	750 vph	188 vph	66(65)	64(62)	66(65)	61(58)	66(65)	54(47)	64(63)	55(52)	63(63)	50(47)	61(60)	43(38)
		375 vph	66(65)	64(62)	66(65)	62(59)	66(65)	53(46)	47(40)	54(52)	63(62)	48(45)	60(60)	44(39)
85% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	65(65)	59(58)	64(64)	56(56)	63(63)	43(41)
		188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	65(64)	59(58)	64(64)	56(55)	63(63)	43(41)
	750 vph	188 vph	66(65)	65(63)	66(65)	63(62)	66(65)	53(48)	64(63)	56(54)	63(63)	52(50)	61(61)	43(39)
		375 vph	66(65)	65(64)	66(65)	62(60)	65(65)	58(54)	64(63)	56(54)	63(63)	51(49)	61(61)	44(39)
No Auto	375 vph	94 vph	66(63)	65(61)	66(64)	64(60)	66(63)	56(47)	64(59)	52(41)	63(58)	45(35)	61(56)	42(33)
		188 vph	66(64)	64(59)	66(63)	64(59)	65(63)	56(48)	63(59)	50(38)	62(58)	45(35)	60(55)	40(31)
	750 vph	188 vph	60(50)	56(39)	61(52)	53(38)	55(44)	51(38)	59(52)	48(34)	58(51)	44(32)	51(41)	41(32)
		375 vph	59(47)	55(38)	60(51)	53(39)	58(49)	51(38)	56(48)	45(31)	55(46)	42(31)	47(38)	40(31)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-7. Ramp Merge Conditions – Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(61)	66(62)	65(61)	66(62)	64(59)	66(62)	65(60)	66(62)	63(59)	66(61)	62(58)
		188 vph	66(62)	64(60)	66(62)	64(60)	66(62)	62(56)	66(62)	64(60)	65(61)	63(58)	65(60)	58(53)
	750 vph	188 vph	65(61)	62(57)	65(61)	60(55)	64(60)	54(50)	65(61)	63(58)	65(61)	60(55)	65(61)	53(49)
		375 vph	64(60)	57(52)	64(59)	54(51)	60(56)	34(35)	64(59)	56(51)	63(59)	51(46)	60(55)	36(36)
90% Auto	375 vph	94 vph	66(61)	65(60)	66(61)	65(60)	66(60)	64(57)	66(61)	65(59)	65(61)	64(60)	65(61)	61(55)
		188 vph	65(59)	63(58)	65(59)	63(57)	65(59)	58(52)	65(60)	63(57)	65(60)	61(56)	64(59)	57(52)
	750 vph	188 vph	64(58)	61(55)	64(59)	60(54)	64(58)	43(40)	64(59)	61(55)	65(59)	58(51)	63(57)	45(42)
		375 vph	62(56)	53(48)	61(55)	59(51)	59(53)	31(33)	62(56)	54(48)	62(55)	49(44)	58(53)	34(34)
85% Auto	375 vph	94 vph	66(61)	65(59)	66(62)	65(60)	65(60)	64(57)	66(62)	65(60)	66(61)	64(59)	66(61)	63(58)
		188 vph	66(61)	64(59)	65(60)	63(58)	65(60)	60(55)	66(61)	64(59)	65(59)	59(54)	65(60)	56(52)
	750 vph	188 vph	65(60)	60(54)	64(59)	60(54)	64(59)	53(48)	65(60)	62(56)	65(60)	60(54)	64(59)	52(48)
		375 vph	63(57)	56(51)	62(56)	59(53)	61(55)	31(33)	63(57)	55(49)	62(56)	49(44)	60(54)	35(35)
No Auto	375 vph	94 vph	60(41)	53(35)	59(41)	51(35)	59(41)	40(30)	61(42)	54(34)	60(40)	53(35)	58(40)	46(32)
		188 vph	56(38)	44(32)	60(41)	42(30)	53(38)	32(25)	57(38)	47(32)	57(39)	44(30)	54(36)	35(28)
	750 vph	188 vph	40(26)	28(19)	37(25)	27(19)	29(20)	26(18)	48(30)	35(22)	45(29)	32(21)	41(26)	31(21)
		375 vph	29(21)	24(18)	26(20)	23(18)	25(19)	24(18)	41(28)	28(20)	38(26)	28(20)	32(23)	27(20)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-8. Ramp Merge Conditions – Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(60)	66(61)	64(60)	65(61)	60(56)	65(62)	64(60)	66(62)	62(57)	65(59)	56(50)
		188 vph	65(61)	63(58)	65(61)	63(59)	65(60)	59(54)	65(62)	62(56)	65(61)	59(54)	64(59)	56(50)
	750 vph	188 vph	65(60)	61(57)	64(61)	56(52)	63(58)	36(36)	65(60)	59(53)	65(60)	57(52)	63(58)	44(41)
		375 vph	63(57)	57(52)	63(58)	50(46)	62(56)	34(36)	62(57)	53(48)	63(58)	48(43)	61(55)	36(35)
90% Auto	375 vph	94 vph	66(60)	63(58)	65(60)	63(57)	65(58)	60(55)	65(61)	63(58)	65(61)	62(56)	65(59)	56(50)
		188 vph	65(60)	62(56)	64(59)	62(57)	64(58)	55(51)	65(59)	61(54)	64(59)	59(53)	63(58)	56(51)
	750 vph	188 vph	63(56)	58(51)	63(58)	53(48)	62(56)	34(35)	64(58)	59(51)	64(57)	53(47)	63(56)	40(38)
		375 vph	60(54)	52(48)	62(55)	46(43)	58(52)	32(33)	62(55)	52(46)	61(55)	47(42)	56(49)	35(35)
85% Auto	375 vph	94 vph	66(60)	64(59)	65(60)	64(59)	65(60)	60(54)	65(61)	64(59)	65(61)	61(56)	65(60)	55(49)
		188 vph	65(60)	63(57)	65(60)	62(56)	64(59)	59(53)	65(62)	62(56)	64(59)	59(54)	64(58)	53(48)
	750 vph	188 vph	64(59)	58(52)	64(58)	54(49)	64(58)	35(35)	65(59)	59(53)	64(59)	54(49)	63(57)	42(39)
		375 vph	63(56)	54(48)	62(56)	48(44)	60(54)	33(34)	63(57)	53(47)	63(57)	48(43)	60(53)	35(35)
No Auto	375 vph	94 vph	59(40)	51(34)	57(39)	43(29)	56(39)	33(26)	61(39)	53(33)	60(40)	46(30)	58(39)	37(26)
		188 vph	55(38)	45(31)	53(37)	39(28)	51(35)	31(25)	57(38)	49(32)	56(38)	43(30)	54(37)	36(27)
	750 vph	188 vph	33(22)	28(19)	31(21)	28(19)	28(19)	27(18)	44(26)	36(21)	41(25)	35(21)	38(23)	33(21)
		375 vph	27(20)	25(18)	26(20)	24(18)	25(19)	24(18)	39(26)	32(20)	36(23)	31(20)	33(22)	30(20)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-9. Ramp Merge Conditions – Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(64)	66(63)	66(64)	65(62)
		188 vph	66(64)	66(64)	66(65)	66(64)	66(64)	65(63)	66(65)	66(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	65(63)	66(64)	65(62)	66(63)	65(62)	66(65)	65(64)	66(64)	65(62)	66(64)	62(60)
		375 vph	66(64)	65(63)	66(64)	65(62)	66(64)	56(55)	66(64)	65(62)	66(64)	64(62)	65(63)	59(56)
90% Auto	375 vph	94 vph	66(64)	66(63)	66(63)	66(63)	66(63)	65(62)	66(64)	66(64)	66(64)	66(63)	66(63)	65(63)
		188 vph	66(63)	65(62)	66(64)	66(63)	66(63)	65(61)	66(64)	65(62)	66(64)	65(62)	66(63)	63(60)
	750 vph	188 vph	66(62)	65(61)	66(63)	64(59)	66(62)	62(58)	66(64)	65(62)	66(63)	64(60)	66(63)	61(58)
		375 vph	66(63)	64(60)	66(62)	63(59)	65(61)	55(53)	66(63)	63(60)	65(63)	63(59)	65(62)	57(53)
85% Auto	375 vph	94 vph	66(64)	66(63)	66(64)	66(63)	66(64)	66(63)	66(65)	66(64)	66(64)	66(64)	66(64)	65(62)
		188 vph	66(64)	66(63)	66(64)	66(63)	66(64)	65(63)	66(64)	66(63)	66(64)	65(63)	66(64)	64(61)
	750 vph	188 vph	66(64)	65(62)	66(63)	65(62)	66(63)	61(57)	66(64)	65(62)	66(64)	65(62)	66(63)	61(58)
		375 vph	66(63)	65(61)	66(63)	64(61)	65(63)	59(57)	66(63)	64(61)	66(63)	63(59)	65(62)	57(54)
No Auto	375 vph	94 vph	63(48)	59(44)	63(49)	56(42)	62(47)	53(40)	64(52)	61(46)	64(52)	60(46)	63(49)	55(43)
		188 vph	62(48)	57(42)	61(47)	56(43)	60(47)	50(39)	63(50)	58(44)	63(50)	57(44)	61(48)	49(39)
	750 vph	188 vph	51(37)	40(26)	49(36)	38(26)	43(30)	36(25)	57(42)	46(30)	57(41)	44(29)	53(38)	41(28)
		375 vph	47(34)	35(25)	47(35)	34(25)	41(29)	35(25)	55(41)	36(26)	52(38)	35(25)	49(36)	33(24)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-10. Ramp Merge Conditions – Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	66(63)	66(64)	65(63)	66(64)	63(62)	66(65)	66(63)	66(64)	65(63)	66(64)	63(61)
		188 vph	66(64)	66(64)	66(64)	65(63)	66(64)	63(60)	66(65)	65(63)	66(64)	65(63)	66(64)	62(59)
	750 vph	188 vph	66(64)	65(62)	66(64)	63(61)	66(63)	51(49)	66(64)	65(63)	66(64)	64(62)	65(63)	55(53)
		375 vph	66(64)	64(61)	66(63)	63(60)	65(63)	52(51)	66(64)	64(61)	66(64)	63(61)	65(62)	58(56)
90% Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(61)	66(63)	63(59)	66(64)	65(62)	66(64)	65(62)	66(63)	62(60)
		188 vph	66(64)	65(62)	66(63)	65(62)	66(63)	62(59)	66(64)	65(62)	66(63)	65(62)	65(63)	62(59)
	750 vph	188 vph	66(62)	64(60)	65(62)	62(57)	65(61)	47(45)	66(63)	64(61)	66(63)	63(59)	65(62)	49(46)
		375 vph	65(62)	63(58)	65(62)	60(57)	65(61)	49(47)	66(63)	63(60)	65(63)	62(58)	65(61)	53(50)
85% Auto	375 vph	94 vph	66(64)	66(63)	66(64)	65(63)	66(63)	64(61)	66(65)	65(63)	66(64)	65(62)	66(63)	61(59)
		188 vph	66(64)	66(63)	66(64)	65(63)	66(64)	65(61)	66(64)	65(63)	66(64)	65(63)	66(64)	62(59)
	750 vph	188 vph	66(63)	64(61)	66(63)	62(59)	65(62)	51(50)	66(64)	64(61)	66(63)	63(60)	65(63)	52(50)
		375 vph	66(63)	64(60)	66(63)	61(58)	65(62)	49(48)	66(63)	64(60)	66(63)	63(59)	65(62)	50(48)
No Auto	375 vph	94 vph	62(48)	58(41)	62(48)	55(40)	61(47)	49(37)	64(50)	60(45)	63(51)	58(44)	62(48)	51(39)
		188 vph	62(47)	55(41)	62(48)	56(43)	61(48)	45(35)	63(50)	59(44)	63(51)	56(43)	62(49)	47(36)
	750 vph	188 vph	47(31)	42(26)	48(34)	40(25)	41(28)	38(25)	58(42)	47(29)	55(38)	43(28)	53(38)	42(27)
		375 vph	48(33)	40(25)	42(28)	39(25)	39(27)	37(25)	54(39)	44(27)	52(37)	41(27)	49(35)	41(27)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-11. Ramp Merge Conditions – Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	66(64)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	64(62)
	750 vph	188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	64(62)	66(65)	66(64)	66(65)	65(64)	66(64)	63(61)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(64)	64(62)	66(65)	65(63)	66(65)	65(63)	66(64)	60(57)
90% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(65)	66(64)	66(64)	65(63)
		188 vph	66(65)	66(64)	66(64)	66(64)	66(64)	65(64)	66(65)	66(64)	66(65)	66(64)	66(64)	63(60)
	750 vph	188 vph	66(64)	65(62)	66(64)	65(62)	66(64)	63(60)	66(64)	65(63)	66(64)	65(62)	66(64)	62(60)
		375 vph	66(63)	65(62)	66(64)	65(62)	66(63)	60(57)	66(64)	65(62)	66(64)	63(61)	66(63)	60(57)
85% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(65)	66(63)	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(64)	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)
	750 vph	188 vph	66(65)	66(64)	66(64)	65(63)	66(64)	64(62)	66(65)	65(63)	66(64)	65(63)	66(64)	62(59)
		375 vph	66(64)	65(63)	66(64)	65(62)	66(64)	62(60)	66(64)	65(63)	66(64)	63(61)	66(64)	60(57)
No Auto	375 vph	94 vph	64(53)	61(49)	64(53)	59(47)	63(51)	58(47)	65(63)	63(52)	65(55)	62(52)	64(54)	59(49)
		188 vph	63(52)	60(47)	64(53)	58(47)	62(51)	53(41)	65(62)	61(50)	64(54)	60(49)	64(54)	56(46)
	750 vph	188 vph	55(41)	48(32)	53(40)	45(32)	47(34)	43(31)	61(48)	51(35)	60(48)	49(34)	58(47)	47(33)
		375 vph	55(42)	43(30)	51(38)	43(30)	47(35)	42(30)	58(46)	37(28)	57(45)	40(29)	54(42)	39(29)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-12. Ramp Merge Conditions – Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	66(65)	65(63)	66(65)	64(62)	66(64)	53(53)	66(65)	65(63)	66(65)	65(63)	66(64)	58(57)
		375 vph	66(65)	65(63)	66(64)	64(63)	65(64)	50(51)	66(64)	65(63)	66(64)	64(62)	65(64)	54(54)
90% Auto	375 vph	94 vph	66(64)	66(64)	66(64)	66(64)	66(64)	65(63)	66(65)	66(64)	66(65)	65(63)	66(64)	63(61)
		188 vph	66(65)	66(63)	66(64)	65(63)	66(64)	64(62)	66(64)	66(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	64(62)	66(64)	64(60)	65(63)	55(53)	54(53)	65(62)	66(64)	63(61)	65(63)	55(54)
		375 vph	66(63)	64(61)	66(64)	63(61)	65(62)	56(54)	54(53)	64(62)	66(64)	63(60)	65(63)	53(52)
85% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	65(64)	66(65)	66(64)	66(65)	65(64)	66(64)	64(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(64)	65(63)	66(65)	65(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	64(62)	66(64)	64(61)	66(64)	52(52)	66(64)	65(63)	66(64)	64(62)	66(64)	54(53)
		375 vph	66(64)	65(62)	66(64)	63(61)	65(63)	55(54)	66(64)	65(62)	66(64)	63(60)	65(63)	54(53)
No Auto	375 vph	94 vph	64(52)	61(46)	64(52)	59(45)	63(51)	50(40)	65(55)	62(49)	64(53)	60(48)	64(54)	51(41)
		188 vph	63(51)	60(46)	63(51)	58(45)	63(51)	50(39)	65(55)	62(50)	64(54)	59(47)	63(53)	52(42)
	750 vph	188 vph	52(36)	49(31)	49(35)	47(31)	47(33)	44(31)	60(46)	53(34)	58(44)	51(34)	54(39)	49(34)
		375 vph	53(38)	47(31)	49(34)	46(31)	47(33)	44(31)	58(43)	50(33)	57(43)	49(33)	53(38)	47(33)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-13. Ramp Merge Conditions – Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(63)	65(62)	66(62)	65(62)	66(63)	65(62)	66(62)	65(62)	66(63)	65(61)	66(63)	65(61)
		188 vph	65(62)	65(61)	65(62)	64(61)	66(63)	62(58)	65(61)	63(59)	65(61)	62(57)	64(60)	61(56)
	750 vph	188 vph	65(62)	64(62)	65(62)	64(61)	65(62)	63(59)	65(61)	63(59)	65(61)	63(59)	64(60)	61(58)
		375 vph	64(60)	61(56)	63(60)	59(56)	63(59)	63(59)	63(58)	59(54)	62(57)	55(50)	62(56)	48(44)
90% Auto	375 vph	94 vph	66(63)	65(62)	66(62)	65(61)	66(63)	65(61)	66(62)	65(61)	66(61)	64(61)	66(62)	64(60)
		188 vph	65(62)	64(61)	65(61)	63(60)	65(62)	63(59)	65(60)	63(59)	65(61)	63(59)	64(60)	60(55)
	750 vph	188 vph	65(62)	64(61)	65(62)	63(59)	65(61)	62(59)	65(60)	63(59)	65(61)	62(58)	64(60)	60(55)
		375 vph	64(60)	57(52)	63(58)	58(54)	61(56)	49(45)	63(58)	58(52)	63(58)	55(49)	60(54)	44(41)
85% Auto	375 vph	94 vph	66(62)	65(62)	66(63)	65(62)	66(62)	65(62)	66(63)	65(61)	66(62)	65(61)	66(63)	62(55)
		188 vph	65(62)	64(61)	65(62)	64(60)	65(62)	63(59)	65(61)	63(59)	65(60)	62(57)	65(60)	52(43)
	750 vph	188 vph	65(62)	64(60)	65(62)	63(60)	65(62)	62(59)	65(61)	62(58)	65(61)	63(59)	64(60)	59(54)
		375 vph	63(59)	58(54)	63(58)	58(53)	62(57)	53(50)	63(57)	56(51)	62(57)	56(50)	60(54)	47(43)
No Auto	375 vph	94 vph	65(57)	63(55)	65(58)	63(55)	65(57)	62(54)	65(57)	62(53)	65(57)	62(52)	65(57)	61(51)
		188 vph	62(54)	58(49)	62(53)	54(44)	61(53)	51(42)	62(52)	56(46)	63(54)	55(46)	61(52)	52(43)
	750 vph	188 vph	62(53)	56(48)	62(54)	53(45)	61(53)	49(42)	63(54)	55(45)	62(55)	53(44)	62(52)	45(37)
		375 vph	48(40)	30(26)	46(38)	28(24)	36(31)	24(22)	52(42)	33(27)	52(43)	29(25)	46(37)	25(23)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-14. Ramp Merge Conditions – Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(62)	66(63)	64(60)	66(63)	64(61)	65(62)	64(59)	65(61)	63(57)	65(61)	59(54)
		188 vph	66(62)	63(60)	65(62)	63(60)	65(60)	63(58)	65(60)	62(57)	65(60)	61(56)	63(58)	56(49)
	750 vph	188 vph	65(62)	63(60)	65(62)	63(60)	65(61)	60(56)	64(60)	61(55)	64(60)	61(55)	63(59)	57(53)
		375 vph	63(59)	60(56)	63(58)	57(53)	61(57)	51(48)	63(58)	55(49)	62(56)	53(48)	60(54)	42(39)
90% Auto	375 vph	94 vph	66(63)	65(61)	66(62)	64(61)	65(60)	64(60)	65(61)	64(59)	65(62)	63(58)	64(59)	61(56)
		188 vph	65(61)	63(58)	65(61)	63(59)	64(60)	61(57)	64(60)	62(56)	64(60)	61(55)	63(58)	55(49)
	750 vph	188 vph	65(61)	63(60)	65(61)	62(58)	65(61)	58(55)	65(61)	61(54)	64(59)	59(53)	63(58)	52(45)
		375 vph	63(59)	57(53)	62(58)	56(51)	62(58)	48(44)	62(56)	54(48)	61(55)	51(45)	59(52)	42(38)
85% Auto	375 vph	94 vph	66(62)	65(62)	66(62)	65(61)	66(63)	63(60)	65(61)	63(57)	65(61)	63(58)	65(60)	59(53)
		188 vph	65(61)	63(60)	65(61)	63(60)	65(61)	61(57)	64(60)	62(56)	64(59)	60(54)	63(59)	56(49)
	750 vph	188 vph	65(61)	63(59)	65(61)	62(59)	64(60)	60(56)	64(60)	61(55)	64(59)	59(53)	63(58)	54(47)
		375 vph	63(59)	58(53)	62(58)	57(53)	60(56)	49(45)	62(56)	55(48)	62(57)	51(45)	58(52)	42(38)
No Auto	375 vph	94 vph	65(56)	62(52)	64(55)	62(53)	64(55)	59(50)	64(53)	60(48)	64(54)	60(50)	63(54)	53(42)
		188 vph	62(51)	58(49)	61(52)	53(43)	61(52)	49(38)	62(51)	53(40)	62(52)	54(42)	60(49)	43(33)
	750 vph	188 vph	61(52)	52(42)	59(50)	46(37)	58(50)	37(28)	61(51)	44(32)	61(50)	42(32)	58(46)	35(27)
		375 vph	45(37)	31(25)	43(34)	30(24)	38(32)	26(23)	52(41)	33(25)	51(40)	30(24)	44(35)	28(23)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-15. Ramp Merge Conditions – Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(65)	65(64)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(63)	66(64)	64(62)	66(63)	64(61)
	750 vph	188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	66(64)	66(65)	65(63)	66(64)	65(63)	66(63)	63(61)
		375 vph	66(65)	65(65)	66(64)	65(64)	65(64)	63(62)	65(63)	63(59)	65(63)	62(59)	65(62)	57(55)
90% Auto	375 vph	94 vph	66(66)	66(65)	66(65)	66(65)	66(66)	66(65)	66(64)	66(64)	66(65)	66(64)	66(64)	65(63)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(62)	66(63)	65(62)	66(64)	63(60)
	750 vph	188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(63)	66(65)	65(64)	66(64)	65(62)	66(64)	64(61)
		375 vph	66(64)	65(63)	65(64)	65(63)	65(63)	63(62)	65(62)	62(58)	64(61)	61(57)	64(61)	55(52)
85% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(63)	66(65)	65(64)	66(64)	65(64)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	66(64)	66(64)	65(63)	66(64)	64(61)	66(64)	64(62)
	750 vph	188 vph	66(65)	66(65)	66(65)	66(65)	66(64)	65(64)	66(64)	65(63)	66(64)	65(63)	66(65)	63(61)
		375 vph	66(65)	65(64)	66(64)	65(64)	65(63)	62(60)	65(63)	62(59)	64(62)	59(56)	64(62)	56(55)
No Auto	375 vph	94 vph	66(64)	66(63)	66(64)	66(64)	66(64)	65(63)	66(62)	65(61)	66(62)	64(59)	66(62)	63(57)
		188 vph	65(62)	64(60)	65(63)	64(62)	65(62)	61(57)	65(59)	61(56)	65(59)	59(52)	64(59)	58(50)
	750 vph	188 vph	65(62)	64(61)	65(63)	64(60)	64(62)	62(61)	65(60)	61(56)	65(60)	59(54)	64(60)	54(46)
		375 vph	62(60)	51(43)	61(57)	46(44)	59(55)	36(33)	59(53)	46(42)	58(52)	39(33)	54(50)	23(24)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-16. Ramp Merge Conditions – Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	65(63)	66(65)	63(62)
		188 vph	66(65)	66(64)	66(65)	66(65)	66(64)	65(64)	66(65)	65(63)	66(64)	64(62)	66(63)	62(59)
	750 vph	188 vph	66(66)	66(65)	66(65)	65(65)	66(65)	64(62)	66(64)	64(63)	66(64)	64(62)	65(64)	61(59)
		375 vph	66(65)	65(64)	66(64)	65(63)	65(64)	63(62)	65(63)	63(60)	65(63)	63(60)	65(62)	59(57)
90% Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(63)	66(65)	65(64)	66(63)	63(59)
		188 vph	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	65(63)	66(64)	64(61)	65(63)	63(60)
	750 vph	188 vph	66(65)	66(64)	66(65)	65(63)	66(64)	64(63)	66(64)	65(62)	66(64)	64(62)	65(63)	61(57)
		375 vph	66(64)	65(63)	66(64)	64(62)	65(64)	63(60)	65(62)	63(60)	65(62)	62(59)	64(62)	59(56)
85% Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(64)	66(65)	65(62)	66(64)	65(63)	66(65)	65(63)	66(64)	63(61)
		188 vph	66(65)	66(65)	66(65)	66(64)	66(64)	64(63)	66(64)	65(64)	66(64)	64(61)	65(63)	62(60)
	750 vph	188 vph	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(63)	65(62)	66(64)	64(61)	65(63)	61(59)
		375 vph	66(65)	65(63)	65(64)	64(63)	65(64)	63(62)	65(63)	63(60)	65(63)	62(60)	64(62)	58(56)
No Auto	375 vph	94 vph	66(63)	65(61)	66(62)	65(62)	65(63)	64(60)	66(59)	64(56)	65(61)	63(58)	65(59)	60(52)
		188 vph	65(63)	64(61)	65(62)	63(59)	65(61)	62(56)	64(59)	62(54)	65(59)	60(53)	64(60)	58(48)
	750 vph	188 vph	65(62)	62(57)	65(62)	62(57)	64(59)	58(52)	64(59)	58(49)	64(59)	57(46)	63(57)	53(45)
		375 vph	62(57)	55(49)	61(58)	49(42)	59(55)	44(38)	61(54)	50(41)	60(52)	46(38)	57(49)	37(31)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-17. Ramp Merge Conditions – Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	67(66)	66(66)	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	64(63)
	750 vph	188 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)
		375 vph	66(65)	65(65)	66(65)	66(65)	66(65)	65(64)	65(64)	64(62)	65(64)	63(61)	65(63)	59(57)
90% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(66)	66(65)	66(65)	65(64)
		188 vph	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(63)
	750 vph	188 vph	66(66)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	63(61)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	64(63)	65(63)	63(61)	65(63)	62(60)	65(62)	59(57)
85% Auto	375 vph	94 vph	66(66)	66(66)	67(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(63)	66(64)	64(63)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	63(62)	65(63)	63(61)	65(63)	62(60)	65(62)	57(55)
No Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(64)	65(64)	66(63)	65(62)	66(62)	65(62)	66(62)	64(60)
		188 vph	66(64)	65(63)	66(64)	65(63)	66(64)	63(61)	65(61)	63(59)	65(62)	62(58)	64(60)	60(56)
	750 vph	188 vph	66(64)	65(64)	65(63)	65(63)	65(63)	63(60)	65(61)	62(57)	65(62)	62(57)	65(61)	57(53)
		375 vph	63(60)	55(51)	63(60)	52(49)	61(58)	42(39)	60(54)	49(44)	61(56)	46(42)	57(52)	31(30)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table B-18. Ramp Merge Conditions – Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 ft per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		188 vph	66(65)	66(65)	66(66)	66(65)	66(65)	65(65)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(63)	66(65)	63(62)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	64(64)	66(64)	64(62)	66(64)	63(62)	65(63)	61(59)
90% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	65(65)	66(65)	66(65)	66(65)	65(64)	66(65)	64(62)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(63)	66(64)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(63)	66(65)	65(63)	66(64)	63(61)
		375 vph	66(65)	65(65)	66(65)	65(64)	65(65)	64(63)	65(64)	64(62)	65(63)	63(61)	65(64)	60(58)
85% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	65(64)	66(65)	66(64)	66(65)	65(64)	65(64)	65(63)
		188 vph	66(65)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(64)	65(63)	63(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(63)	66(64)	63(61)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	64(63)	65(64)	64(62)	65(63)	64(62)	65(63)	61(59)
No Auto	375 vph	94 vph	66(65)	65(63)	66(64)	66(64)	66(64)	64(61)	66(63)	65(60)	66(63)	65(60)	66(62)	62(57)
		188 vph	66(64)	65(63)	66(63)	65(63)	66(63)	63(61)	65(62)	63(58)	65(61)	63(57)	65(60)	60(54)
	750 vph	188 vph	66(64)	64(61)	66(63)	64(61)	65(63)	62(59)	65(61)	62(54)	65(60)	62(55)	64(59)	55(45)
		375 vph	64(61)	59(56)	63(61)	55(50)	62(58)	50(45)	62(57)	54(47)	62(56)	53(46)	60(54)	42(37)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

APPENDIX C: SIMULATION OUTPUT FOR RAMP SAFETY MODELING

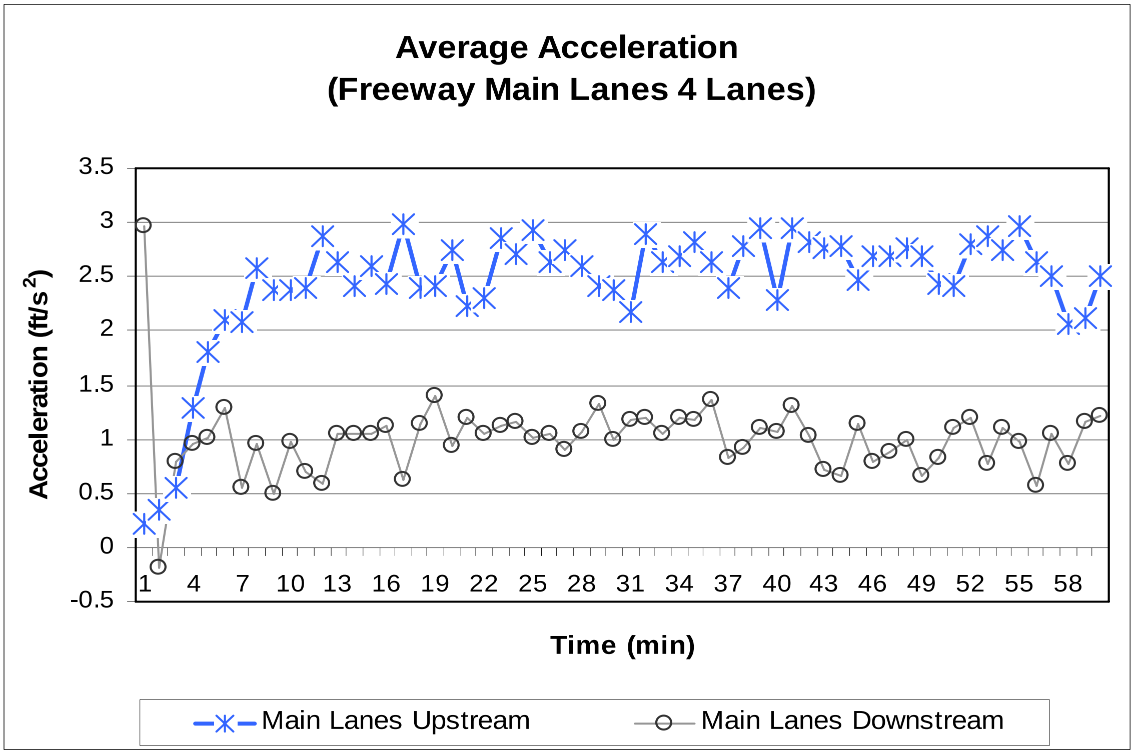

Figure C-1. Average Acceleration for Cars and Buses Restricted – Mainlanes.

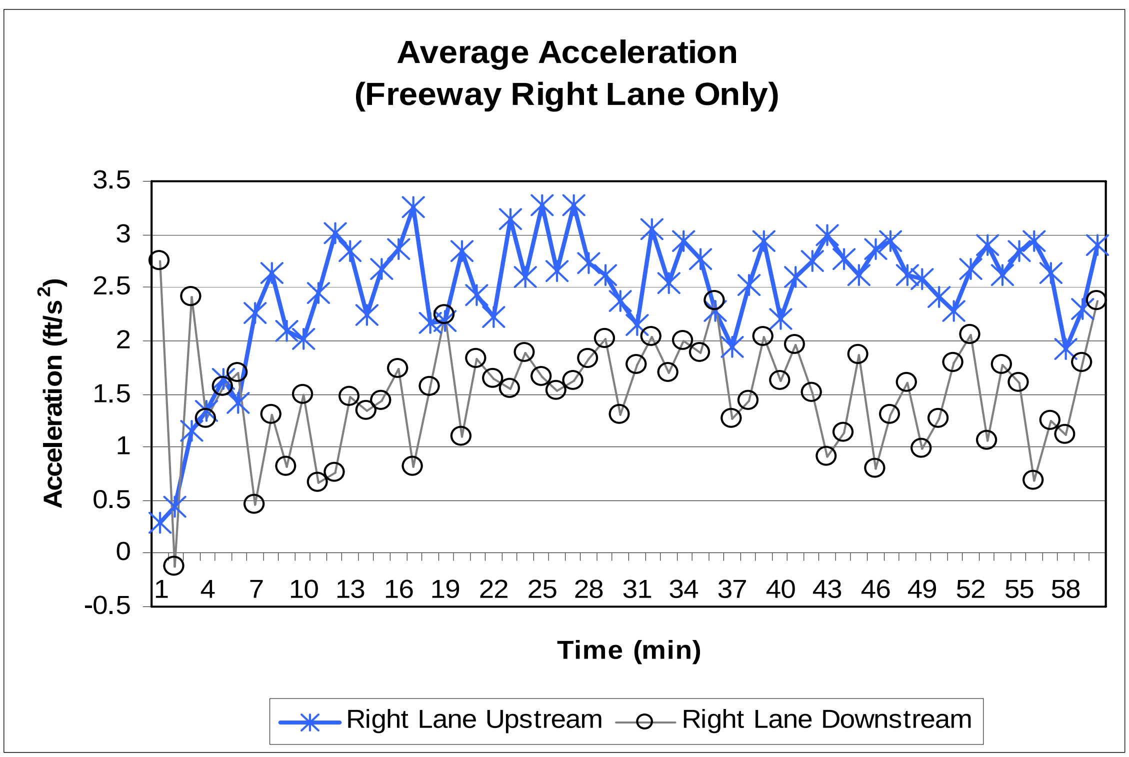

Figure C-2. Average Acceleration for Cars and Buses Restricted – Right Lane Only.

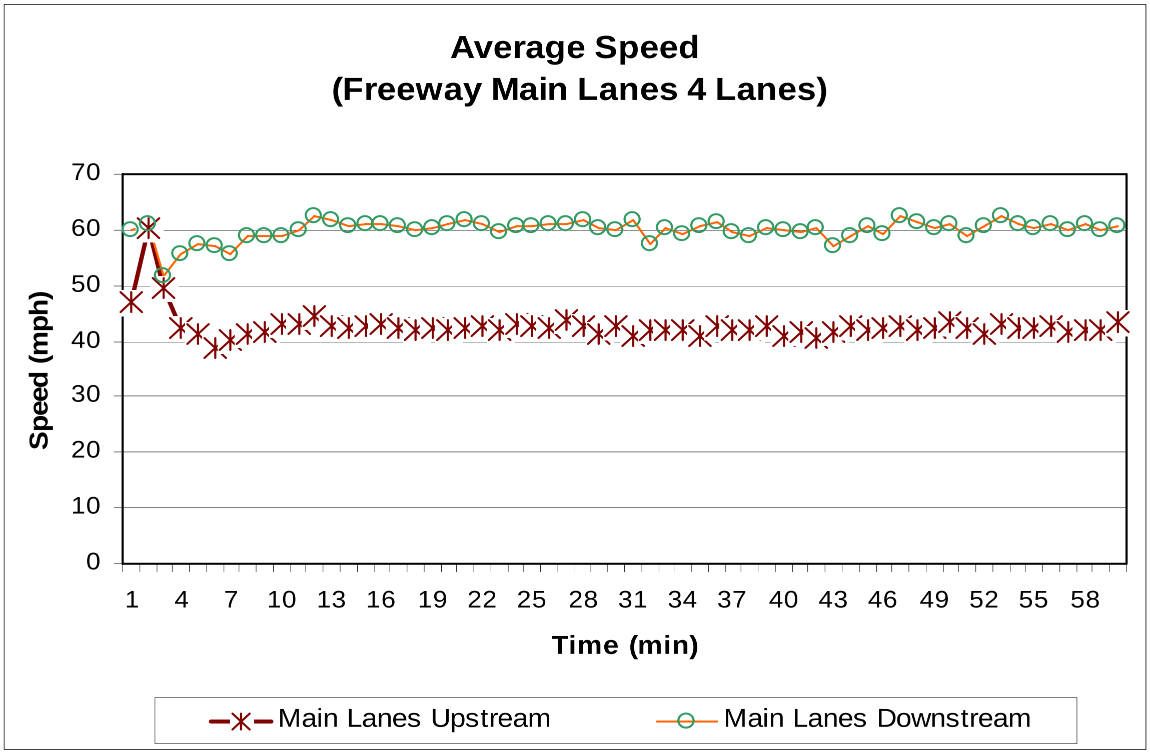

Figure C-3. Average Speed for Cars and Buses Restricted – Mainlanes.

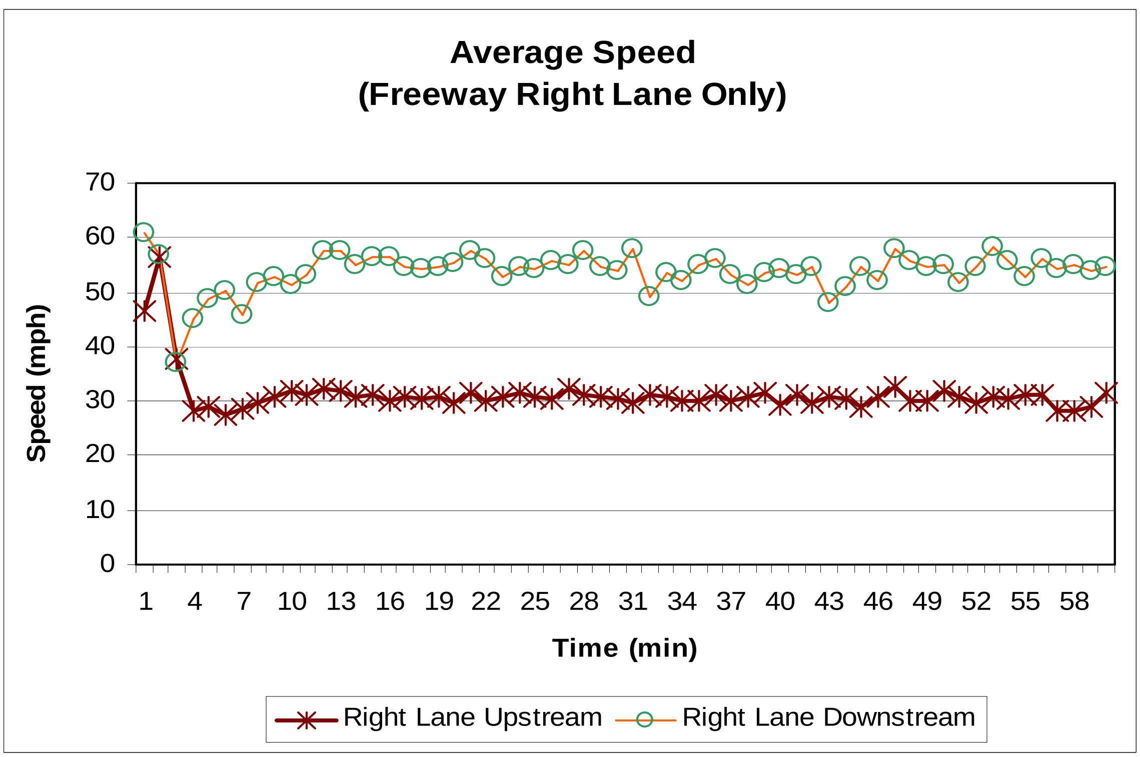

Figure C-4. Average Speed for Cars and Buses Restricted – Right Lane Only.

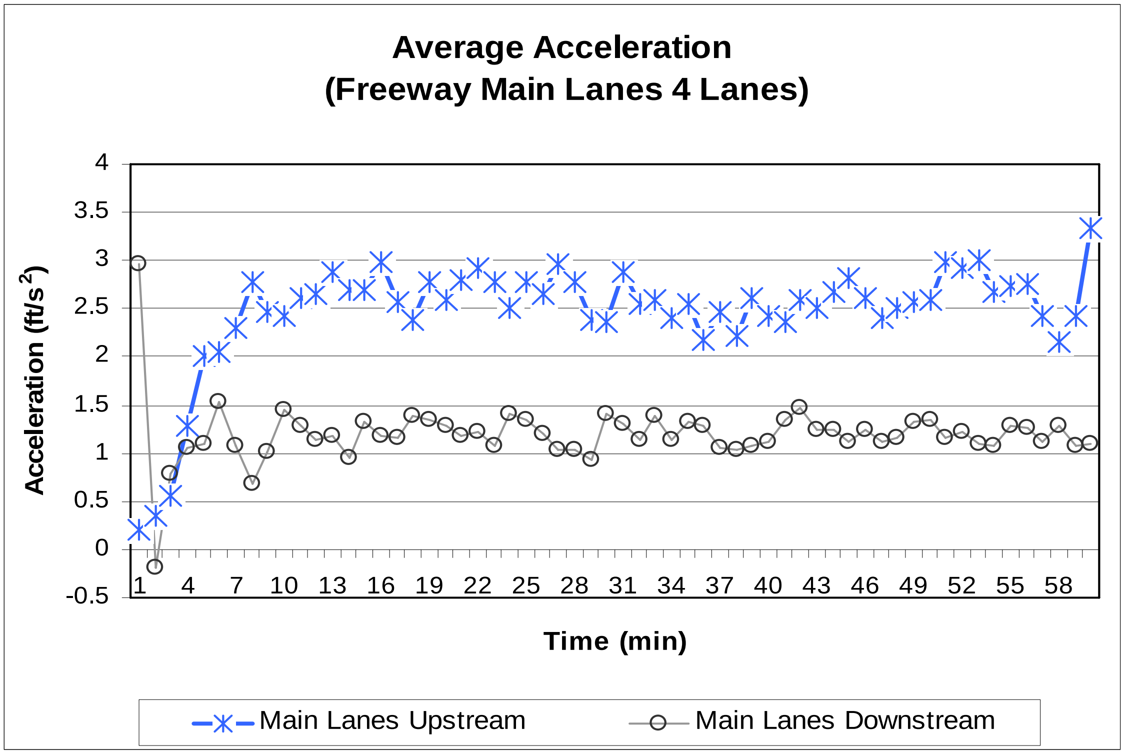

Figure C-5. Average Acceleration for All Vehicles Restricted – Mainlanes.

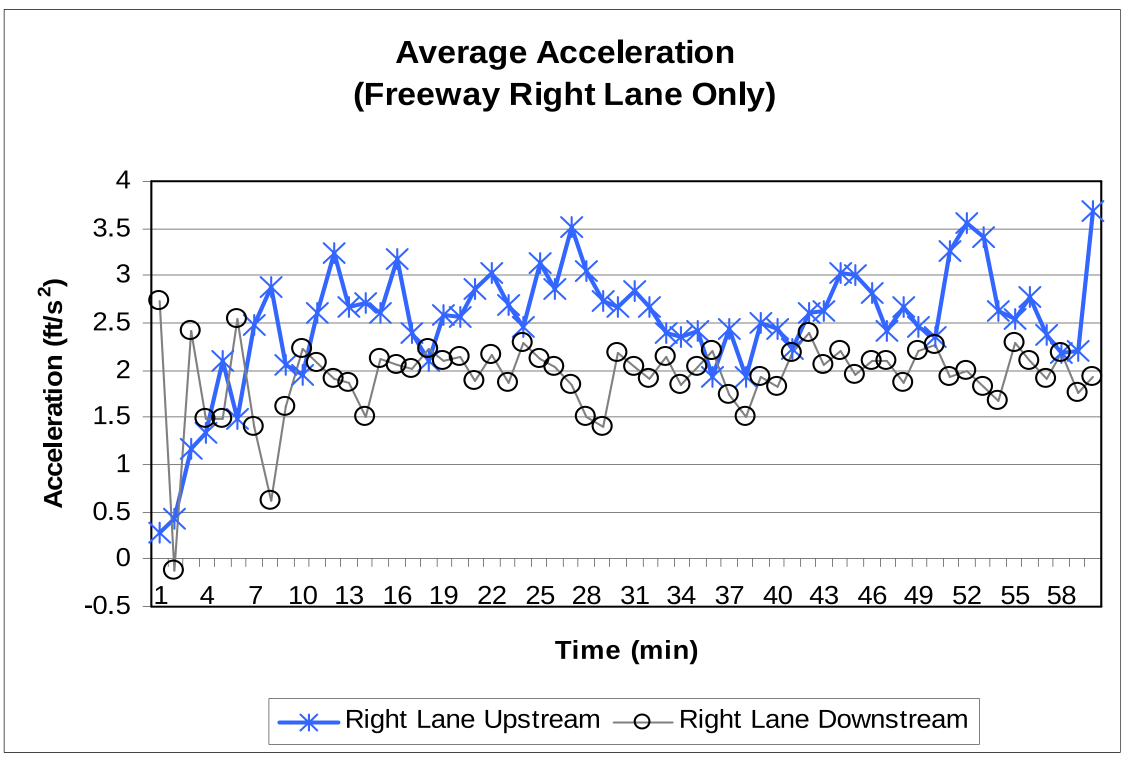

Figure C-6. Average Acceleration for All Vehicles Restricted – Right Lane Only.

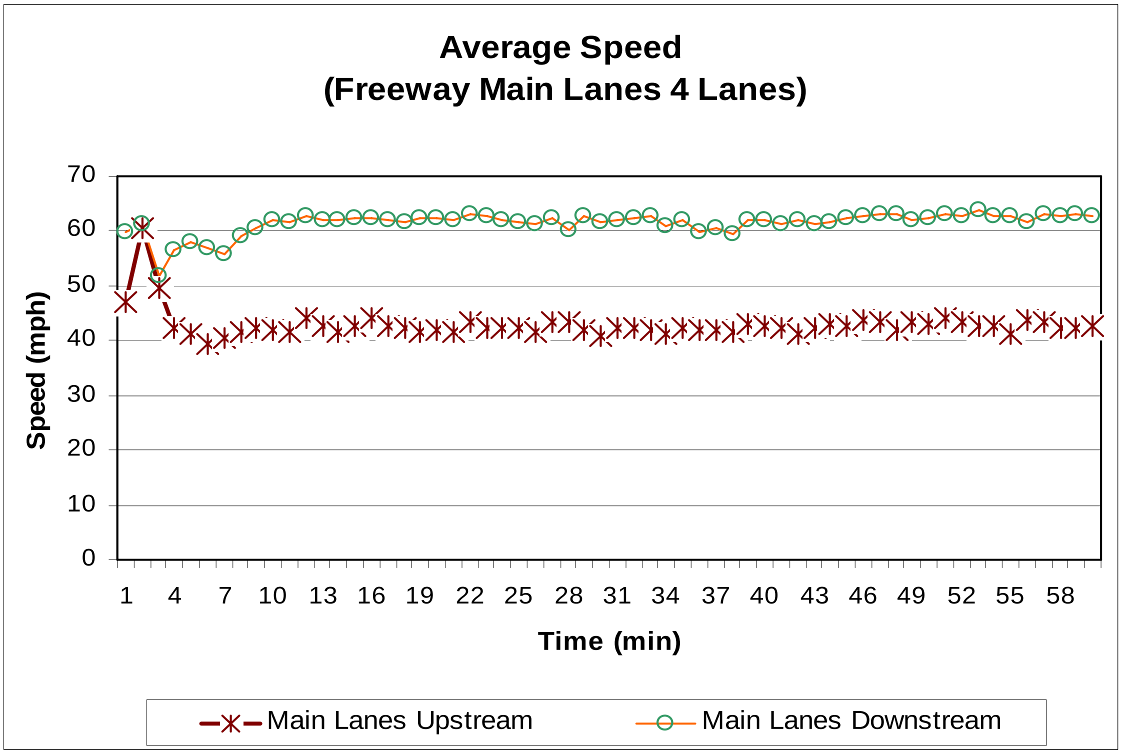

Figure C-7. Average Speed for All Vehicles Restricted – Mainlanes.

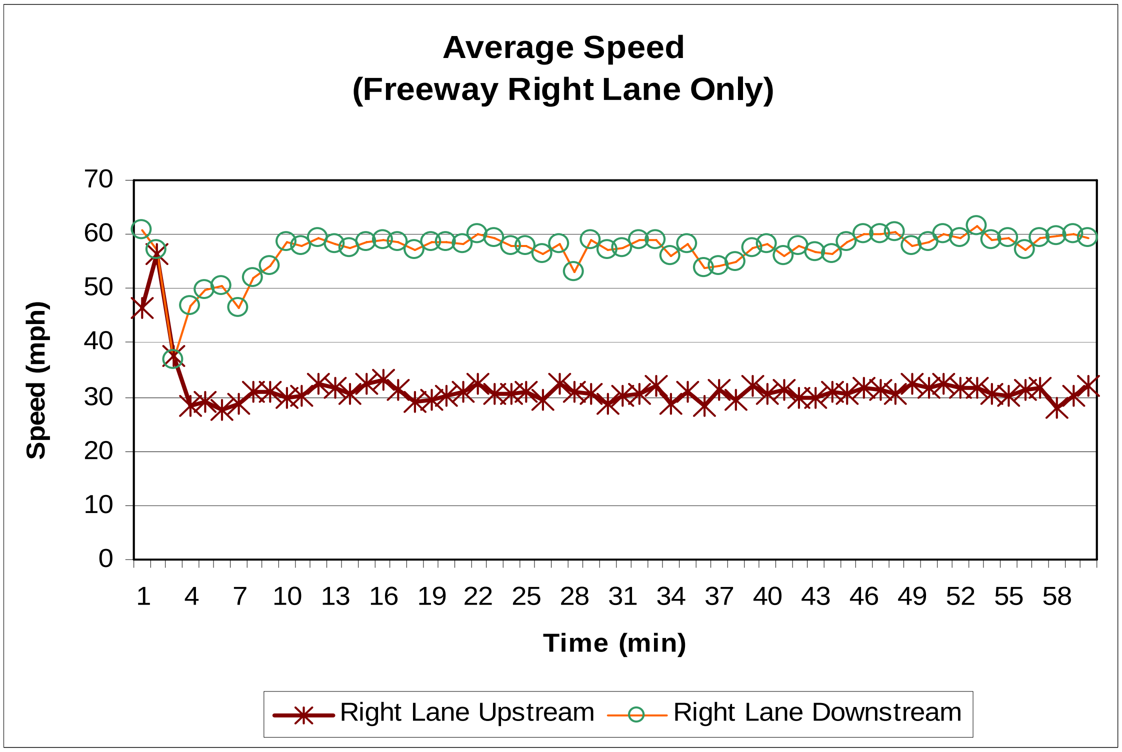

Figure C-8. Average Speed for All Vehicles Restricted – Right Lane Only.

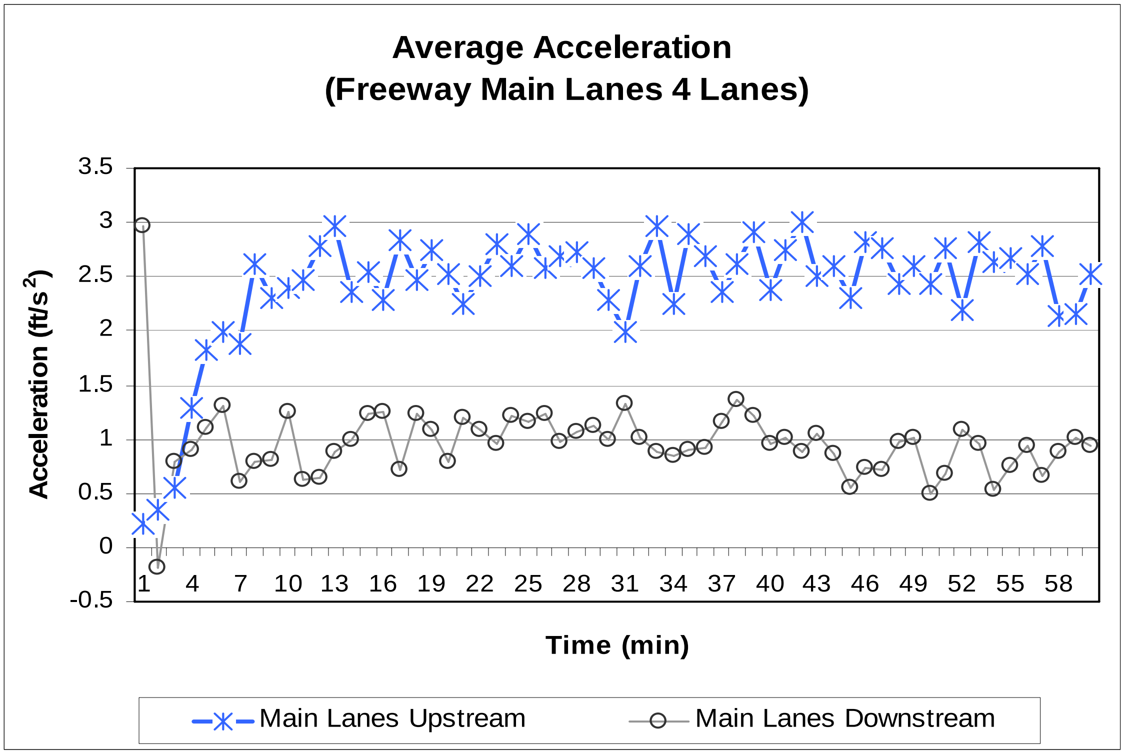

Figure C-9. Average Acceleration for Cars Restricted – Mainlanes.

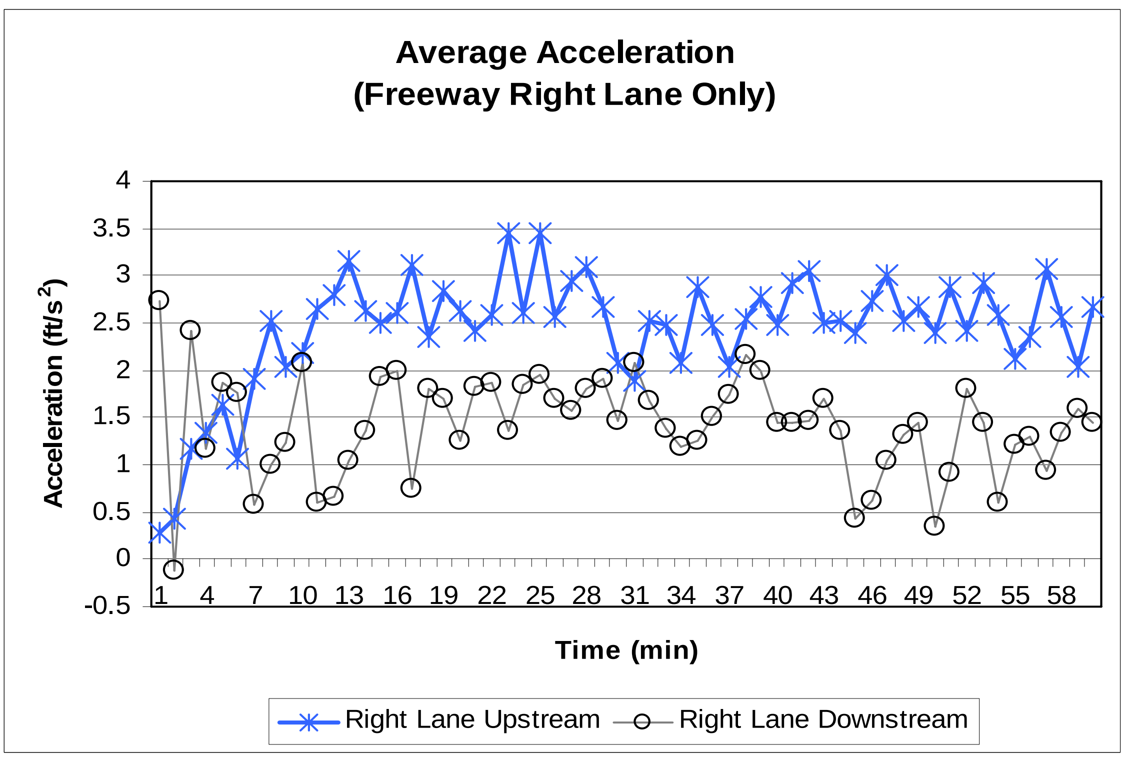

Figure C-10. Average Acceleration for Cars Restricted – Right Lane Only.

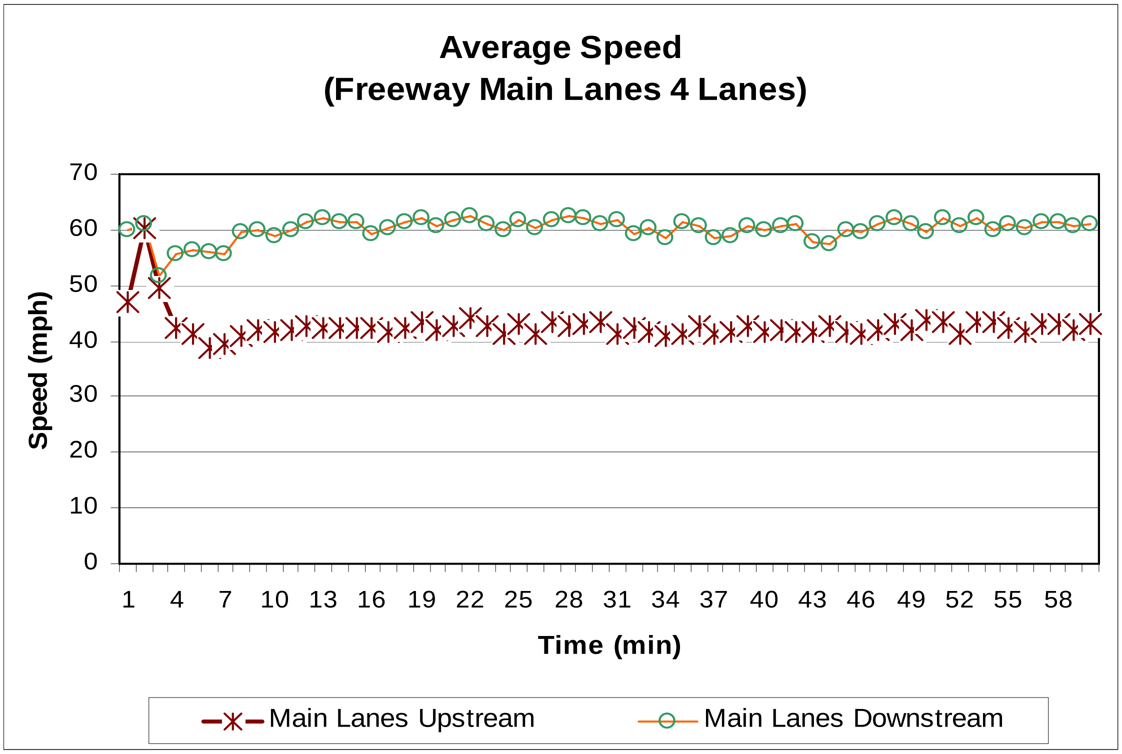

Figure C-11. Average Speed for Cars Restricted – Mainlanes.

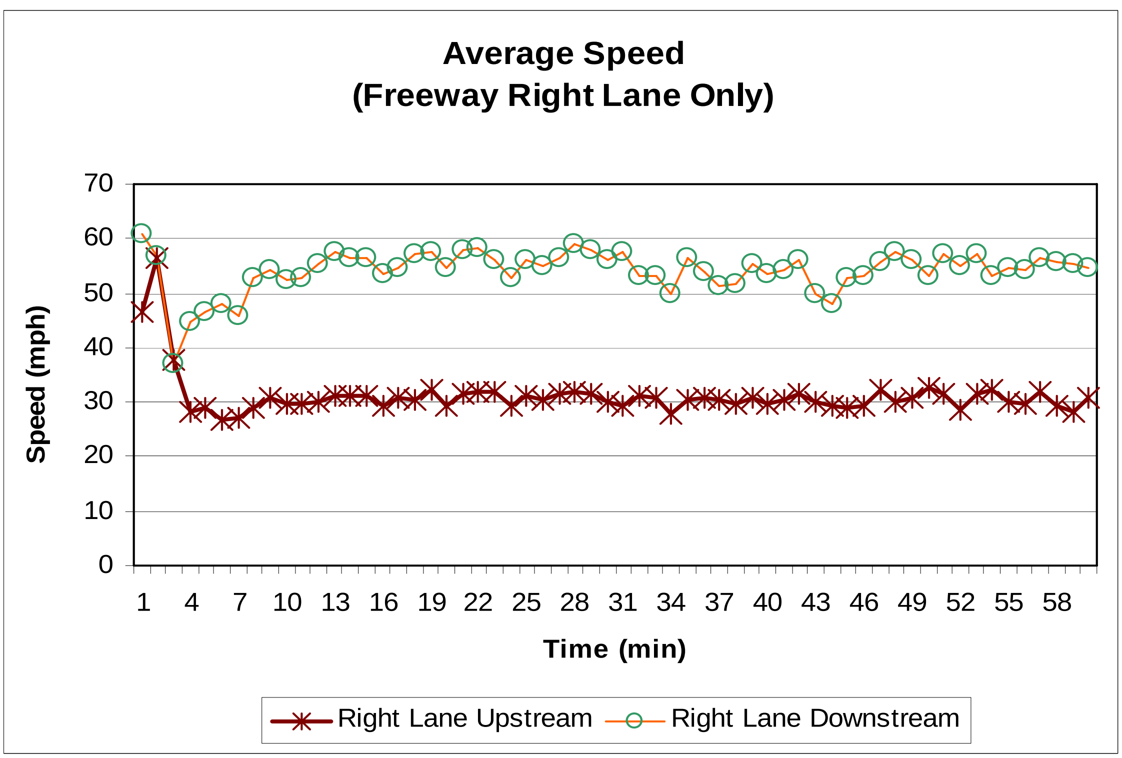

Figure C-12. Average Speed for Cars Restricted – Right Lane Only.

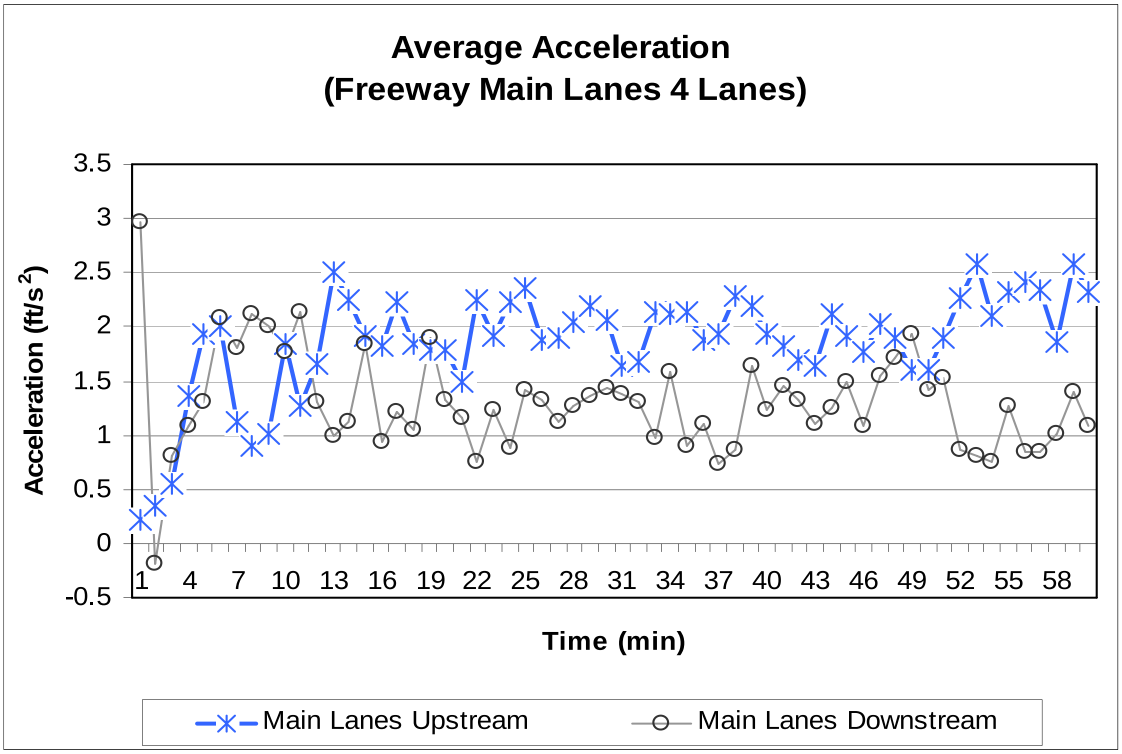

Figure C-13. Average Acceleration for No Vehicles Restricted – Mainlanes.

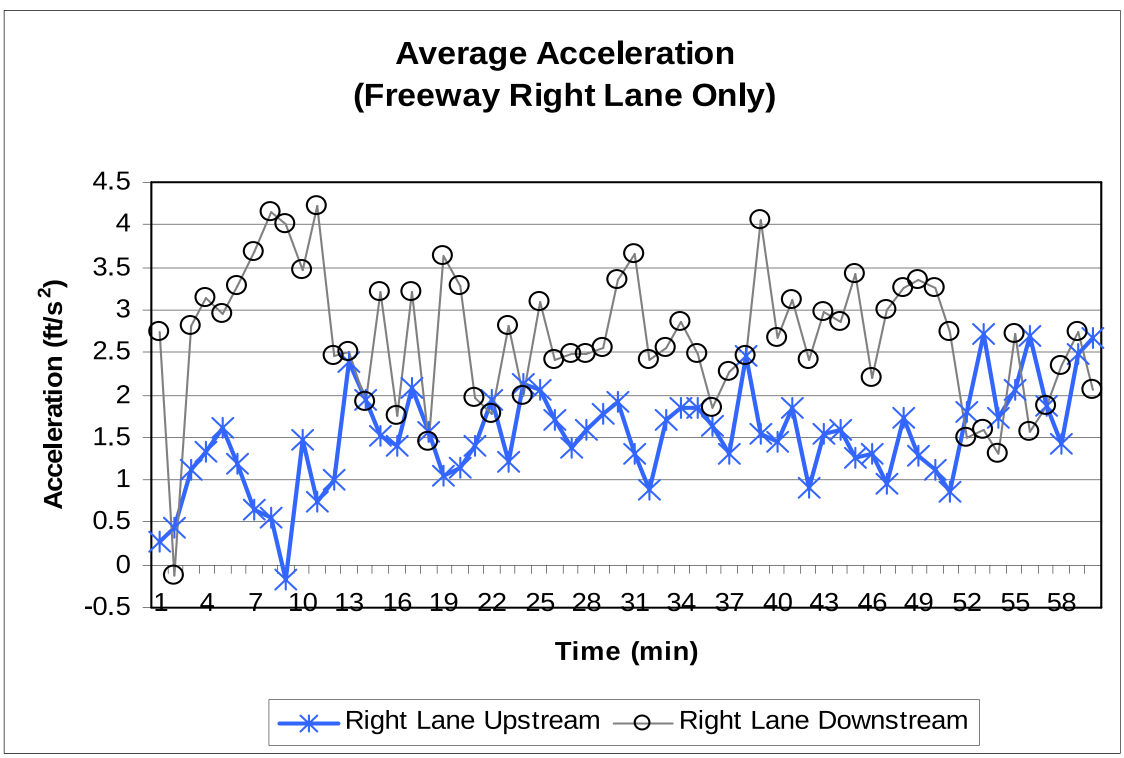

Figure C-14. Average Acceleration for No Vehicles Restricted – Right Lane Only.

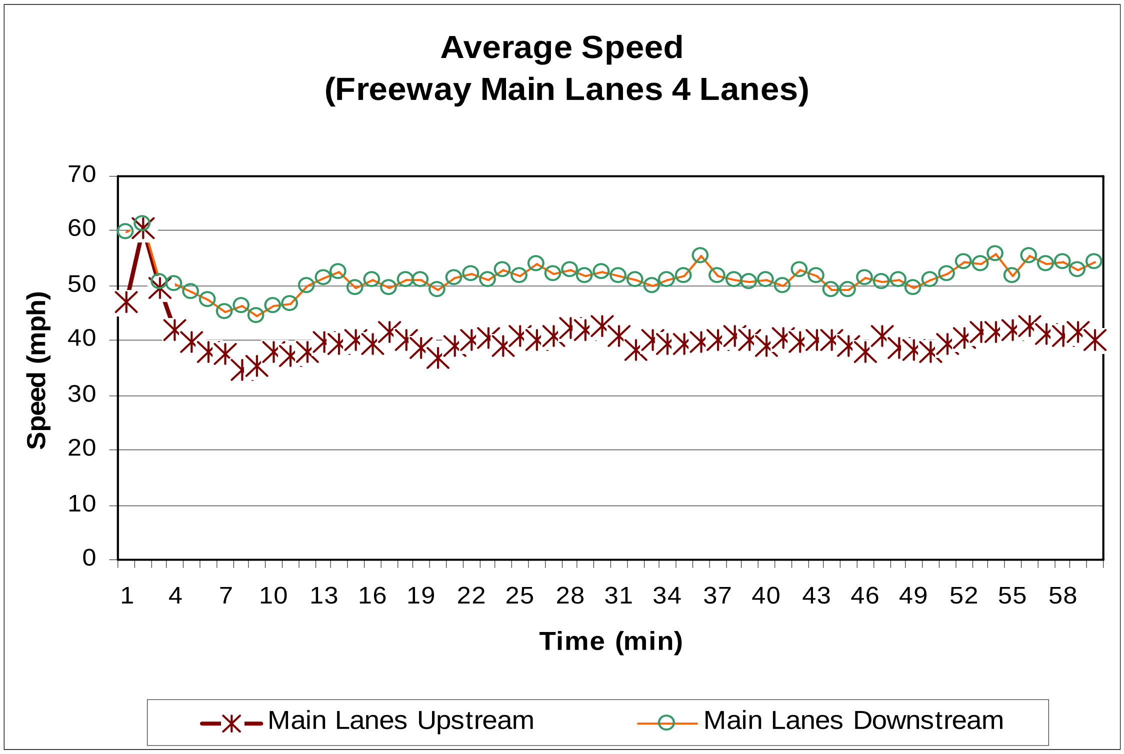

Figure C-15. Average Speed for No Vehicles Restricted – Mainlanes.

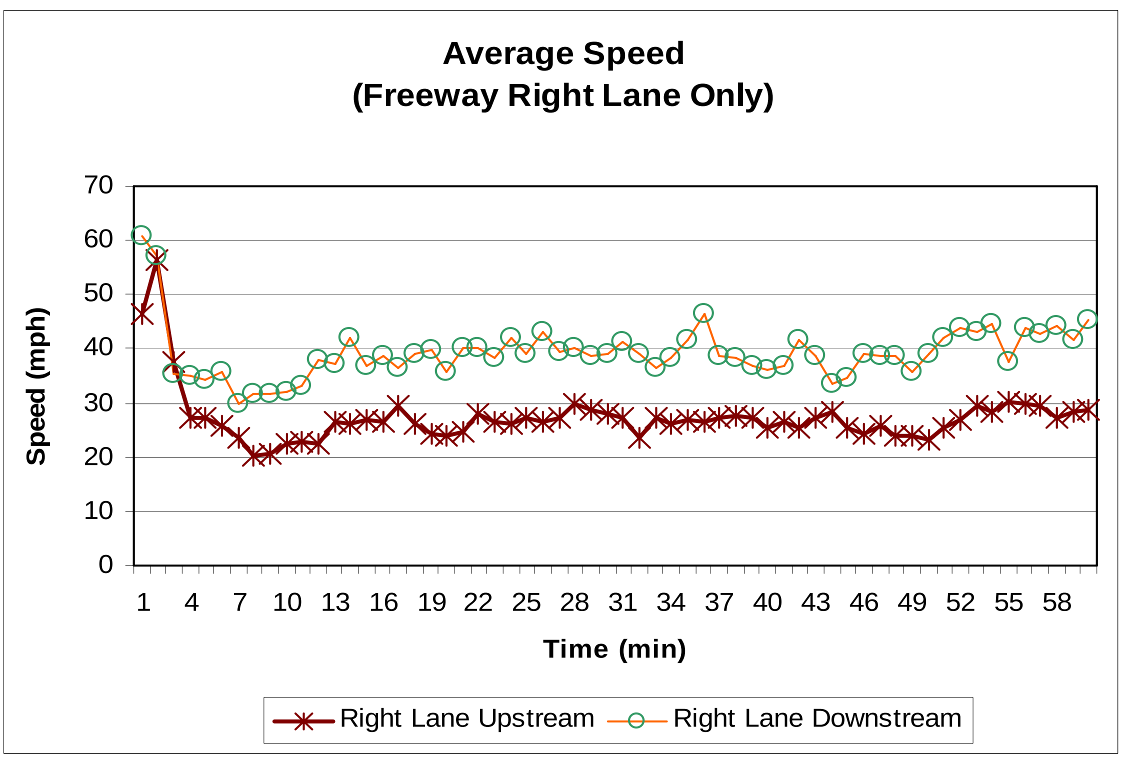

Figure C-16. Average Speed for No Vehicles Restricted – Right Lane Only.

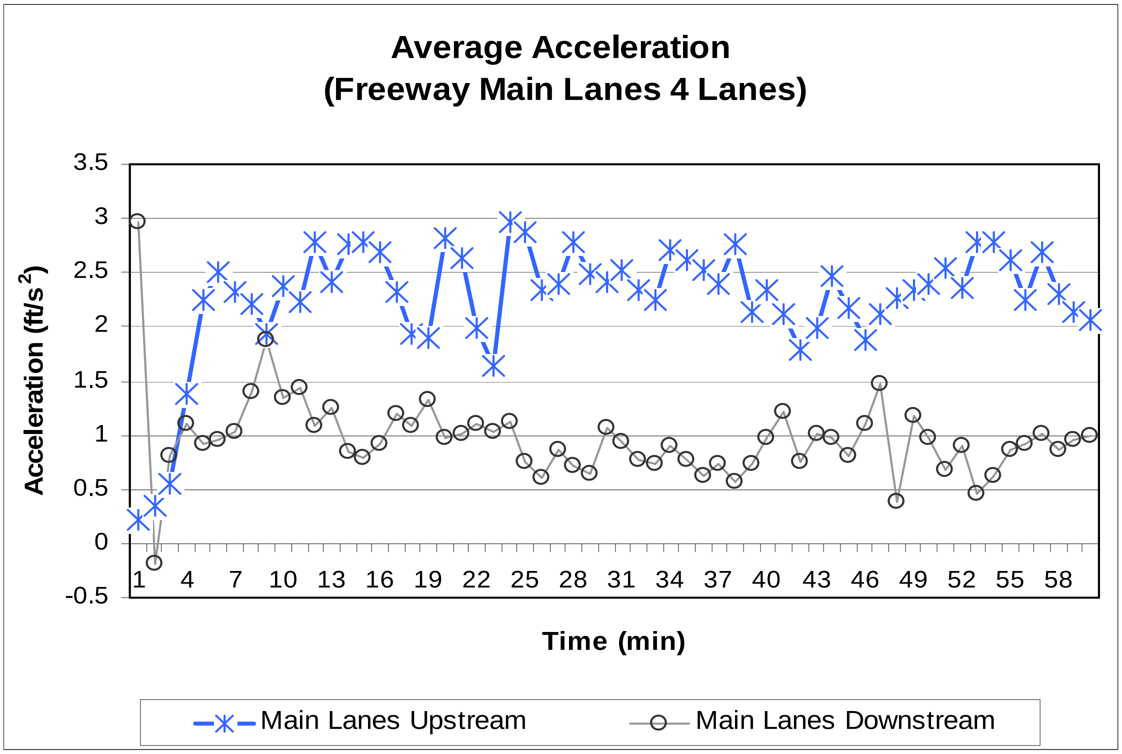

Figure C-17. Average Acceleration for Trucks Restricted – Mainlanes.

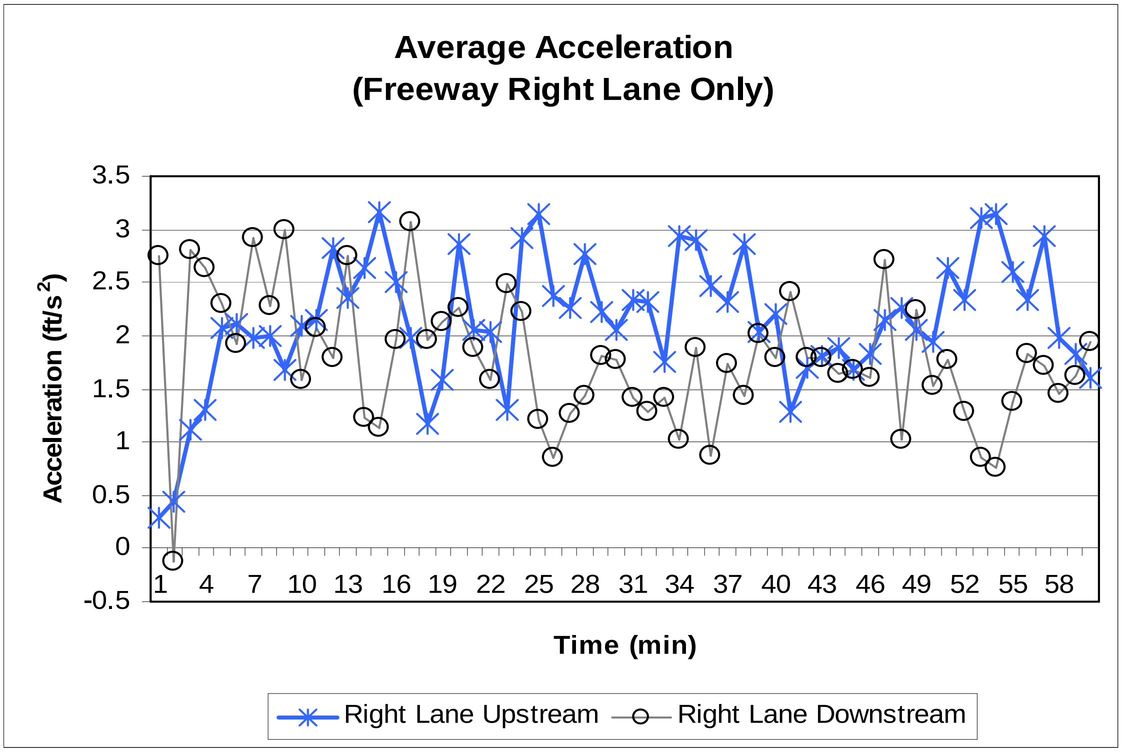

Figure C-18. Average Acceleration for Trucks Restricted – Right Lane Only.

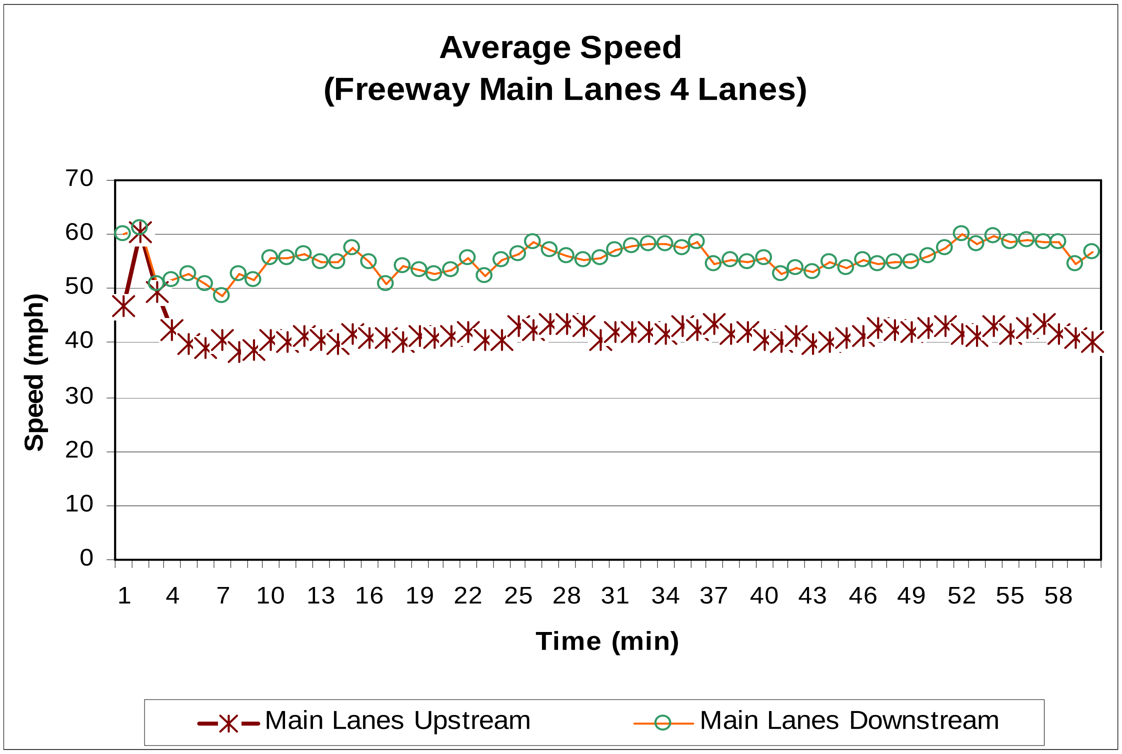

Figure C-19. Average Speed for Trucks Restricted – Mainlanes.

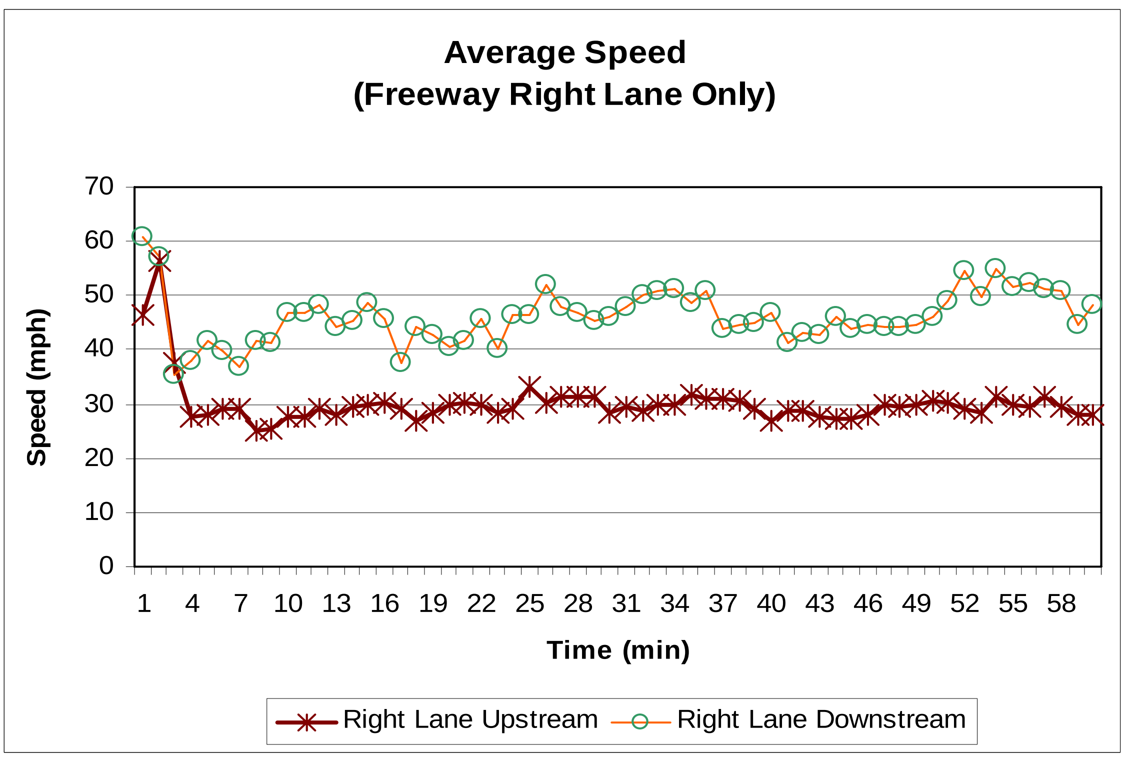

Figure C-20. Average Speed for Trucks Restricted – Right Lane Only.

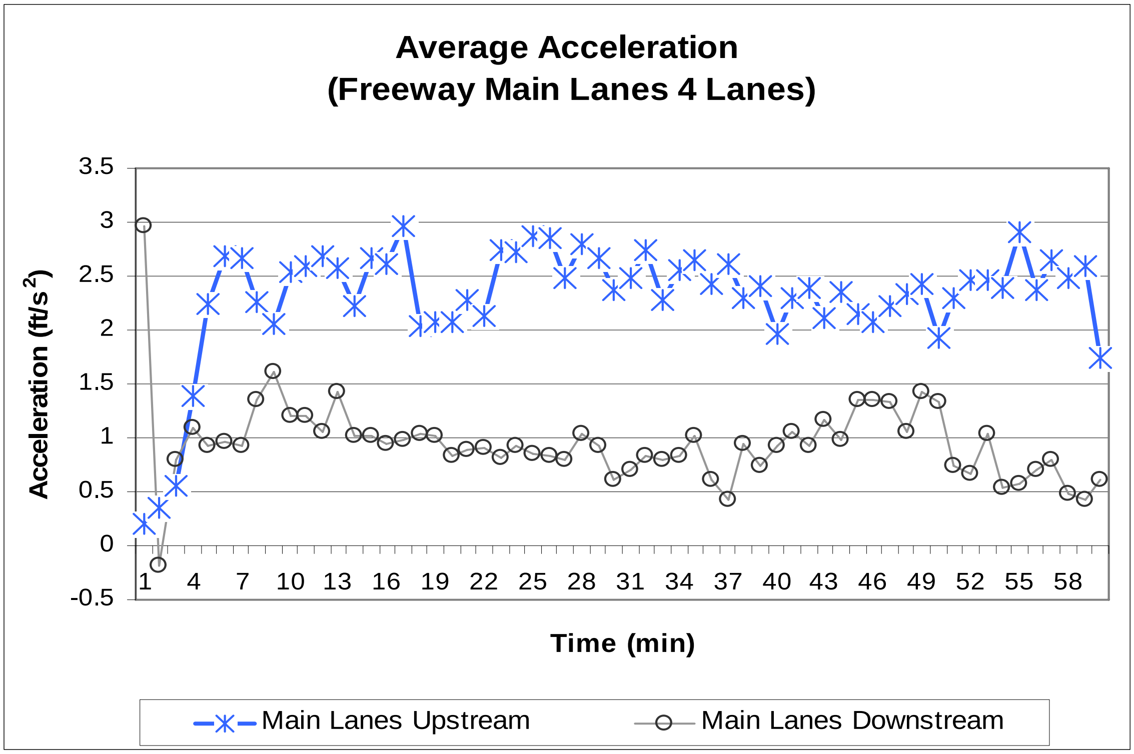

Figure C-21. Average Acceleration for Trucks and Buses Restricted – Mainlanes.

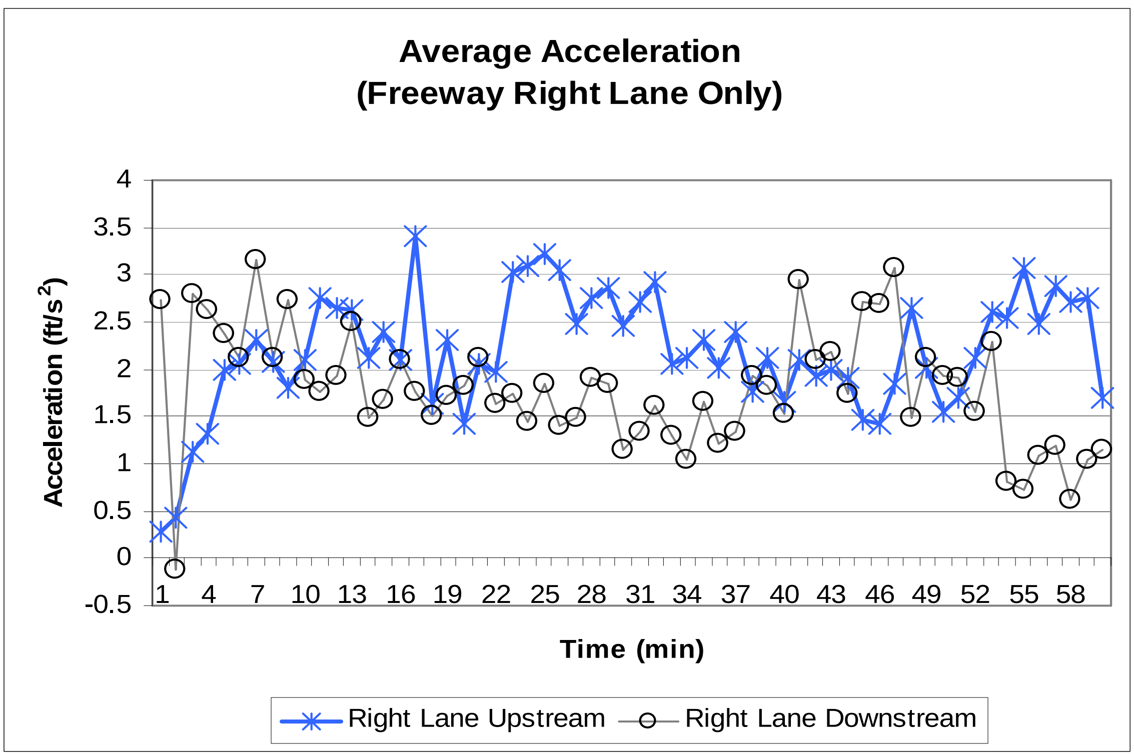

Figure C-22. Average Acceleration for Trucks and Buses Restricted – Right Lane Only.

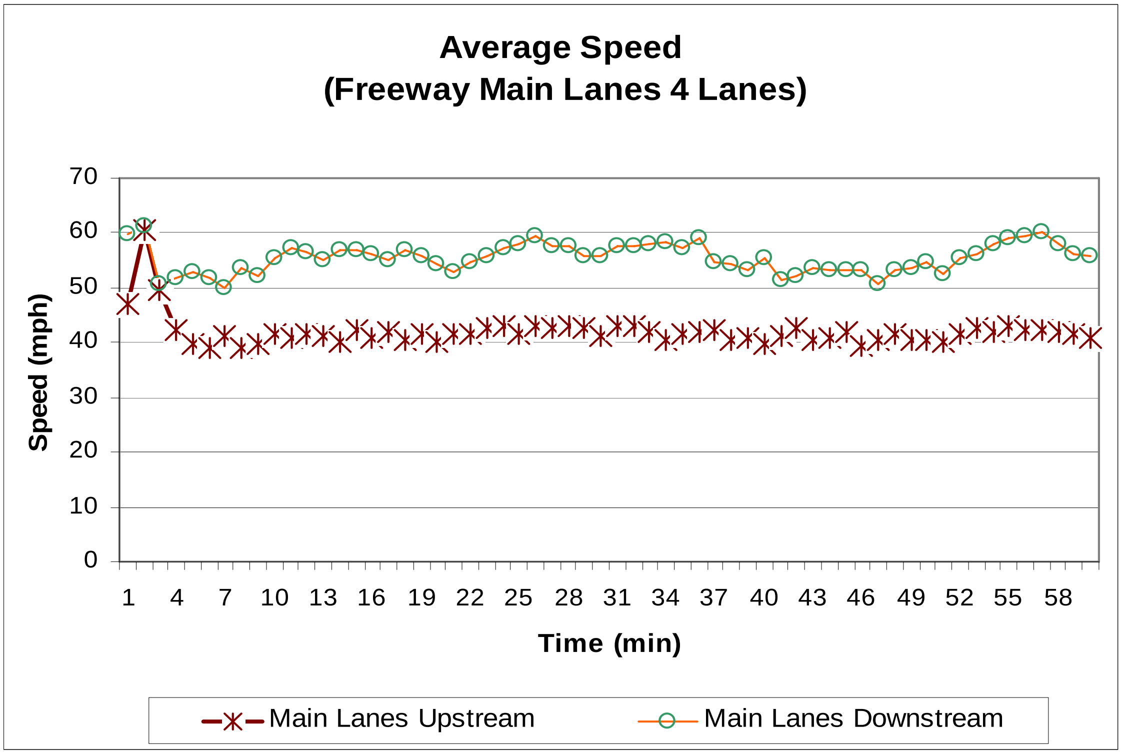

Figure C-23. Average Speed for Trucks and Buses Restricted – Mainlanes.

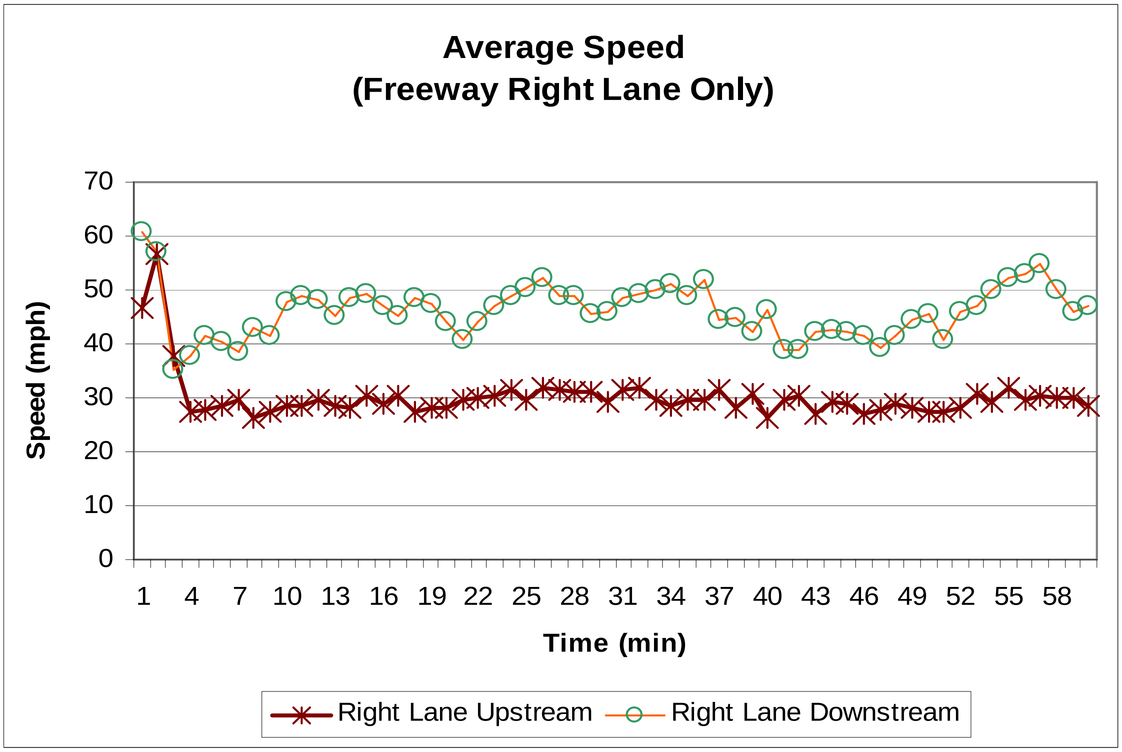

Figure C-24. Average Speed for Trucks and Buses Restricted – Right Lane Only.

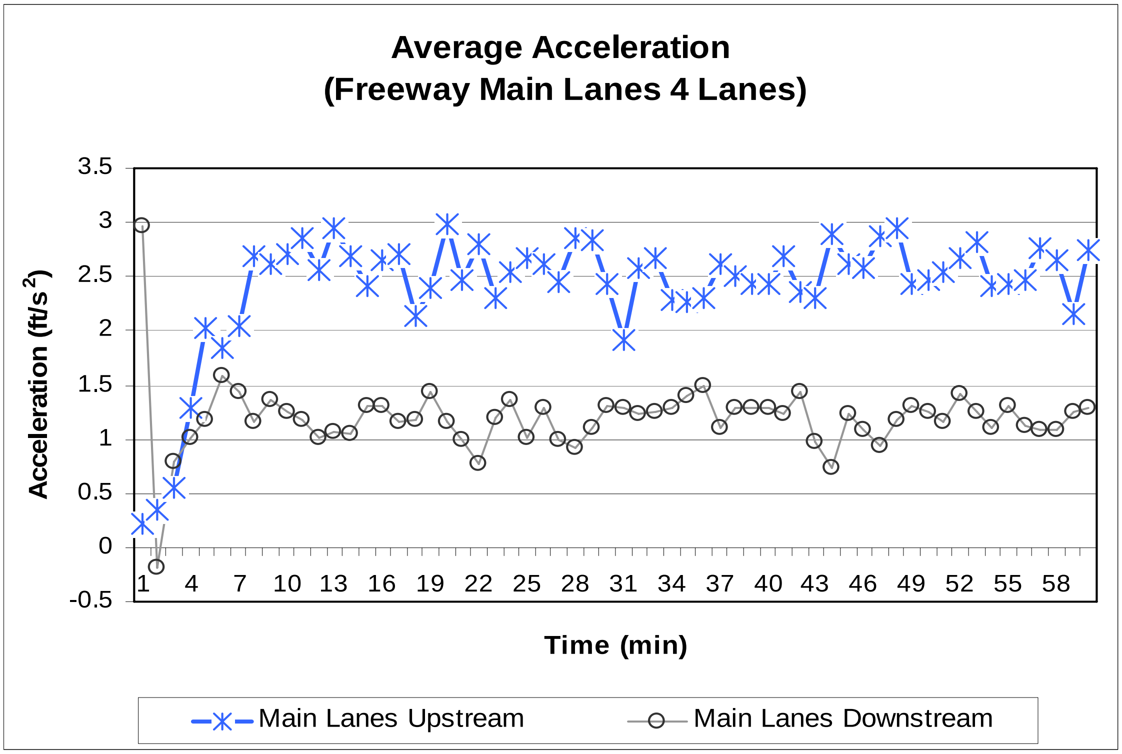

Figure C-25. Average Acceleration for Cars and Trucks Restricted – Mainlanes.

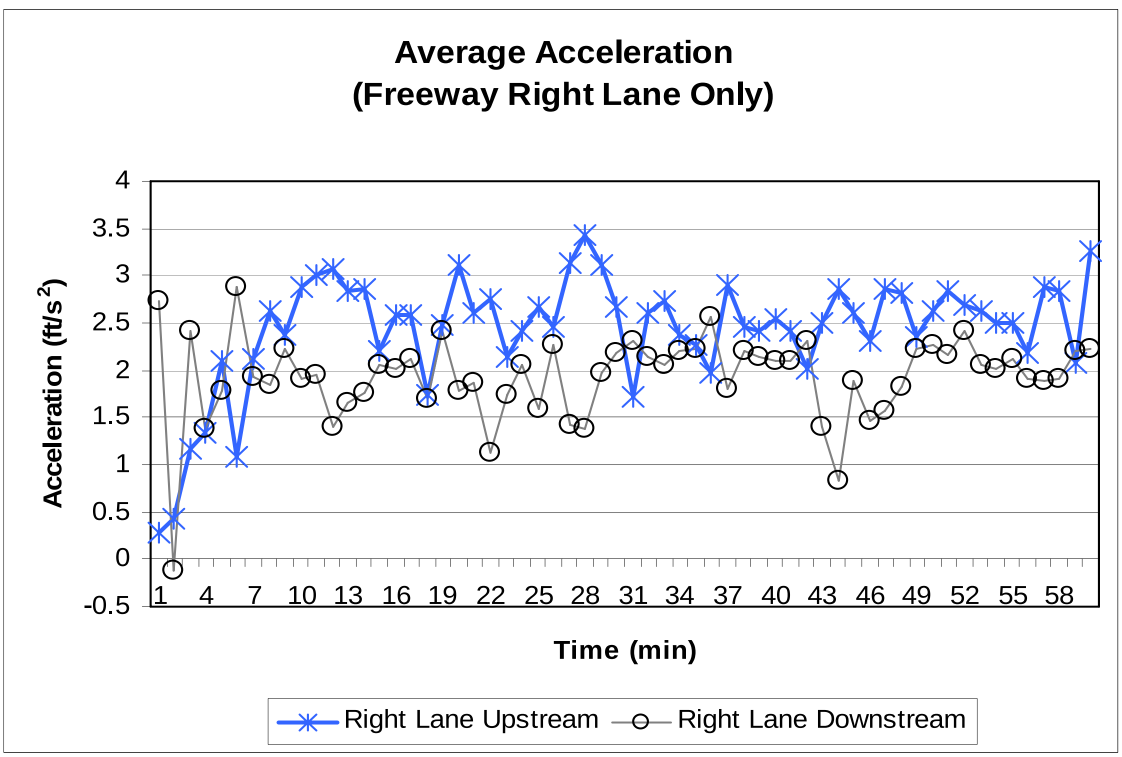

Figure C-26. Average Acceleration for Cars and Trucks Restricted – Right Lane Only.

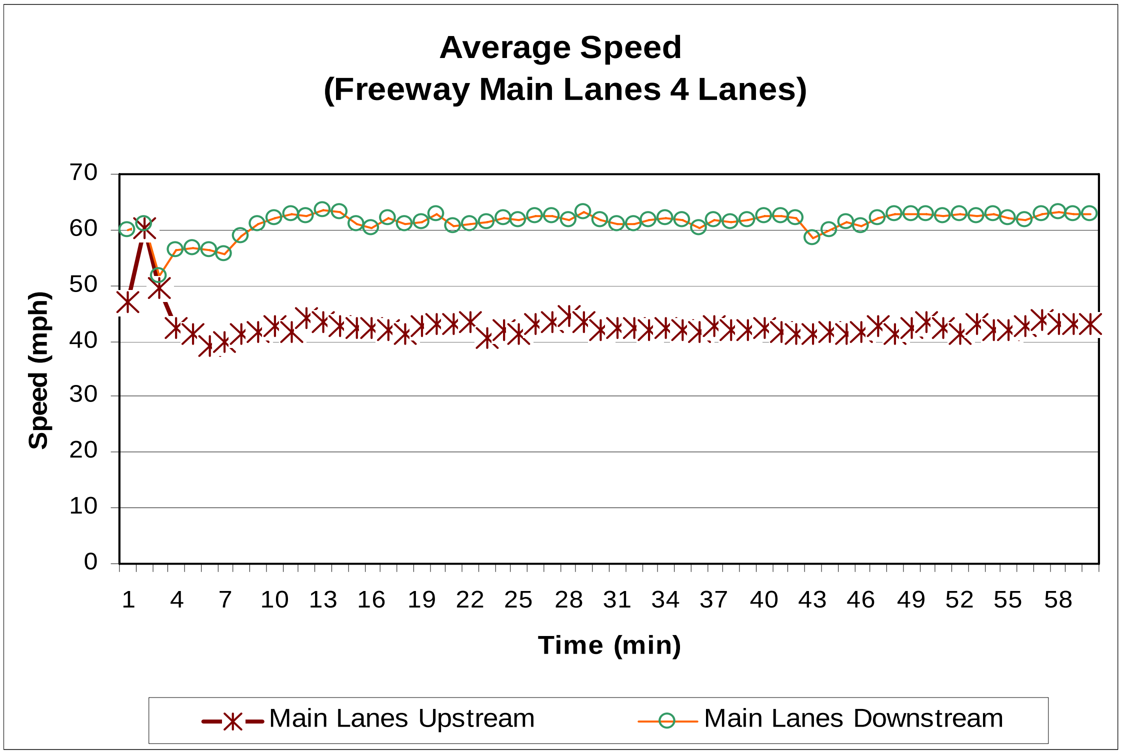

Figure C-27. Average Speed for Cars and Trucks Restricted – Mainlanes.

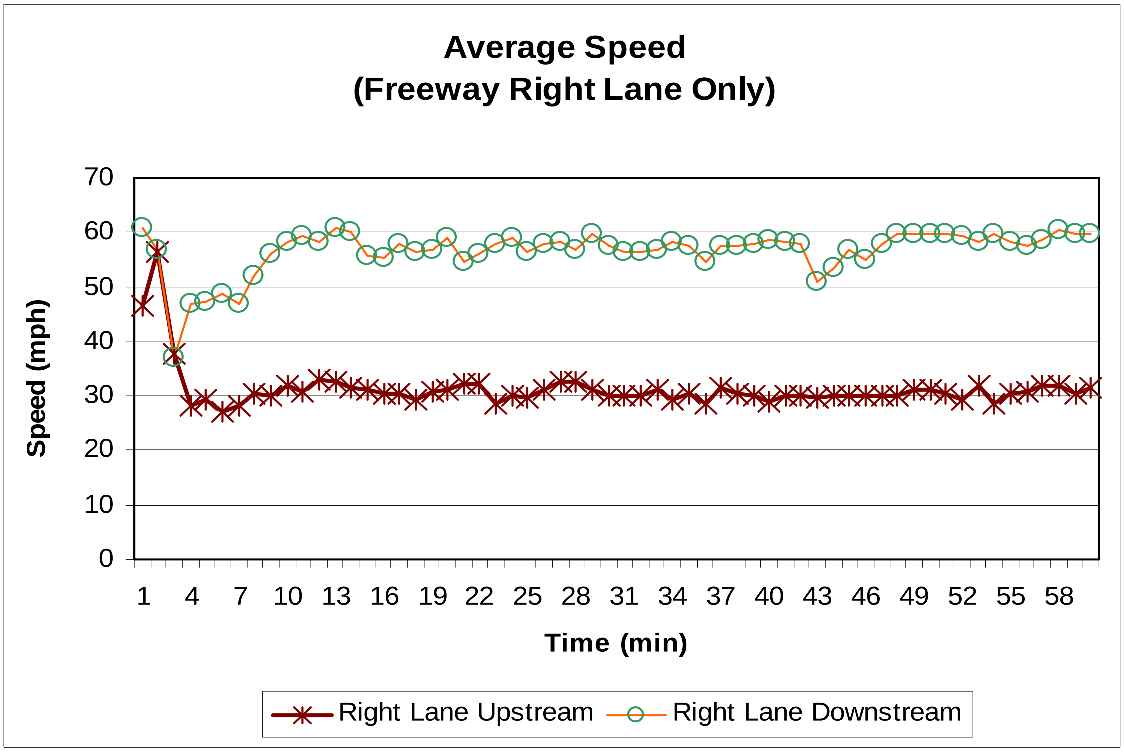

Figure C-28. Average Speed for Cars and Trucks Restricted – Right Lane Only.

Table C-1. Link Evaluation Result Density and Speed Upstream and Downstream.

	NONE		ALL RESTRICTED		CARS	
Upstream	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)
Lane 1	79.87	25.46	66.66	30.83	68.15	30.43
Lane 2	34.03	31.99	29.33	36.26	30.88	37.57
Lane 3	27.39	44.59	26.25	47.35	26.73	46.25
Lane 4	29.02	52.74	28.57	54.37	26.92	55.15
Downstream	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)
Lane 1	62.56	38.43	40.61	56.50	42.55	52.66
Lane 2	23.62	46.73	14.61	61.34	15.31	60.60
Lane 3	20.83	58.22	18.55	63.08	19.65	62.13
Lane 4	24.82	62.12	23.27	64.22	23.50	64.17

	TRUCKS		CAR & TRUCKS		TRUCK & BUSES	
Upstream	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)
Lane 1	70.97	29.03	67.58	30.56	70.21	28.94
Lane 2	30.96	34.70	29.46	36.07	30.01	34.73
Lane 3	26.78	46.49	26.53	47.28	26.19	46.40
Lane 4	28.55	53.88	28.50	54.38	27.92	53.85
Downstream	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)	Density (veh/mi)	Speed (mi/hr)
Lane 1	57.34	45.03	41.27	56.13	56.54	44.47
Lane 2	20.12	53.36	14.53	61.30	20.22	52.37
Lane 3	19.90	60.90	18.60	63.08	19.77	60.34
Lane 4	24.23	63.29	23.47	64.17	23.70	63.01

	CARS & BUSES	
Upstream	Density(veh/mi)	Speed (mi/hr)
Lane 1	67.68	30.54
Lane 2	29.43	36.03
Lane 3	26.29	47.46
Lane 4	28.41	54.36
Downstream	Density(veh/mi)	Speed (mi/hr)
Lane 1	44.67	52.80
Lane 2	15.05	60.20
Lane 3	18.69	62.83
Lane 4	23.48	64.11

Table C-2. Percentage Difference Compared with Base Case Scenario.

	NONE		ALL RESTRICTED		CARS	
Upstream	(%)	(%)	Density Decrease (%)	Speed Increase (%)	Density Decrease (%)	Speed Increase (%)
Lane 1	100	100	16.54	21.08	14.67	19.53
Lane 2	100	100	13.81	13.34	9.25	17.44
Lane 3	100	100	4.14	6.19	2.41	3.73
Lane 4	100	100	1.56	3.09	7.23	4.58
Downstream						
Lane 1	100	100	35.10	47.01	32.00	37.01
Lane 2	100	100	38.16	31.27	35.18	29.70
Lane 3	100	100	10.97	8.34	5.67	6.72
Lane 4	100	100	6.23	3.38	5.30	3.31

	TRUCKS		CAR & TRUCKS		TRUCK & BUSES	
Upstream	Density Decrease (%)	Speed Increase (%)	Density Decrease (%)	Speed Increase (%)	Density Decrease (%)	Speed Increase (%)
Lane 1	11.1	14.0	15.4	20.0	12.1	13.7
Lane 2	9.0	8.5	13.4	12.8	11.8	8.6
Lane 3	2.2	4.2	3.1	6.0	4.4	4.1
Lane 4	1.6	2.2	1.8	3.1	3.8	2.1
Downstream						
Lane 1	8.3	17.2	34.0	46.0	9.6	15.7
Lane 2	14.8	14.2	38.5	31.2	14.4	12.1
Lane 3	4.5	4.6	10.7	8.4	5.1	3.6
Lane 4	2.4	1.9	5.4	3.3	4.5	1.4

	CARS & BUSES	
Upstream	Density Decrease (%)	Speed Increase (%)
Lane 1	15.3	20.0
Lane 2	13.5	12.6
Lane 3	4.0	6.4
Lane 4	2.1	3.1
Downstream		
Lane 1	28.6	37.4
Lane 2	36.3	28.8
Lane 3	10.3	7.9
Lane 4	5.4	3.2

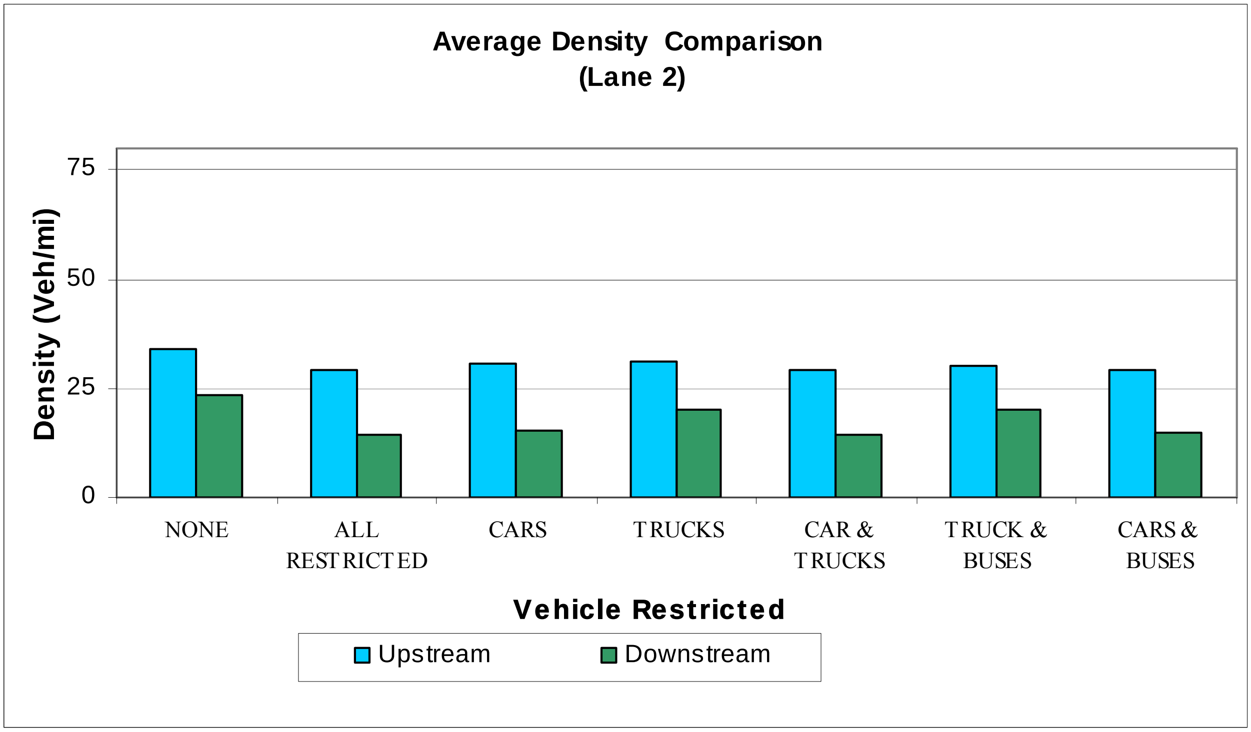

Figure C-29. Average Density Comparison for Lane 2-Upstream and Downstream.

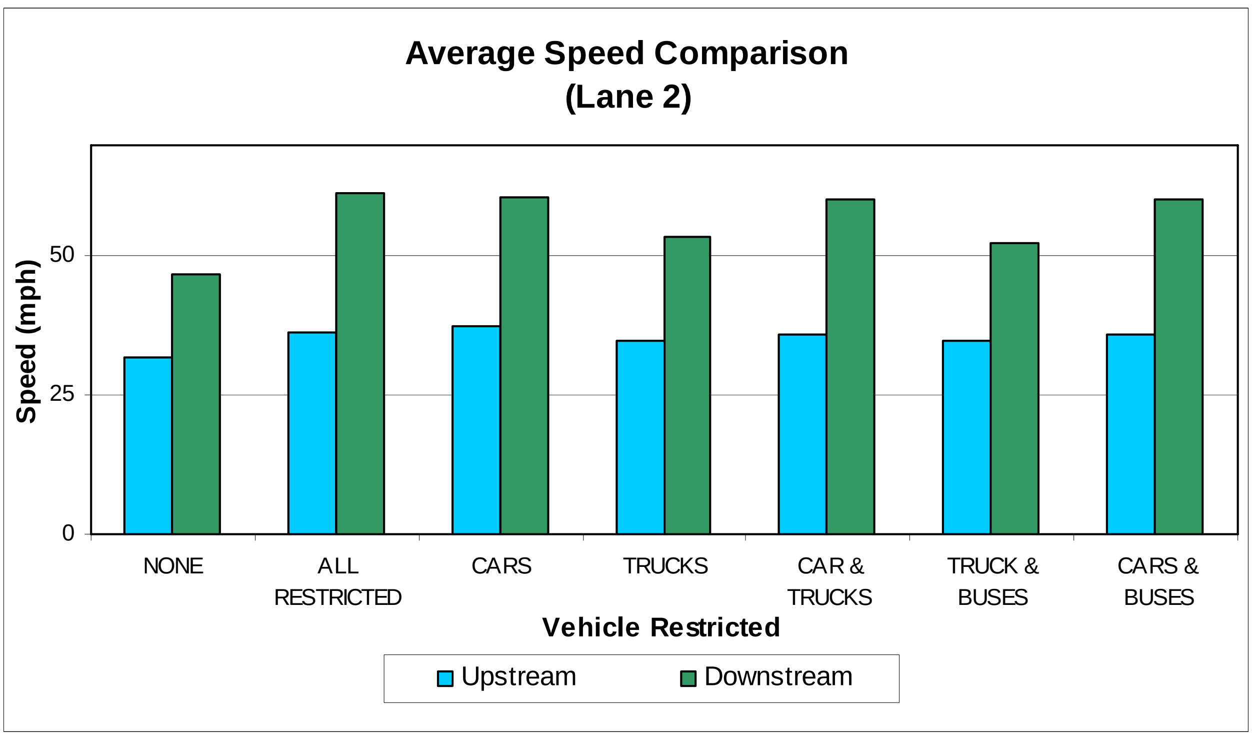

Figure C-30. Average Speed Comparison for Lane 2-Upstream and Downstream.

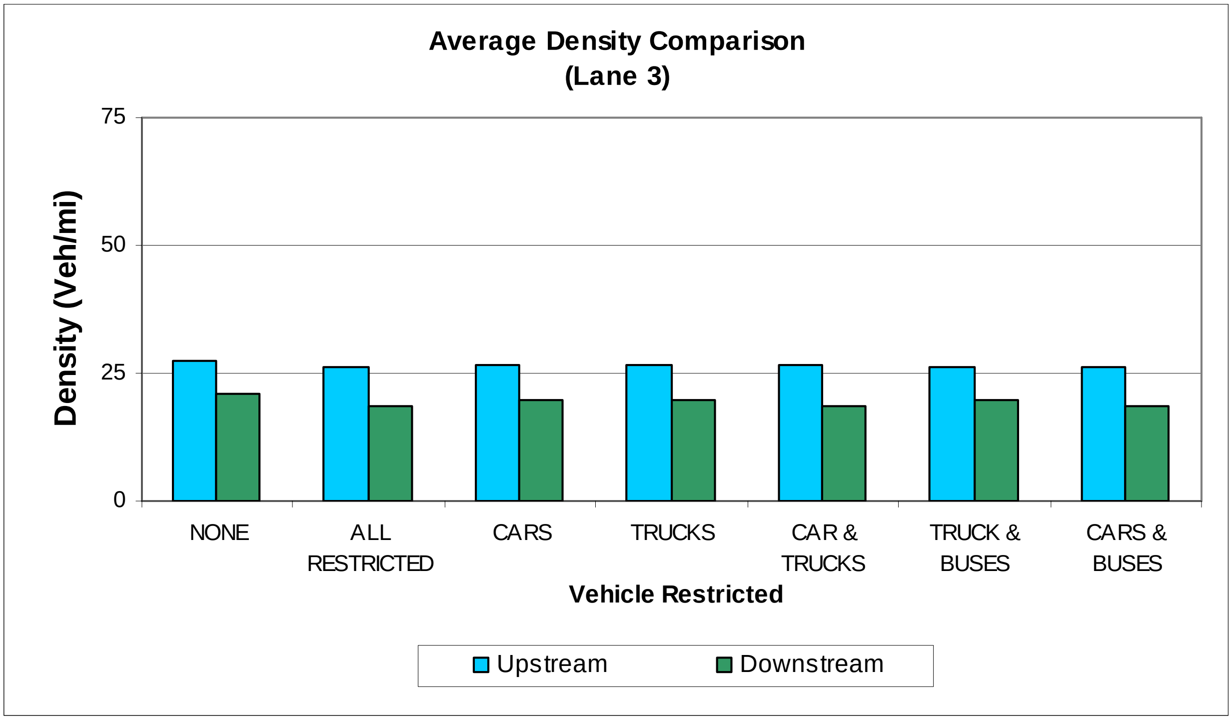

Figure C-31. Average Density Comparison for Lane 3-Upstream and Downstream.

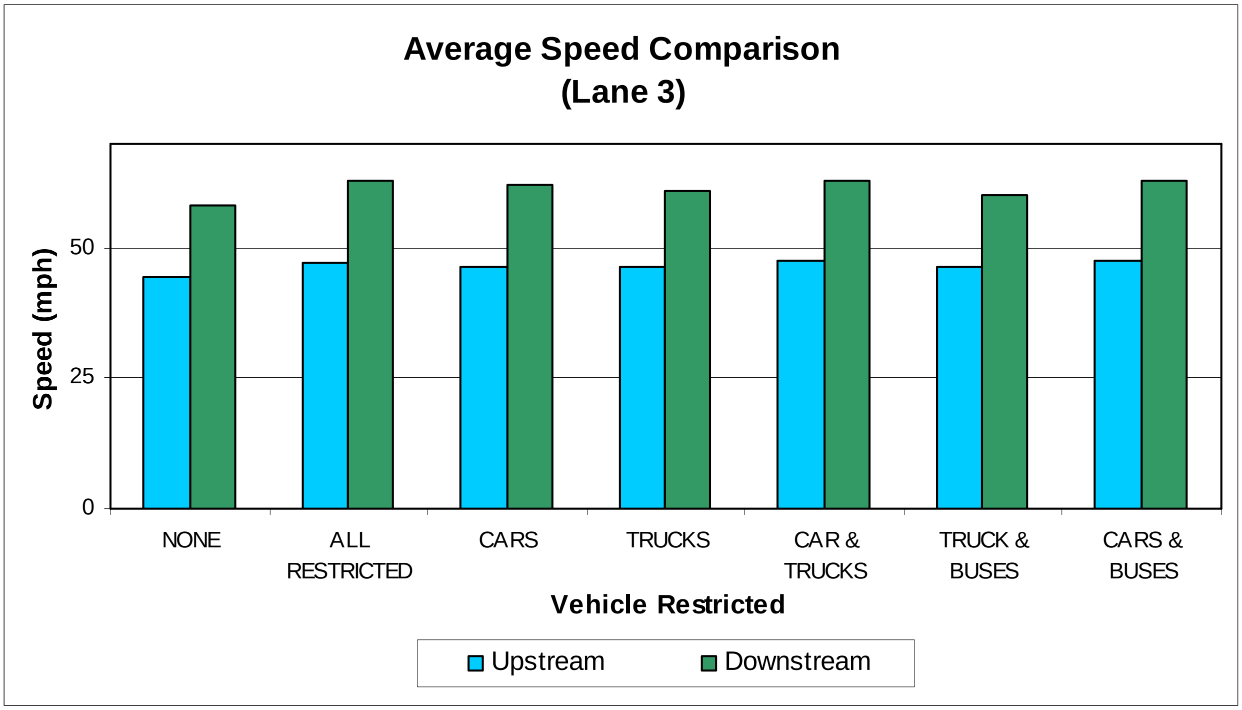

Figure C-32. Average Speed Comparison for Lane 3-Upstream and Downstream.

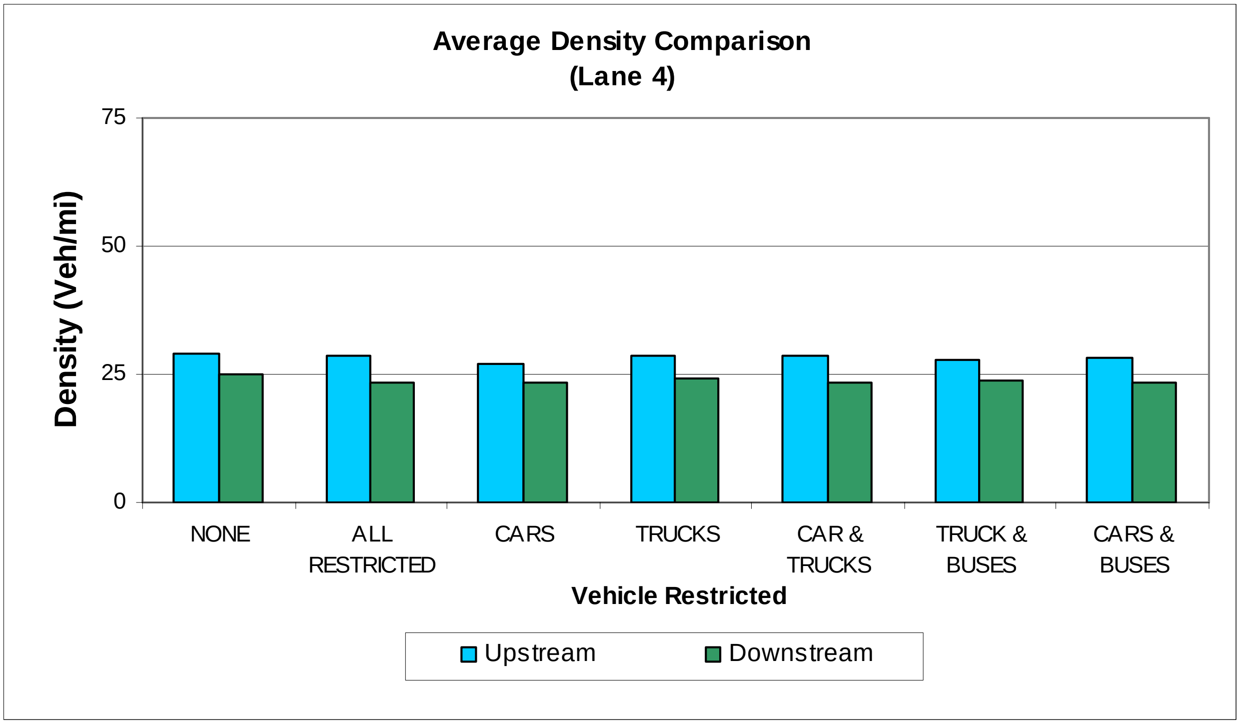

Figure C-33. Average Density Comparison for Lane 4-Upstream and Downstream.

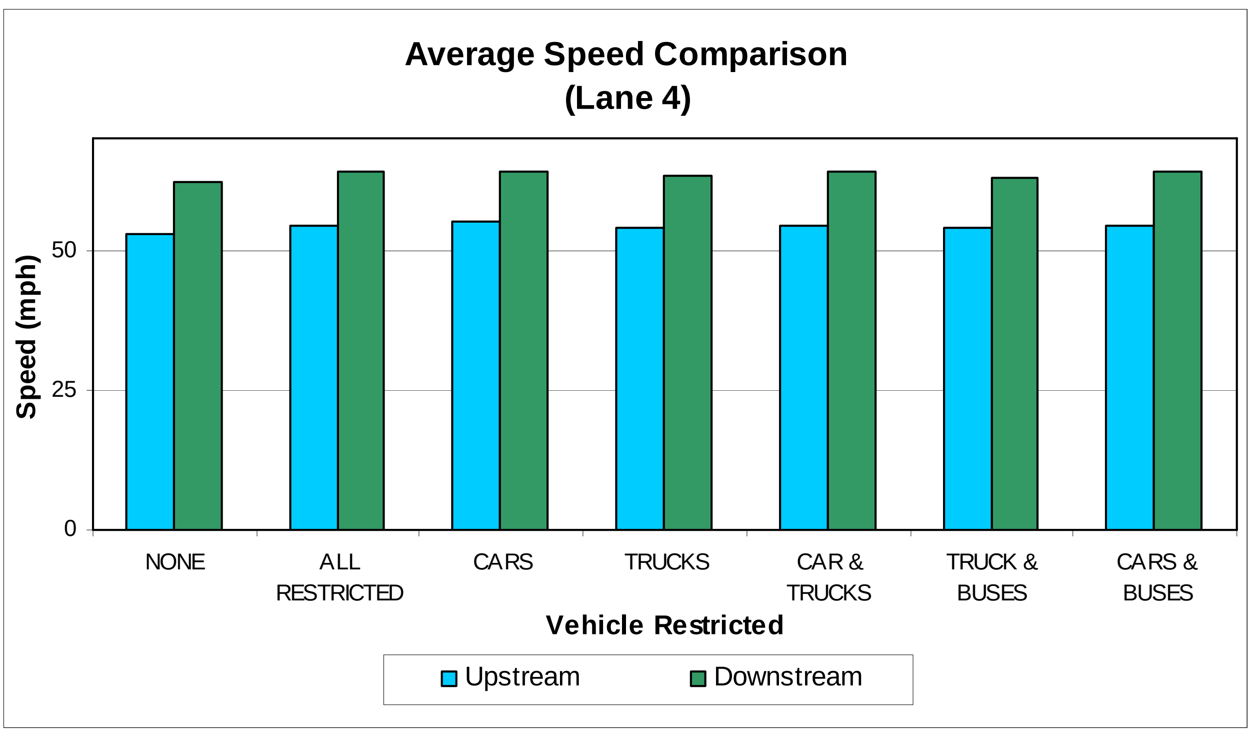

Figure C-34. Average Speed Comparison for Lane 4-Upstream and Downstream.

APPENDIX D: FOCUS GROUP TRANSCRIPTS

452847: Managed Ramps Focus Group
College Station, TX
June 14, 2007

(Numbers preceding answers represent participant numbers, strictly used for notetaking purposes).

<u>Slides 1 & 2</u>

Q: Have you ever seen a freeway ramp like this?
Yes, everyone had seen this ramp; no one knew the name though.

Q: Have you ever used a freeway ramp where the meter was active?
Some had used this; others had not.

Q: What did you do at the ramp?
1 sat at the red light for a long time before entering the ramp.
4 used the ramp as a straight shot onto the freeway; he didn't have to stop at all.

Q: What are you supposed to do at the ramp?
2 said you wait and then proceed onto the freeway.
All agreed.

Q: What did you think was the purpose of the ramp meter?
3 & 4 said to control the volume of cars entering the freeway and to reduce traffic.
1 said to limit the number of vehicles entering the freeway.

Q: Do you think the ramp meter makes access to the freeway easier?
1, 3, & 4 said it does the job, it works.

Q: Do you think the ramp meter affects the freeway?
4 said it does affect the freeway.
7 said it doesn't affect the freeway; there might be a problem further down the freeway.
5 said not good effect on freeway.

Q: How does it affect the freeway?
5 said that it could cause bottlenecks and problems getting on the freeway.

Q: Overall, do you have a favorable opinion about ramp meters?
Most agreed that they were a good thing.
2 said there should be a time limit of being used.

<u>Slide 3</u>

Q: What are some other ways in which TxDOT could manage vehicles getting onto a freeway in place of ramp meters?
4 said toll roads.
1 said toll.

2 said blinking lights.
3 said something that keeps traffic flowing at a steady rate.

Q: In what situations would you see using these methods?
4 said to keep traffic flowing; toll; change the rates.
8 charge less or more depending on time of day.
4 public relations so people know when it will be cheaper to use toll road, what time of day.
3 hates tolls.
8 said to raise tolls in event of accident or road being serviced.
3 managing access to the freeway.

Q: What are the drawbacks?
7 said you still spend same amount of time on the road, it (toll roads) doesn't get you there any faster.
4 alternate routes are not always available so you have no choice/option.
8 some people know the back roads/alternate routes but others don't, especially out-of-towners.
3 will still use the toll road, pretty much no matter what.
7 would just take the service road if freeway was shut down or jammed.

Q: What are the benefits?
3 said to stop or control traffic.
2 said it might save you time.
8 said it could help or hinder if there was an accident.

<u>Slides 4, 5, 6, and 7</u>

Q: Have you ever been on a freeway with an HOV/carpool lane?
Yes, all have seen one.

Q: Have you ever used an HOV/carpool lane?
3, 4, & 5 have used an HOV lane.

Q: What do you think the purpose of the HOV/carpool lane is?
1 said it encourages people to carpool.
8 said it creates less congestion on the road.
4 said it helps with the through traffic.
3 said it makes your travel time quicker and safer.
2 said it helps to decrease the amount of pollution.
6 said it helps keep traffic down.

Q: If you saw this sign at a ramp, what would you think it meant?
1 thought the sign was very misleading and would hesitate to use it.
4 & 3 said you can take the ramp and that there is an HOV lane on the freeway.
3 also thought that the ramp could be for HOV only.
5 & 6 would hesitate to use the ramp because they do not understand the sign.

7 thought about TxTag and if you have one you can use the ramp?
8 thought if he couldn't use this ramp because his vehicle is not high occupancy, will there be another ramp he can use later to enter the freeway, he might get lost if there is not a clear sign of entry soon.

Q: Does it tell you anything about the main lanes on the freeway?
3 & 4 thought it could mean there is an HOV lane on the freeway.

Q: Would you know how to behave?
Almost everyone said they would be hesitant to use the ramp in fear that it wasn't for them.

Q: If you traveled this road frequently, what would you do?
3 said he would use an alternate route if there was one available.
6 said that it would encourage her to carpool with people that lived near her.

Q: If you knew there was an HOV lane in the center of the freeway, that you could use, what would you do?
5 said that she would definitely carpool.
3 said he would feel a little safer, especially since it would go one way at certain times of the day; he also brought up the example in D.C. and said that this would offer incentive for carpooling as well.
2 said if you live in the same neighborhood then this would be a great way to carpool.
4 brought up the California carpool for big employers; all park at one place and then one person drives them into the city.
1 said we could start using more public transportation systems to take advantage of the center lane HOV lane.

<u>Slide 8</u>
Q: What if the ramp sign said bus and taxi only?
All said they would take another route.
4 said he might just take it anyway.
7 said she wouldn't take it because it's for bus and taxi only, but what if they took it, would they be able to get off.
1 said she would never take it, no matter what.
8 brought up the idea that maybe these particular ramps should be marked on a map so the public knows which ways they should be accessing the freeway.

Q: Overall, do you have a favorable opinion of this ramp treatment?
Most said it was unclear who could use which ramps and therefore wouldn't use them. If they did for some reason decide to use it, could they get off somewhere, would they get in trouble, how would they know these things?

<u>Slides 9 and 10</u>
Q: Have you ever been on a toll road?
Everyone had been on a toll road.

Q: What do you think you get for your money on a toll road?

Most said that it helped you get to your destination quicker.

Q: If you saw this sign at a ramp, what would you think it meant?

8 said it was trying to help control the amount of traffic on the freeway.
All thought it meant that you had to pay $1.25 to use the ramp.
Do you have to pay again and what about when you get off?

Q: Does it tell you anything about the main lanes on the freeway?

All agreed that it didn't tell you anything about the freeway, if there was traffic or how much faster it would get you to your destination.

Q: Would you know how to behave?

3 said pay the toll and get to your destination quicker.
4 didn't know if it would help you get there faster, there might be traffic jams or an accident but would pay the toll anyway, pretty much no matter how much the price was.

Q: What do you think the purpose of this ramp treatment would be?

4 said that it could be a major exchange area and therefore higher volumes of traffic so you only pay this amount if you really need to get on the freeway; also if there was an emergency or an accident, this high price could help weed out the number of cars on the road.
5 brought up the GOOD POINT that this ramp could mean that by entering this HOV ramp you wouldn't have to cross three lanes of traffic to get to the HOV lane or to exit when you wanted off the freeway.

Q: If you traveled this road frequently, what would you do?

4 said he would pay the toll anyway.
2 said he would get EZ tag.
3 would pay it anyway.
8 said would use it if he got reimbursed from employer, or he would use alternate route.

Q: What do you think you would be willing to pay to use this ramp?

3 & 4 said they would pay anything to use it if it got them to their destination quicker.
Others said if the price got too high they would find another route, but otherwise would pay the $1.25.

Q: If you knew there was a ramp upstream or downstream of this one that didn't charge a toll, what would you do?

Almost everyone said they would take the toll free ramp.
Some said they would still take the ramp; they didn't care if they had to pay, just as long as they got to their destination faster.

Q: Overall, do you have a favorable opinion of this ramp treatment?

Everyone said that this sign had merit for some reason or another, whether it is an accident, or the regular toll.

You could change the amounts for when construction or an accident had occurred or just to reduce the amount of vehicles entering if it were a major exchange area.

<u>**Slide 11**</u>

Q: If you saw this sign at a ramp, what would you think it meant?

1, 2, & 3 said no trucks allowed period.

4 said yes, no trucks but what kind of trucks are we talking about.

1 said pick-up trucks should still be allowed to use the ramp.

All agreed that BIG trucks (semis) are not allowed to use the ramp from between 6:30 am and 9:30 am Mon-Fri.

Q: Does it tell you anything about the main lanes on the freeway?

All agreed that the sign doesn't reveal very much information about the main lanes on the freeway except for the fact that semis cannot use the ramp from 6:30 am to 9:30 am Mon-Fri.

Q: Would you know how to behave?

All agreed that if they were driving a semi they would not use the ramp during the specified hours.

Q: What do you think the purpose of this ramp treatment would be?

1 said to help reduce the amount of semis on the road during rush hour.

2 & 8 said that they would use the ramp either really early in the morning or at midday when they were allowed to use it.

No one was sure that there was really a very big benefit of having a ramp with this signage.

Q: What would you hope to gain by this?

1 said it would help to keep the traffic moving.

8 said that it would help out at high traffic hours.

3 mentioned that it could help to protect the road, although he also said that he didn't really see the benefit of this.

Q: Overall, do you have a favorable opinion of this ramp treatment?

4 said he wasn't sure of what the sign was trying to accomplish.

3 didn't see too much of a benefit either.

<u>**Slide 12:**</u>

Q: Say you were traveling on a freeway and there was an incident, do you think the ramps could be managed?

All agreed that if all the ramps closed during an incident that this would be beneficial by using road blocks or police cars.

1, 2, 3, 4, & 8 said that if these ramps were closed alternate routes should be given.

Others said to have some ramps remain open for people to get on and off but have a higher toll to pay.

Q: When would you close these ramps and for how long?
If there was an incident or some construction being done, all agreed to close the ramps until the issue had been resolved.

Q: Who could and could not use them?
1 said the police.
3 said emergency medical services.

Q: What might a sign need to say?
2 & 4 said that we could have signs to direct the drivers' attention to a radio channel so they can learn more about what's going on.
1 said a short description of what might be going on.

Q: What might you hope to gain managing them?
All agreed that by closing the ramps emergency vehicles and police could get to the problem faster and clean it up quicker allowing drivers back on the road quicker.

Q: Overall, do you have a favorable opinion of this approach?
All said yes.

Slide 13
Q: What do you think this is?
All knew it was a gate.

Q: When do you think it might be used?
8 said when you have to shut a ramp down.
3 said it might be an HOV or to help regulate the ramp.
2 said it could be closed because of weather issues.
1 said it could help the freeway run smoother at certain times of the day.

Q: What do you think the purpose of this ramp treatment might be?
4 said that some people might drive up the ramp too slowly during high-traffic hour and might cause accidents.
4 also said to help limit the access to the freeway at that particular area.
6 said that there could be problems with speed limit issues.
1 brought up the idea that it might have to close during weather issues.

Q: What might you hope to gain by using it?
4 said fewer accidents.
3 said to reduce traffic in that area of the freeway.

Q: Overall, do you have a favorable opinion of this approach?
All agreed that this has merit and benefits.

3 was not quite sure of what those benefits might be.
1 was dead set on the weather aspect.

452847: Managed Ramps Focus Group
Houston, TX
July 17, 2007

Q: What are ways in which you think we can manage traffic on our freeways?

7 Finish construction.
6 Cut down on the number of people driving.
3 Have longer on-ramps; allow people to have a longer time to gain speed before entering the freeway.
6 Take longer for lanes to converge.
7 Have an on-ramp parallel with the freeway.
4 On US 59, have a mile to get on and get off; likes design.
3 The on- and exit ramp are the same thing, makes life a little easier.
6 Wants better striping and reflections.
2 Likes the signs that tell you what's going on, i.e., DMS.
4 Raise the speed limit; people who aren't going the speed limit, under everyone else makes it more dangerous.
8 Better signage, didn't see exit in time or were going too fast.
7 Especially during construction, better and bigger signs, once you miss the exit you miss it, the signs are too small or are not far enough in advance for you to slow down and get over.
3 Guidelines for sign size and distance?
4 Carpooling, not efficient in Texas, train system.

<u>Slides 1 and 2</u>

Q: Have you ever seen a freeway ramp like this?

Yes, everyone had seen this ramp.

Q: Have you ever used a freeway ramp where the meter was active?

All had used this ramp while activated.

Q: Were you unsure of what you were supposed to do at this ramp?

6 Have to stop and obey the signals.
All agreed with this statement.

Q: What are you supposed to do at the ramp? What is its purpose?

2 Supposed to monitor the amount of cars entering the freeway.
1 Helps to let people actually get on the freeway, let people in.
7 Help to mediate the overall traffic.
3 Helps time the vehicle in front of you so that there is enough space for you to get on and allows you to accelerate and meet the flow of traffic.
5, 7 Goes really fast.
6 It's a gap finder, find gaps in that lane so you know when to go.
7 It's a timer for entering the freeway.
2 Manage the number of cars entering the freeway on that ramp.
4 Has nothing to do with the traffic.

Q: Do you think the ramp is effective?

5 At high traffic time, yes.
3 At some places on the freeway, yes.
Everyone else said no.
1 More effective as a stop sign, one vehicle per green light, or stop sign.
7 Really all this is doing is shifting the congestion to behind the ramp instead of entering the freeway.
6 Put the light in a different location.

Q: Overall, do you have a favorable opinion about ramp meters?

No one thought this was a good idea; no favorable opinions.

<u>**Slide 3**</u>

Q: Do you think there are other ways that traffic can be managed?

4 All you're doing is delaying people from getting on the freeway, staggering when people get off work.
5, 7 Good point, agree.
6 Take far lane and make the speed limit slower; extend the ramp so cars can gradually gain speed and then once they are on can move over to the normal speed limit lane and blend in with traffic.
2 Make the ramp a longer lane.
3 Merging lanes, have a warning for people already on the freeway to slow down because of merging traffic ahead.
4, 6 Yield sign, or encourage people to get out of the merging lane.
2 Be courteous.
7 Make more lanes, lane all by itself, slowing merging to the highway.
6 Law to slow down for people in the right lane, especially cops, more lanes, better laws to manage the traffic.
4 Train system.
7 Do something radical, a monorail system; you have to wait, going to school it allows you quicker access.
2 Goes in every direction.
1 If I take the monorail, how do I get back? I won't have a car.
6 Cross traffic, buses, taxis.
7 Would be helpful for I-10, 610, and I-45 south, reducing traffic on the roads.
3 Arms come down in conjunction with the lights.

Q: Under what situations would you want to manage the access?

5 High traffic time.
8 All the time.
2 All the time so that they become accustomed to it — might be more apt to follow it.

Q: What are the benefits of managing access?

2 Traffic jams
3 Should be used 24-7 to increase approval.
1 Spacing out the cars, allow some gaps in the traffic to enter the freeway.

2 Keep the freeway flowing so you can get on.
3 Help people to make better decisions.
7 Take a u-turn and keep going, it's a guarded situation, you can safely get on the freeway, make the entrance ramps two lanes.
6, 7, 5, 2 Offer incentives to use the railway, carpool.

Q: What are the drawbacks?
7 Having to wait to get on the freeway, then causing a backup on the ramp loop around.
2 Too many cars on the freeway.
All agree there are too many cars on the road.

Slide 4

Q: Have you ever been on a freeway with an HOV/carpool lane?
Yes, all have seen one.

Q: Have you ever used an HOV/carpool lane?
5 Accidentally used it — wasn't well signed.
All have used an HOV lane.

Q: What do you think the purpose of the HOV/carpool lane is?
6 To relieve traffic on the main freeway.
7 To encourage people to carpool.
8 To decrease the number of cars on the road.

Slide 5

Q: If you saw this sign at a ramp, what would you think it meant?
3 Do not enter unless you have the correct number of passengers between those hours.
8 Only use HOV between those hours, 6:30 - 9:30 am.

Q: Does it tell you anything about the main lanes on the freeway?
No, it doesn't tell you anything about the main lanes on the freeway.

Q: If you came up to this ramp, would you know what to do?
5 You would assume that if you were alone that you couldn't get on that ramp.
7 If it was 9:31 I would get on; for those previous three hours it is an HOV ramp only.

Q: What do you think the purpose of this sign or the treatment of this ramp is?
4 Only the people who carpool can use that ramp, and the whole freeway.
7 Offers the incentive that between those hours in a high traffic area, if you meet the requirement you can jump on that ramp and take the fast track. The whole facility is an HOV facility between those hours.

Q: If you traveled this road frequently, what would you do?
2 Find someone to ride with me.
7 Switch the work times so that you could use the ramp.

Slides 6 and 7

Q: If you knew there was an HOV lane in the center of the freeway, that you could use, what would you do?

4 That sign would be wrong.
6 Use an off-ramp.
7 Congestion could be skipped if you have enough people to meet the HOV requirements.

Q: Allow HOV to access to this ramp to allow them to get to their lane, do you think this is a good idea, bad idea?

2 HOV cars get extra access to the regular freeway, bad idea, already encouragement to have their own lane.
1 Good idea.
7 Might help, possibly if you had an overpass over the freeway that let you enter directly in the HOV lane; do not use unless you are an HOV vehicle, all day long, all night.
8 Good idea, inbound, must go to transit stop to use the HOV lane.
5 Not convenient, currently, there are few entrances.
2 Few entrances.
6 Transit system, HOV lane is bad idea, waste, still people driving.
2 Railways going in all areas out of town and then have busses in between.

Slide 8

Q: What if the ramp sign said bus and taxi only?

We can't get on it because it's only for busses and taxis.
2 HOV lanes only.
5 They are usually carrying more than one person.

Q: Overall, do you have a favorable opinion of this ramp treatment?

4 Sees this ramp treatment as useless.
3 Sees the diamond and thinks this is HOV hours.

Slide 9

Q: Have you ever been on a toll road?

Everyone had been on a toll road.

Q: What do you think you get for your money on a toll road?

6 A faster way around.
2 Faster if you have an EZ-Tag.
Saves time if you have EZ-Tag, otherwise you might have to wait in line to pay.
Saves time but you pay the price.

Slide 10

Q: If you saw this sign at a ramp, what would you think it meant?

Anyone can use it but you will have to pay $1.25 somewhere on it, or to get off it somewhere.

Q: Does it tell you anything about the main lanes on the freeway?

That it's a toll road.

Q: What do you think the purpose of this ramp treatment would be?

2 To let you know that it is going to cost you money to use it.

5 You would think there would be fewer cars on the toll road because it's not free.

Q: If you traveled this road frequently, what would you do?

5 Wouldn't pay.

2 If she knew traffic was flowing quickly would pay.

7 Would not pay if knew was going to have to sit in traffic.

It's worth it if it's not rush hour and there isn't a lot of traffic on the toll way.

Q: What do you think you would be willing to pay to use this ramp?

2 Would not pay to sit in traffic when there is a feeder road she can use for free.

4 She would pay $0.25.

7 EZ-Tag.

Q: If you knew there was a ramp upstream or downstream of this one that didn't charge a toll, what would you do?

6 Drive to the next ramp.

2 If there's not traffic on the toll way, yes would drive down and take it.

6 Give some sort of incentive to buy EZ-Tag, incentive to use HOV lane.

1 Nothing is working, if you make it tax deductible.

4 Credit your card; credit your EZ-Tag, rebate.

Q: Overall, do you have a favorable opinion of this ramp treatment?

4 If there is a free one then this is a bad idea.

7 Why pay to wait in traffic when you can get on free or wait in traffic for free, lower the price in general.

6 Objective is to relieve traffic off the main streets, offer an incentive to get people to use it.

3 Point of toll road was to raise enough money to pay for the road and then it would become free, registration renewal, increase in pricing.

Slide 11

Q: If you saw this sign at a ramp, what would you think it meant? What does it tell you about the main lanes on the freeway?

7 No heavy trucks are allowed on the ramp during that time span.

4 Big trucks can't have access to this entire freeway, including the ramp during those hours.

2 That anyone else can use the ramp besides big trucks.

6 No trucks can use this ramp and they certainly can't use the freeway during those hours.

Q: Would you know how to behave?

2 If driving a truck cannot use the ramp, go down further and find another one.

Q: What do you think the purpose of this ramp treatment would be?

2, 6 Keep trucks off the freeway in that particular area.

Q: What would you hope to gain by this?

2 Drivers don't have to beware of trucks as much in this particular area.

5 Reduce the amount of traffic in that area of the freeway.

Q: Overall, do you have a favorable opinion of this ramp treatment?

5 Have all the truckers drive in one lane on the highway, have their own lane, their own entrance ramps.

7 Agreed with having a lane for them.

1 Need to have bigger entrances, longer ramps for the trucks to enter as well as everyone else.

<u>Slide 12</u>

Q: Say you were traveling on a freeway and there was an incident, do you think the ramps could be managed?

All said yes to having the ramps managed if there were an incident.

4 Close the ramps if there is an incident, all of them.

2 Divert the traffic trying to enter the freeway to somewhere else until the accident is cleared, close the entrance ramps before the incident, and open ramps after so that people can still get on but not right in the traffic of the incident.

1 Skip two ramps, close two, and then open the rest after the incident.

Q: When would you close these ramps and for how long?

6 Manage the ramps until the accident is clear and there is a free flow of traffic again. All agreed with this statement.

Q: Who could and could not use them?

7 Only allow emergency personnel to use the ramps (police, ambulance, fire department.

Q: What might a sign need to say?

1 That there is a car accident ahead, prepare to slow down, prepare for traffic. All agreed with this idea.

Q: What might you hope to gain managing them?

1 Keep the traffic jam from growing any larger.

7 Divert drivers trying to enter the freeway or exit to the feeder roads to get people off the freeway.

5 Could use the gate to close the ramp in this kind of situation.

6 Keep one lane open to keep the traffic flowing, have signs and police officers directing traffic to keep things flowing.

7 Close the nearest ramps.
3 Needs to be better management by the city/police to help traffic move along.

<u>Slide 13</u>
Q: When do you think it might be used?
2 Use this when evacuation is in place.
6 Help prevent gridlock on the freeway.
1 Emergency situations.

Q: What might you hope to gain by using it?
4 Close every other ramp to prevent too much traffic on the freeway, to control the traffic and entrances to the freeway.
1 Help control traffic in an emergency situation.
3 Might create a back-log of traffic if closed.

Q: Overall, do you have a favorable opinion of this approach?
4 Glad it's an option, they are accessible to close.
Yes, favorable opinion.
2 Move them further back so people don't drive up to the ramp and have to back up; have signs saying gate closed far in advance.

APPENDIX E: MANAGED LANES HANDBOOK CHAPTER

Chapter 16 – Applying Managed Lanes Strategies to Ramps

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Section 1 – Overview

Managed lanes operational strategies can maximize existing capacity, manage demand, offer choices, improve safety, and generate revenue. The key to successfully operating managed lanes is the ability to alter the operations of the lanes in ways that keep traffic flowing. This strategy provides flexibility, not only in the day-to-day operations of the lanes, but in situations where isolated incidents such as a major accident call for the lanes to be open to more or different user groups.

Current Ramp Management Strategies

Historically, ramp management strategies refer to ramp metering and ramp closures. These strategies with special use treatments and ramp terminal treatment are the most commonly accepted methods of ramp management strategies. Ramp metering is the most extensively used strategy. A ramp meter is simply a device (similar to a traffic signal), which regulates the flow of traffic entering a freeway. Ramp metering was first implemented in 1963 on the Eisenhower Expressway (I-290) in Chicago, Illinois. This first application involved a police officer who would stop traffic on an entrance ramp and release vehicles one at a time at a predetermined rate to provide safer and smoother merging onto the freeway traffic without disrupting the mainlane flows. Since then, transportation agencies have systematically deployed ramp meters in many urban areas including Los Angeles, California; Minneapolis-St. Paul, Minnesota; Seattle, Washington; Denver, Colorado; Phoenix, Arizona; Houston, Austin, Dallas and San Antonio in Texas; Columbus, New York; Detroit, Michigan; Toronto, Canada; and in the city of Portland, Oregon. In some instances, cities have withdrawn the use of ramp meters for various reasons, although many studies indicate that ramp metering is a successful strategy (*1*).

In recent years ramp metering has again been at the forefront of operational options, with plans for deployment in various European countries including Belgium, the Netherlands, France, the United Kingdom, and Germany (*2*), as well as in Minneapolis, Cleveland, Denver, Los Angeles, the Pennsylvania Turnpike, and Salt Lake City. To encourage car pooling and high-occupancy vehicles (HOV), many states currently provide separate bypass lanes on ramps (*2, 3, 4*). The California Department of Transportation manual also provides guidelines for proper signs to use with HOV and car pool bypass lanes on ramps (*2*). As another example, the Washington Department of Transportation *Design Manual* states: "[C]onsider HOV bypass lanes with ramp meters" (*3*). Some states also use metering on freeway-to-freeway connectors and mainlanes (*3*).

One example of ramp closures in Texas was located in Corpus Christi on State Highway (SH) 358, also known as South Padre Island Drive (SPID). Vehicles entering at the Kostoryz Road on-ramp to westbound SH 358 weaved through vehicles exiting at the Ayers off-ramp and the freeway-to-freeway off-ramp from SH 358 to SH 286 (Cross-town Expressway), creating unsafe weaving conditions. This weaving problem occurred during a 30-minute morning peak. It should be noted that most of the traffic from Kostoryz Road was westbound through traffic at SPID. This weaving resulted in several accidents on SPID. A gate was installed at the Kostoryz Road on-ramp to westbound SH

358 (SPID). The drop-down electromechanical gate was operated on a timer. When the ramp was closed, the westbound SPID portion of Kostoryz Road on-ramp traffic was diverted to the Ayers on-ramp and had to go through a traffic signal. Any SH 286-bound traffic from Kostoryz also had an easier access from the frontage road to SH 286. Ramp closure significantly reduced accidents on SPID and improved traffic flow. Another example of ramp closure is in El Paso on the Paisano ramp on westbound Interstate 10 (IH-10). Vehicles entering the freeway using this ramp during peak traffic conditions experienced merging problems, and congestion was a problem on IH-10 within the proximity of the ramp. Although TxDOT considered ramp metering, they decided to use a ramp closure strategy. A gate was thus installed on the ramp.

Applying Managed Lanes Strategies to Ramps

One of the areas for potentially improving freeway performance is at ramp locations. Those current ramp treatments discussed above only address point demand. Simply put, ramp management is the application of control devices, such as traffic signals, signing, and gates to regulate the number of, and rate by which, vehicles enter or leave the freeway. The concept of managed ramps would be to apply any of the myriad of managed lanes operational strategies along a corridor to optimize the use of the overall freeway facility. For example, agencies could use tolling to manage ramp access with no regard to vehicle occupancy. During the peak period, agencies could restrict the use of specific entrance or exit ramps to HOVs and/or transit. The high-occupancy toll (HOT) lane strategy could also be used where HOVs and transit would use specific ramps at no charge, and single-occupant vehicles (SOVs) pay a toll. If the conditions are appropriate, heavy trucks may not be allowed to use particular ramps during certain periods of the day or may be the only vehicles allowed to use particular ramps. Furthermore, agencies could apply these strategies to managed lanes access points if they become so congested that they negatively impact both the mainlanes and the managed lanes. Such operational strategies as discussed above could help maximize existing capacity, manage demand, offer choices, enhance mobility, improve safety, and generate revenue within the freeway corridor itself.

Sections in this chapter cover:

- managed ramp decision matrix,
- flow balance,
- incident and special event management,
- managed lanes facility preference,
- ramp safety, and
- related issues.

Section 2 – Managed Ramp Decision Matrix

Background

A variety of managed lanes operational strategies exist that have the potential to meet the aforementioned goals. Primarily, the overall goals for the implementation of managed lanes can be divided into five distinct categories: mobility, safety, community, financial, and homeland security. TxDOT uses managed lanes to improve the overall quality of life for transportation system users and ensure the long-term viability of the community. The following sections provide a description and rationale behind these categories of goals.

Mobility

Mobility goals of managed lanes are focused upon such wide topics as demand and accessibility. The strategies deployed under this goal aim to improve the mobility of the facility or the entire transportation system in the region.

Safety

Safety goals are designed to reduce the frequency and severity of collisions and conflicts between users and vehicles on a particular facility or along a corridor. No managed lanes implementation should compromise the safety a facility experienced under previous operations.

Community

Community goals are generally defined as those goals that aim to help maintain or improve the economic sustainability and viability, and quality of life of a local community based on the interests of its constituents.

Financial

Financial goals, much like their name implies, are those which aim to address the financial realities of infrastructure expansion with limited funding, and the financing methods by which an agency pursues the development of projects.

Homeland Security

Homeland security goals are those that aim to develop a transportation system that can effectively and efficiently support emergency operations in the event of natural disasters or homeland security related incidents.

Specific Managed Lanes Goals

Table 16-1 highlights the different mobility, safety, community, financial, and homeland security goals that may be associated with managed lanes operational strategies. While these goals are associated with managed lanes facilities on major freeways, they can also apply to managed lanes strategies applied to freeway ramps for the purpose of ramp management. For example, managing ramps using alternative strategies can enhance *mobility* by providing congestion relief and improve accessibility at either point locations or along an entire corridor. They can modify travel demand and may enhance alternative modes of travel depending on the implemented strategy. Furthermore, they may enhance *safety* by reducing congestion along a corridor and/or at ramp locations where weaving increases the potential for incidents.

Table 16-1. Possible Managed Lanes Goals (Adapted from *5*).

Goal Category	Possible Managed Lanes Goals
Mobility Goals	• Provide a transportation system that can handle current and future demand • Increase mobility and accessibility by offering travel options • Provide additional facility capacity • Optimize existing managed lanes capacity • Provide congestion relief • Modify travel demand • Enhance alternative modes • Improve accessibility
Safety Goals	• Improve the safety of corridor travel • Maintain the level of safety on a facility
Community Goals	• Minimize environmental impacts • Preserve neighborhoods • Maintain an urban form • Maintain land use patterns
Financial Goals	• Develop transportation improvements that are financially self-sustaining • Maximize the benefit-cost ratio of infrastructure investment
Homeland Security Goals	• Enhance and support emergency management operations • Enhance and support disaster management operations

Applying Managed Lanes Goals to Managed Ramps

Applying managed lanes strategies to ramps could meet *community* goals by reducing the environmental impacts of congestion. If pricing is applied to ramp management, then it may help meet the *financial* goals of the region by generating revenue to help improve the benefit-cost ratio of a project. Finally, ramp management implementation can support *homeland security* goals if specific strategies are applied during incidents to support emergency management and/or disaster management operations.

As described previously, these operational options are categorized by lane management strategy or a combination of multiple lane management strategies. All of these strategies have potential application to ramps and ramp management. However, the overall effectiveness of these strategies may vary depending on a number of factors. These factors may include, but not be limited to, the existing conditions of the general-purpose lanes, the specific problems and issues impacting performance at ramp locations, the willingness of travelers to accept managed ramps, the preexistence of managed lanes in the region, and the overall goals and objectives of TxDOT and partner agencies regarding mobility, congestion, and transportation project finance.

The same goals and related objectives generally applied to managed lanes strategies could also apply to strategies for managing ramps. Furthermore, the application of managed lane strategies at ramps can help address operational problems at a specific location or can be applied at a series of ramps to achieve corridor level benefits. Once again, the potential for meeting these goals lies with the specific lane management strategy implemented at either isolated ramps or along an entire corridor. Four operational scenarios that have the most potential to meet various needs of TxDOT districts across the state include:

- flow balance,
- incident/special event management,
- managed lanes facility preference, and
- ramp safety.

Managed Ramps Decision Matrix

Based on detailed modeling analysis of the aforementioned managed ramp scenarios, specific applications of these strategies have the potential to improve freeway operations. These managed ramp strategies can be matched to managed ramp goals to help a transportation agency clearly identify which managed ramp operational strategies are best suited for a region, corridor, or facility.

Table 16-2 presents the managed ramp strategies and the related managed ramp goals to be achieved. The intent of the table is to provide guidance on selecting a managed ramp operational strategy that can address specific managed ramp goals identified by the transportation agency as critical components of an overall managed lanes planning process. The remaining sections in this guideline document will provide general guidance on selecting these managed ramp strategies based on potential benefits and also address other implementation and operational issues critical for success.

Table 16-2. Managed Ramp Goals and Related Strategies.

		Flow Balance	Incident Management			Special Event Management		Managed Lane Facility Preference			Ramp Safety	
Goal Category	**Managed Ramp Goals**		**Ramp Closure**	**HOV**	**Pricing**	**Select User Restriction**	**Ramp Closure**	**Forced Merge**	**Acceleration Lane**	**Full Auxiliary Lane**	**Automobile Restriction**	**Total Closure**
Operational / Mobility	Prevent freeway from breaking down in bottleneck location	X				X	X	X			X	X
	Provide priority access to special class of user to general purpose facility	X				X		X	X	X		
	Overcome geometry deficiency to particular class of vehicles										X	X
	Overcome ramp storage problems		X	X	X	X	X				X	X
	Provide priority access to special class of user destined for managed lanes facility							X	X	X		
	Promote balanced flow in corridor	X	X			X	X				X	X
	Enhance and support incident management		X	X	X	X	X					
	Delay the onset of congestion on the freeway corridor	X				X	X	X	X	X	X	X
Safety	Reduce vehicle crashes in merge and weaving areas	X	X			X	X	X	X	X	X	X
	Reduce vehicle conflicts in merge and weaving areas	X	X	X	X	X	X	X	X	X	X	X
	Channelize vehicles with different operating characteristics to ramps which can better [missing word?] them			X				X	X	X	X	X
	Reduce the potential of rear-end collisions at ramps where congestion frequently occurs	X	X	X	X	X	X	X	X	X	X	X
Community	Balance perception of penalizing short vs. long trips	X						X	X	X		
	Promote the use or discourage the use of certain facilities, ramps, or adjacent roadway(s) by certain vehicle users (i.e., trucks)	X		X		X	X					X
	Serve as an alternative to installing ramp meter signals at a specific location	X		X	X						X	
	Enhance TxDOT's ability to operate the corridor in an integrated fashion with other transportation providers in the community	X						X	X	X		
Financial	Generate revenue for particular ramp or facility	X			X							
	Delay the need to widen a freeway facility by maximizing the use of all the available capacity in the corridor through better operations	X						X	X	X	X	X
Homeland Security	Enhance and support emergency management operations		X	X	X	X	X					
	Ensure access to a managed lane facility to aid in the rapid deployment of emergency vehicle and disaster relief resources in an emergency event		X	X	X	X	X	X	X	X		

Section 3 – Flow Balance

Ramp meters are one of the tools in the traffic engineer's toolbox for reducing congestion and improving safety on urban freeways. Past research and evaluations have shown the benefits of ramp meters to be as follows:

- Improved system operation by increased vehicle throughput, increased vehicle speeds, and improved utilization of the existing capacity on the freeway;
- Reduced number of crashes and the crash rate in the merge area and on the freeway upstream of the ramp/freeway merge zone;
- Reduced environmental effects caused by congestion through reduced vehicle emissions and reduced fuel consumption; and
- Promotes multi-modal operation.

Table 16-3 shows some of the measured benefits from variations of ramp meter deployment in the United States.

Table 16-3. Measured Benefits of Ramp Meter Deployments in the United States (*6*).

Measure	Location	Benefits
Safety	Minneapolis, MN	26% reduction in peak period collisions and 38% decrease in peak period collision rate.
	Seattle, WA	34% decrease in collision rate.
	Denver, CO	50% reduction in rear-end and side swipe collisions.
	Detroit, MI	50% reduction in total collisions, 71% reduction in injury collisions.
	Portland, OR	43% reduction in peak period collisions.
	Long Island, NY	15% reduction in collision rate.
Travel Time and Speed	Long Island, NY	9% increase in average vehicle speed
	Portland, OR	26 to 66 km/h increase in vehicle speeds (16 to 41 mi/h).
	Denver, CO	69 to 80 km/h improvement in average vehicle speeds (43 to 50 mi/h).
	Seattle, WA	Decrease in average travel time from 22 to 11.5 minutes.
	Minneapolis, MN	64 to 69 km/h improvement in average peak hour speeds (40 to 43 mi/h)
Throughput	Minneapolis, MN	25% increase in peak volume.
	Seattle, WA	74% increase in peak volume
	Denver, CO	18% increase in peak volume.
	Long Island, NY	2% increase in throughput.
Environmental	Minneapolis, MN	2 to 55% reduction in fuel consumption. Savings of 1,160 tons of emissions.

While ramp metering can generate significant benefits, potential negative impacts do exist with ramp meters. First, ramp meters have the potential to divert traffic away from the freeway as motorists, especially those making short trips, bypass queues that form at the ramp meter. If the potential adjacent street network cannot support the diverted traffic, operations on nearby arterials can be negatively affected. Second, a question concerning equity may also exist with ramp meters. Some individuals argue that ramp meters favor suburban motorists who make longer trips versus those that live in the immediate areas around the ramp meter. They argue that those who live in locations where the ramps are not metered are not delayed as much when they enter the freeway than those who have to access the freeway at the ramp meter. Finally, opponents of ramp meters often cite that ramp meters merely shift traffic congestion (and its associated impacts) from one location to another. Queues for improperly operated ramp meters have the potential to back up through an adjacent arterial intersection, thereby, cause specific approaches or movement to become congested. Because of these perceived disbenefits, some practitioners in Texas are hesitant to deploy ramp meters where needed.

While traditionally managed lanes strategies have been deployed to the mainlanes of a freeway facility, an agency may elect to deploy one or more of these strategies to a ramp 1) as an alternative to installing a ramp meter, and/or 2) for the expressed purposes of improving operations on the mainlanes. For example, instead of installing a ramp meter, an agency may elect to restrict the use of a particular ramp to high-occupant vehicles or convert a ramp into a value pricing lane. Likewise, an agency may want to consider charging a toll on a vehicle for using a particular ramp during certain periods of the day to reduce demand on the ramp to avoid the political hassle of installing a ramp metering system. Finally, an agency may be more willing to restrict or limit the use to a specified vehicle class instead of installing a ramp meter. Regardless of the type of managed lane strategy deployed at a ramp in place of a ramp meter, one question that applies equally for all strategies is as follows:

How much traffic must be diverted away from the ramp by a managed lane strategy to achieve the same level of operation on the freeway if a ramp meter was used at the same ramp?

To address this question, the idea is to compare the performance of a section of freeway with and without a ramp meter active at an entrance ramp in the corridor. The objective is to specifically quantify how much traffic needs to be diverted from the ramp at different freeway and ramp volume conditions and ramp geometries (specifically the length of the ramp acceleration lane) to achieve the same level of performance on the freeway if the ramp was controlled by a ramp meter. For the purposes of this guideline document, the research team does not did not attempt to quantify how effective any one particular managed lane technique might be at diverting traffic and the assumption is that a single managed lane strategy (or combination of strategies) could be deployed at a ramp to achieve the required amount of diversion.

Freeway/Ramp Configurations

For the purpose of this guideline document, the ramp hypothetical freeway/ramp configuration shown in Figure 16-1 serves as the basis for comparison. The network consists of a two-lane section of frontage road connected to a two-lane section of freeway by a single lane entrance ramp 1000 ft in length with a merge area of 1500 ft on the freeway. To ensure that the effects of queues that form on the freeway approach lanes are adequately captured and to ensure adequate storage for entering demands, the configuration includes a long approach links upstream of the entrance ramp on both the freeway (48,000 ft) and the frontage road (10,400 ft). Likewise, to ensure that the freeway traffic had adequate time to recover after clearing the merge area around the ramp, the link downstream of the merge area is 4500 ft. Also, the length of the acceleration lane for the ramp is varied using five different acceleration lane lengths, as shown in Figure 16-2.

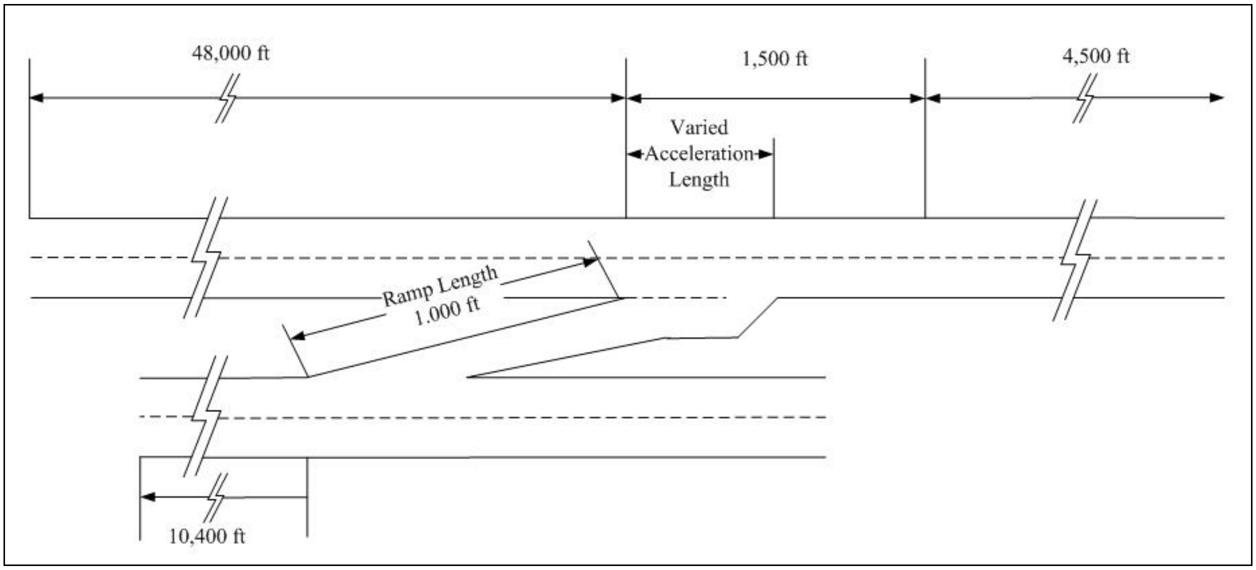

Figure 16-1. Basic Freeway/Ramp Configuration.

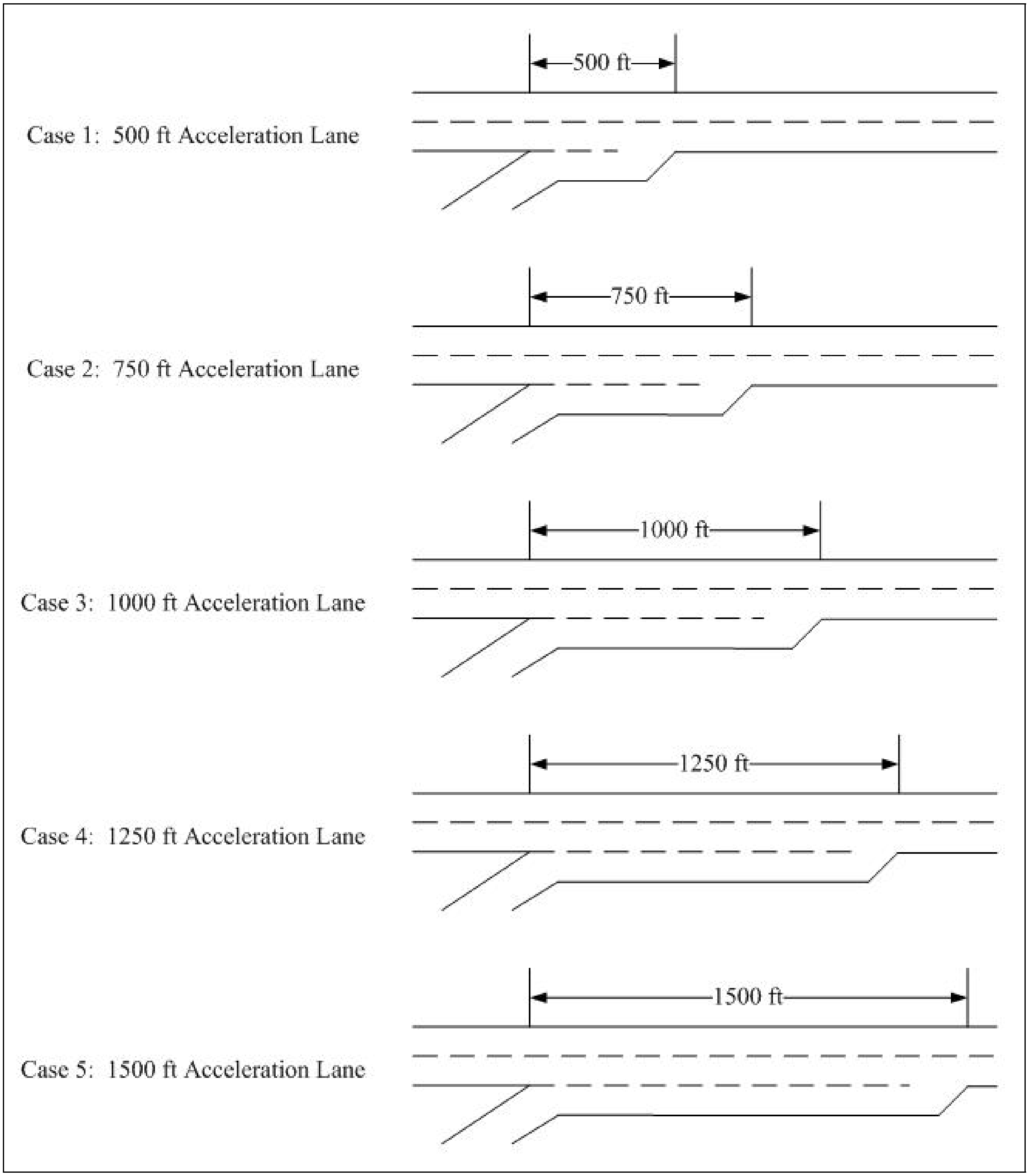

Figure 16-2. Different Acceleration Ramp Lengths.

Traffic Demands

It is important to note that ramp metering is generally a strategy that is employed when traffic demands on the freeway are beginning to approach capacity. If ramp metering is employed when freeway volumes are relatively light, ramp delays will become excessive and drivers will become frustrated waiting at the ramp meter for no apparent purpose or benefit. Likewise, if too much demand exists on the freeway, not enough adequate gaps exist in the freeway traffic stream to "absorb" traffic that is entering from the ramp. When this occurs, traffic entering the ramp stops in the merge area to wait from a gap that is big enough into when to merge into the freeway lane or, if the driver is aggressive enough, will create their own gap in the freeway traffic stream by forcing their way onto the freeway. Therefore, the relative window where ramp metering provides the maximum benefit is relatively small and is when traffic demand on the freeway is approaching, but not exceeding capacity.

As such, this guideline document considers traffic demands to be at or near capacity. For the purposes of using this document, a theoretical capacity for a single freeway lane is 2400 passenger cars per hour per lane (pcphpl), which serves as the maximum demand level, is assumed. Also, freeway demand levels vary from 1500 pcphpl to 2400 pcphpl, in 100 pcphpl increments. Furthermore, in addition to varying the freeway demand level, ramp demand levels also vary. For each freeway demand level, ramp demand levels, ranging from 0 pcphpl to 900 pcphpl (the maximum amount supported by a single lane, single vehicle ramp meter), are used. Ramp demand levels of more than 900 pcphpl are NOT used as 900 pcphpl represents the maximum amount of vehicles that can be supported by a single-lane, single-vehicle ramp metering strategies. Generally, ramp demands greater than 900 pcphpl require either dual lane metering or bulk meter to accommodate the total demand without excessive queues building on the ramp. Table 16-4 shows the freeway demand levels we examined at each ramp configuration, while Table 16-5 shows the ramp demand levels examined at each freeway volume level. Finally, a vehicle mix of 90/10 is assumed: 90 percent passenger vehicle, 5 percent buses, and 5 percent heavy vehicles (i.e., trucks).

Table 16-4. Freeway Demand Levels.

Freeway Demand Level	Desire Passenger Car Equivalent Per Lane Volume	Simulation Input Volume
1	1500 pcphpl	2727 vph
2	1600 pcphpl	2909 vph
3	1700 pcphpl	3091 vph
4	1800 pcphpl	3272 vph
5	1900 pcphpl	3455 vph
6	2000 pcphpl	3636 vph
7	2100 pcphpl	3818 vph
8	2200 pcphpl	4000 vph
9	2300 pcphpl	4182 vph
10	2400 pcphpl	4364 vph

Table 16-5. Ramp Demand Levels.

Ramp Demand Level	Desired Passenger Car Equivalent Ramp Demand	Simulation Input Volume
1	0 pcph	0 vph
2	100 pcph	91 vph
3	200 pcph	182 vph
4	300 pcph	273 vph
5	400 pcph	364 vph
6	500 pcph	455 vph
7	600 pcph	545 vph
8	700 pcph	636 vph
9	800 pcph	727 vph
10	900 pcph	818 vph

Performance Measures for Flow Balance

The primary measure of performance used in this guideline document for this operational scenario is average running speed. Running speed is the speed computed as the length of the highway section divided by the running time required for the vehicle to travel through a section. The American Association of State Highway and Transportation Officials (AASHTO) indicates that the average running speed is the most appropriate speed measure for evaluating a level of service and operations.

To compute the average running speed, a segment of the freeway was established over which travel time measures are collected. The total length of the travel time segment was 52,787.5 ft (or approximately 10 miles). We set a long length of the travel time segment because our initial investigation showed a queue extending approximately 9 miles upstream of the entrance ramp during some combination of ramp and freeway demand level. We set VISSIM to record the average travel time every 60 seconds during the data collection period. We averaged the 60-second travel time measures for the total duration of the data collection window, which was 5400 seconds (or 90 minutes).

In addition to average running speed, throughput serves as a secondary measure of effectiveness. Throughput is defined as the total number amount of traffic passing through the section of the freeway downstream of the merge area of the ramp. Throughput is determined by installing data collection points in each lane of the freeway on the link downstream of the ramp merge area, configured to count the number of vehicles traversing the point every 60 seconds. Throughput is calculated by summing all the 60-second vehicle counts in each lane for the entire data collection window.

Application of Managed Lanes Strategies as an Alternative to Ramp Metering

The results of simulation analysis clearly show that metering the demand on higher volume ramps allows operators to maintain a higher level of operating speed and throughput on freeways; however, the purpose of this study was to assess how much traffic needs to be diverted away from a ramp through the application of a managed lane strategy to achieve the same level of operation on a freeway if ramp metering was deployed. To do this, one must identify at what level of ramp demand when no ramp meter is present produces the same level of operation on the freeway (i.e., average running speed) that occurred when ramp metering is used on a ramp. The process one can use to determine the amount of ramp demand that could be accommodated at a non-metered ramp to achieve an equivalent level of operations in a freeway section where ramp metering was utilized is illustrated Figure 16-3. Begin by first determining the level of operation of the freeway at a particular ramp demand level with the ramp meter active (see ① in Figure 16-3). Then working parallel to the x-axis (see ② in Figure 16-3), find the point on the performance line of the freeway when no ramp metering was used. Finally, determine the amount of ramp traffic that could be accommodated on the ramp that achieved that same level of operation when ramp metering was not used (see ③ in Figure 16-3). This ramp demand level represents that maximum amount of ramp demand that can be accommodated on a ramp that utilizes some type of managed lane strategy to limit the demand on the ramp. The difference between the two ramp demand levels (with and without ramp metering) represents the amount of traffic that needs to be diverted away from the ramp by the managed lane strategy to achieve the equivalent level of operation on the freeway that utilizes ramp metering. This process can be repeated everywhere the performance of the freeway with ramp metering is statistically significant.

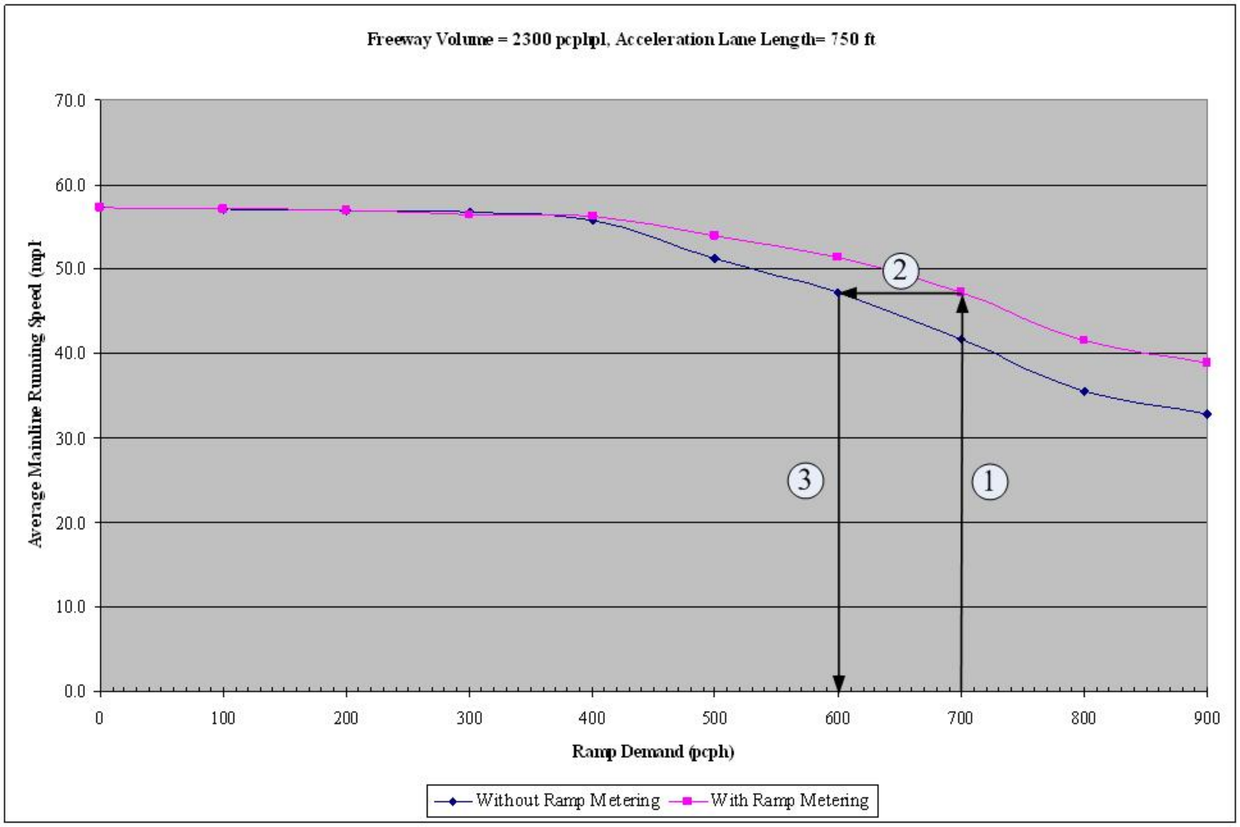

Figure 16-3. Illustration of Process Used to Determine Ramp Demand at a Non-Metered Ramp to Achieve an Equivalent Level of Operations on the Freeway Where Ramp Metering Was Utilized. [Author: y-axis label cut off.]

Figure 16-4 through Figure 16-10 are graphs depicting the results of this process. The graphs show the maximum amount of ramp demand that can be supported without ramp metering to achieve the same level of performance on a freeway section where ramp metering was used. This guideline provides graphs for freeway volumes ranging from 1800 pcphpl to 2400 pcphpl. Each volume level contains lines depicting the ramp demand levels that can be supported without ramp metering for the different ramp acceleration lane lengths.

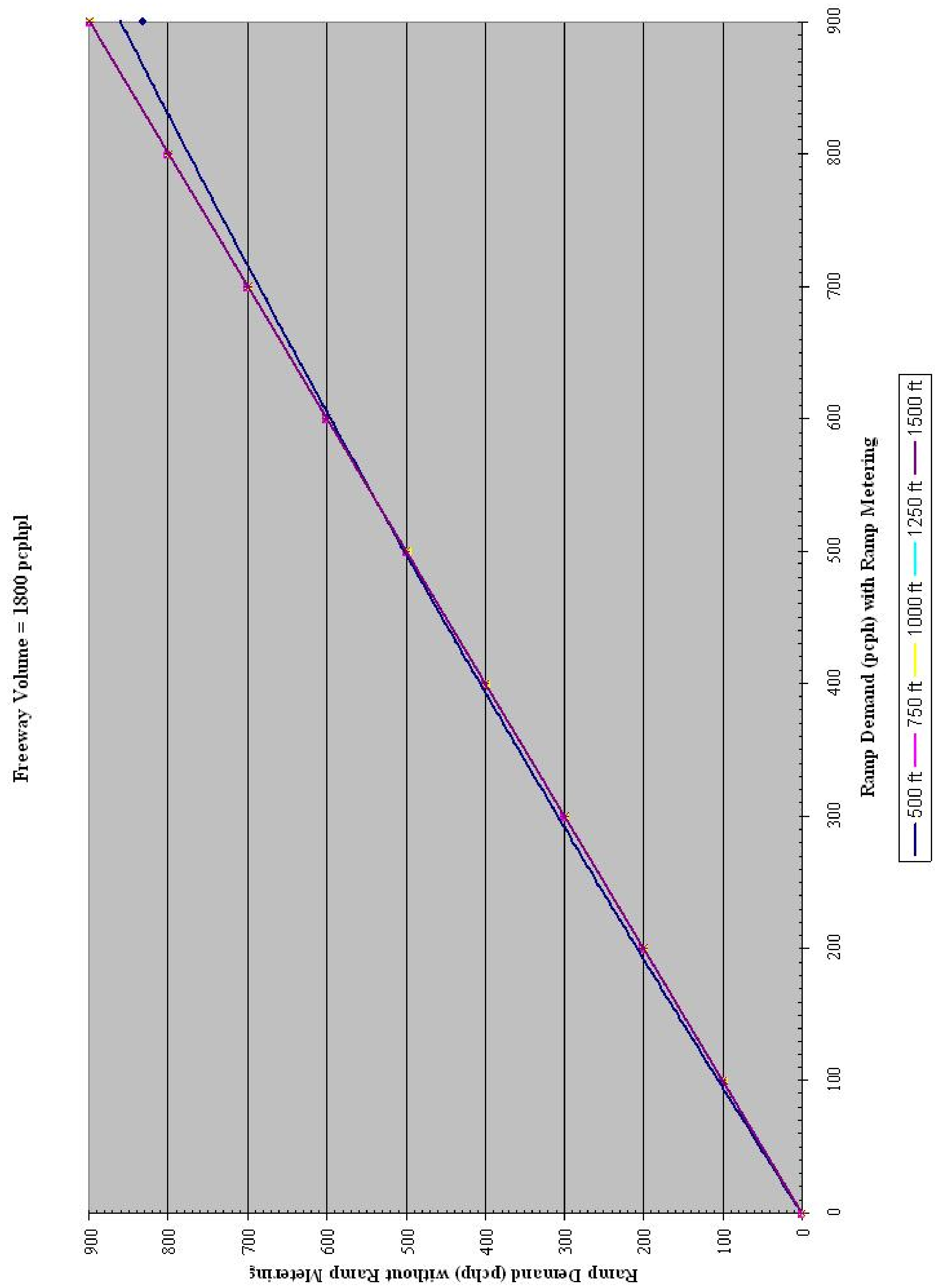

Figure 16-4. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1800 pcphpl

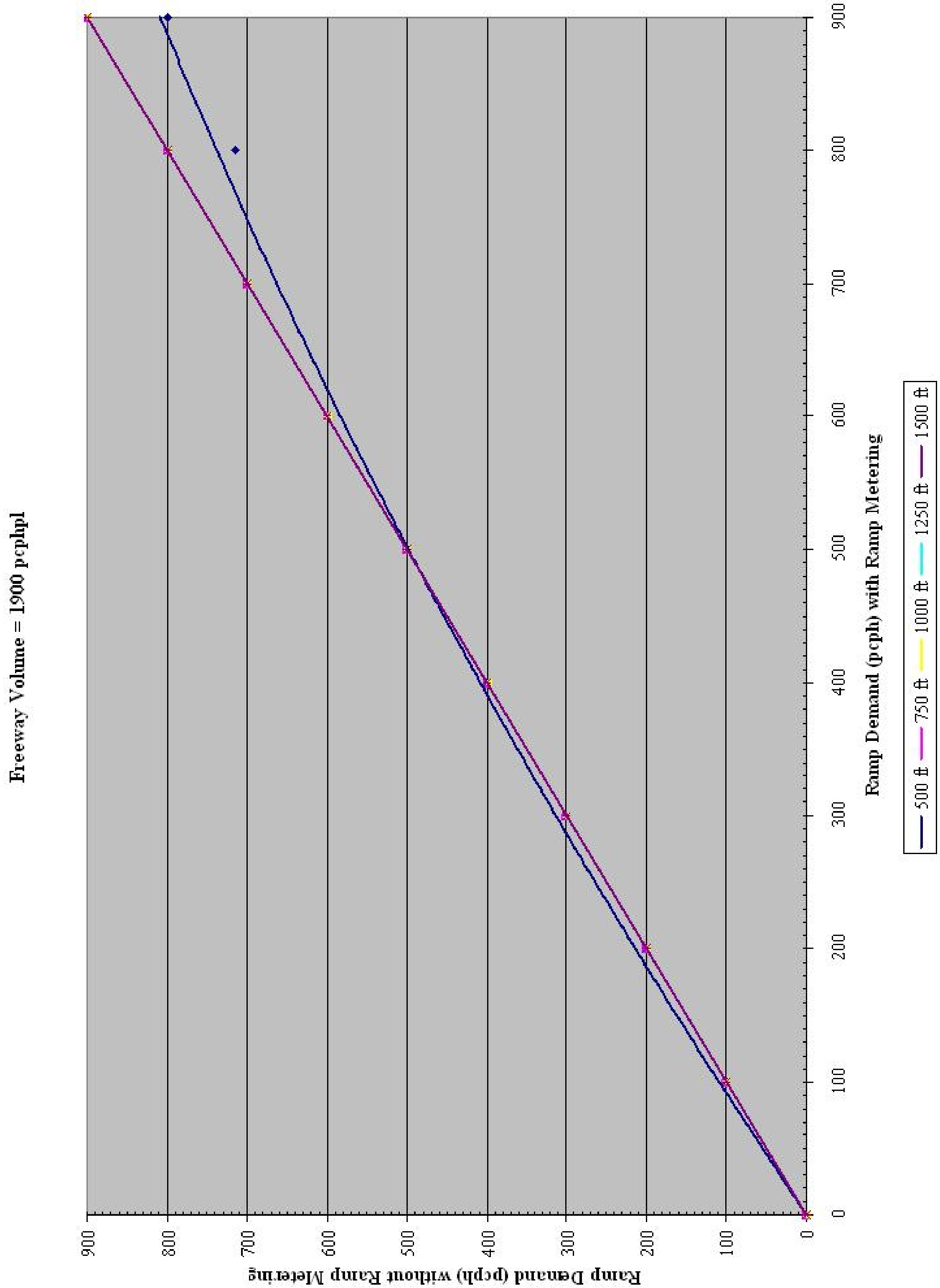

Figure 16-5. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1900 pcphpl

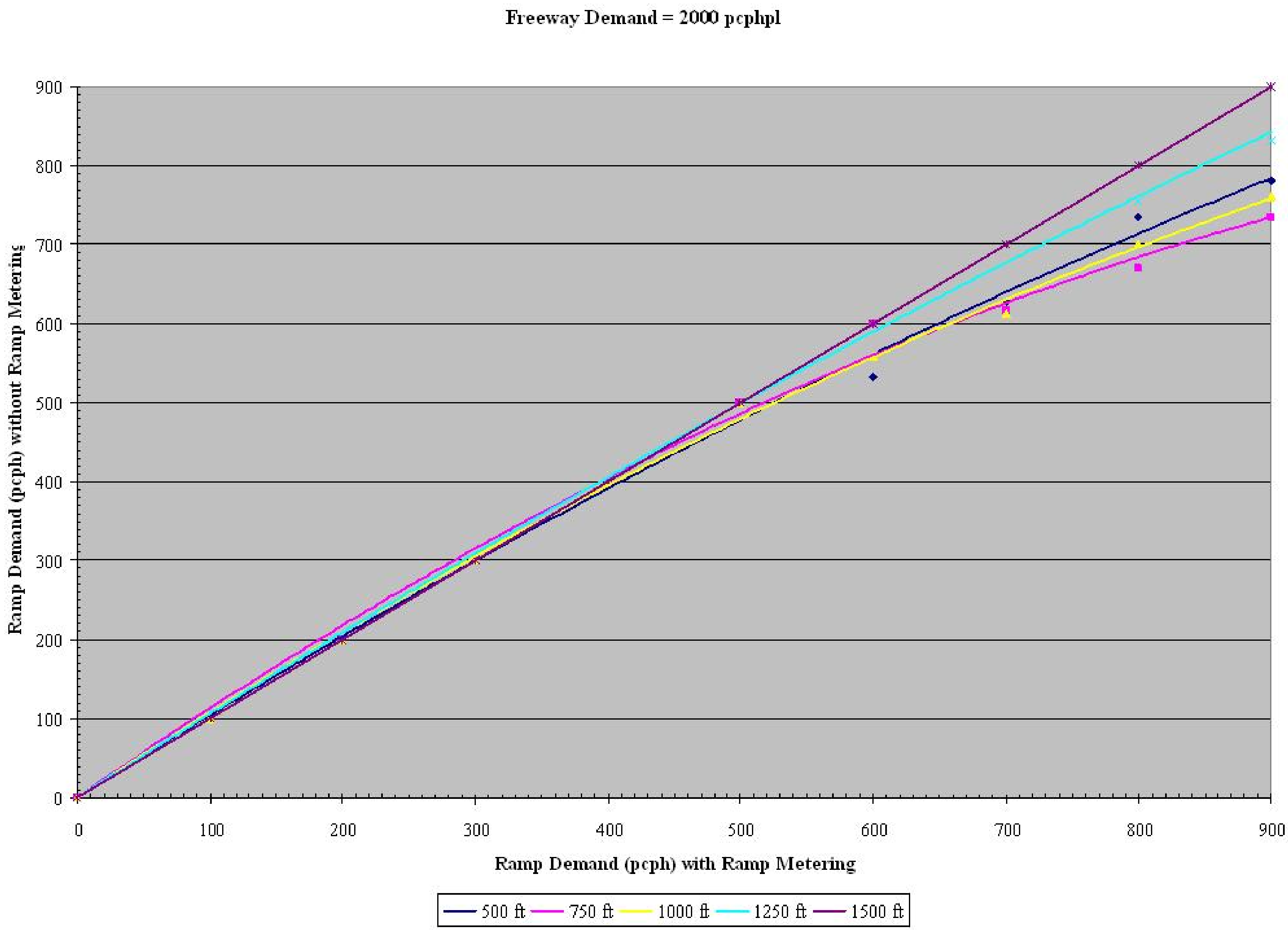

Figure 16-6. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2000 pcphpl

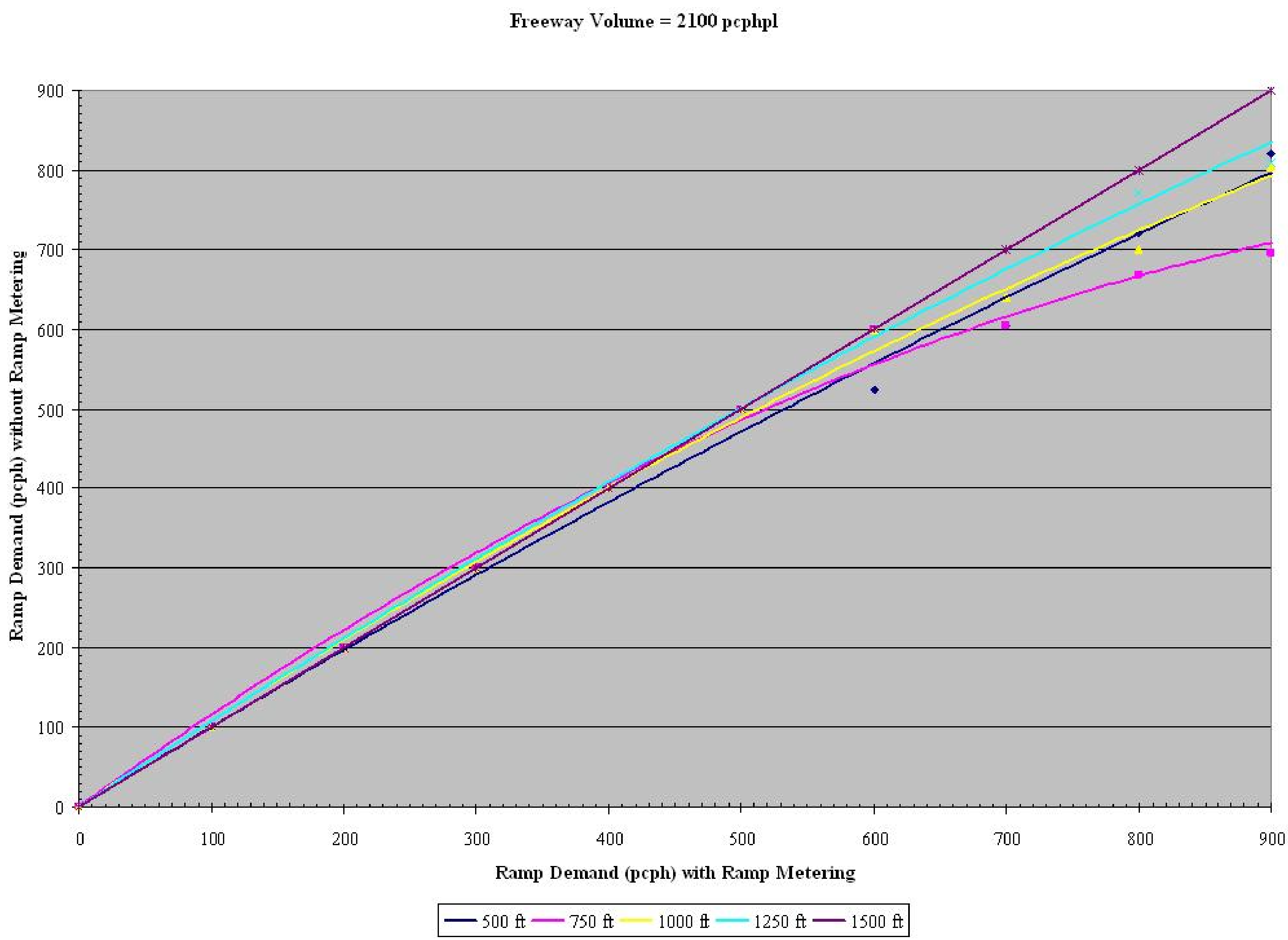

Figure 16-7. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2100 pcphpl

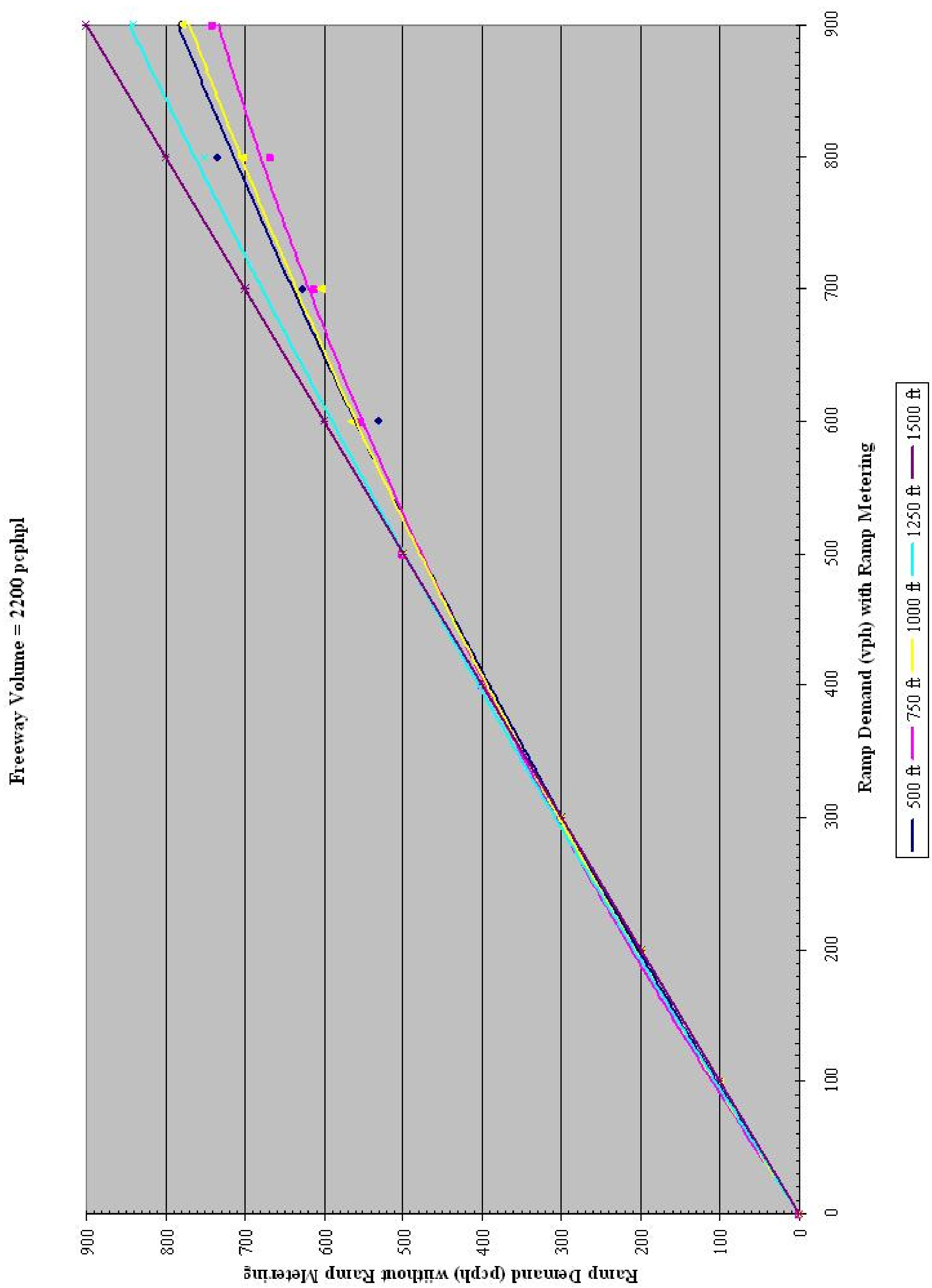

Figure 16-8. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2200 pcphpl

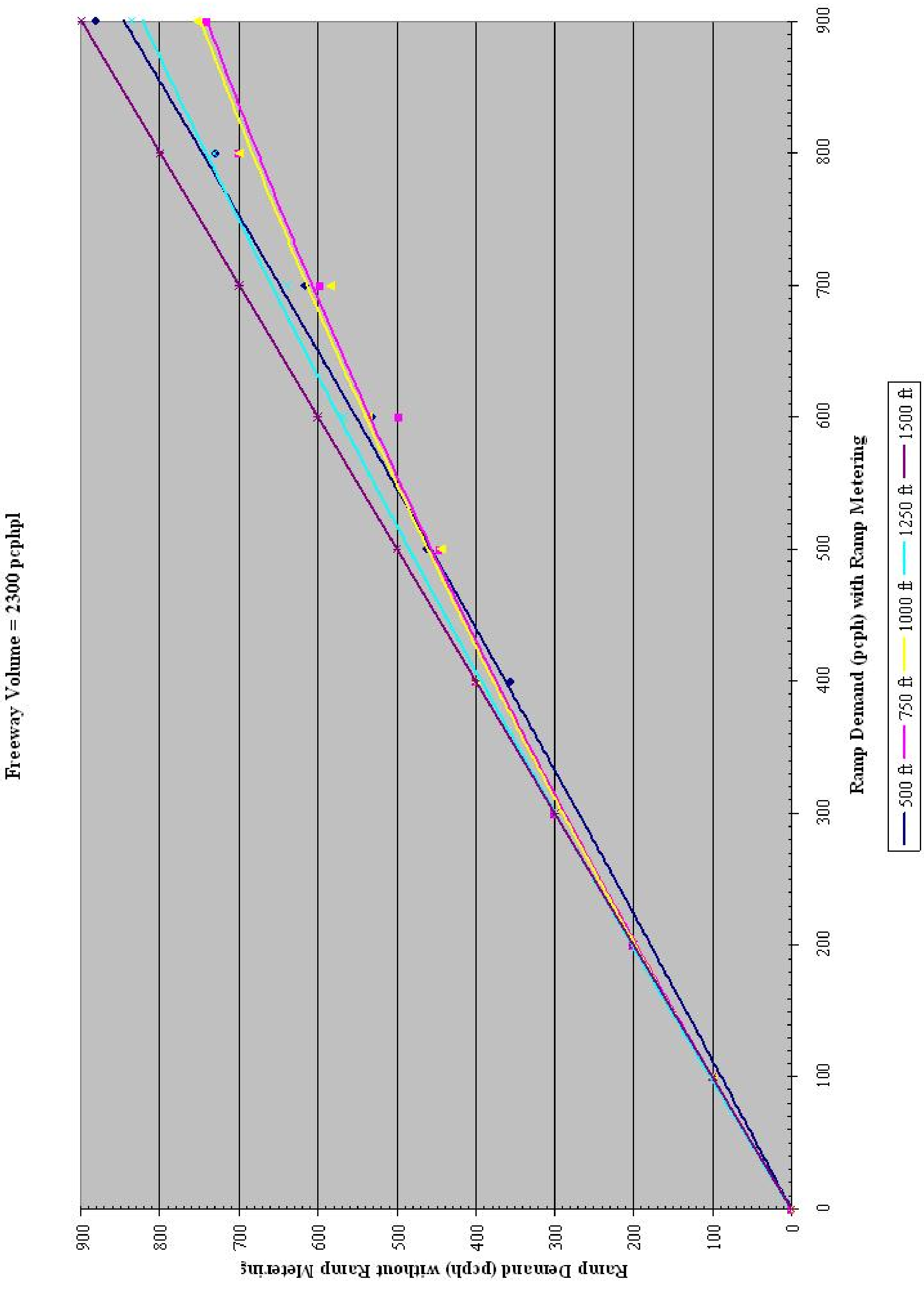

Figure 16-9. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2300 pcphpl

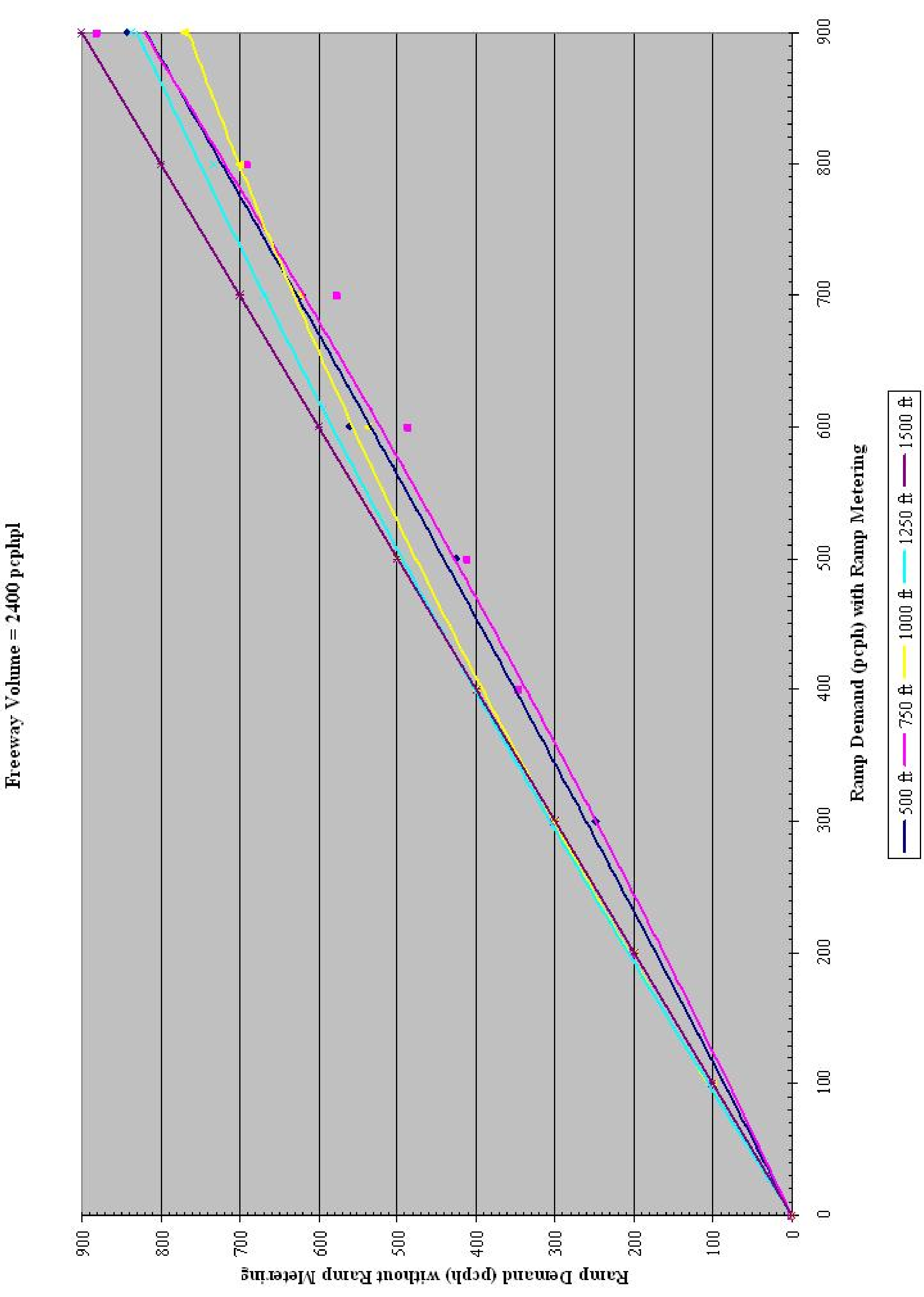

Figure 16-10. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2400 pcphpl

To use the graphs, a practitioner would first find the series of graphs which correspond to the prevailing freeway volume conditions. For purposes of illustration, assume that the demand on the freeway is equal to 2200 passenger cars per hour per lane. After determining which series of graphs to use (Figure 16-8), the practitioner would then locate on the x-axis the amount of traffic that currently exists on the ramp (in our example, let us say that it is 680 pcph). To determine the equivalent amount of ramp traffic to achieve the same level of performance on the freeway section if a ramp meter was installed, the practitioner would then travel up from the x-axis to the line corresponding to the length of the ramp acceleration lane (in this case, 750 ft). Then moving to the left parallel to the x-axis, the practitioner would find the amount to ramp traffic that could be supported on the ramp without installing a ramp meter (in our example 615 pcph). With this number, the practitioner could then determine the amount of traffic that needs to be diverted from the ramp by the managed lane strategy in order to achieve the same level of performance on the freeway if a ramp meter was installed at the ramp – in our example, the amount of traffic that would need to be diverted away from the ramp by a managed lane strategy equals 65 pcph.

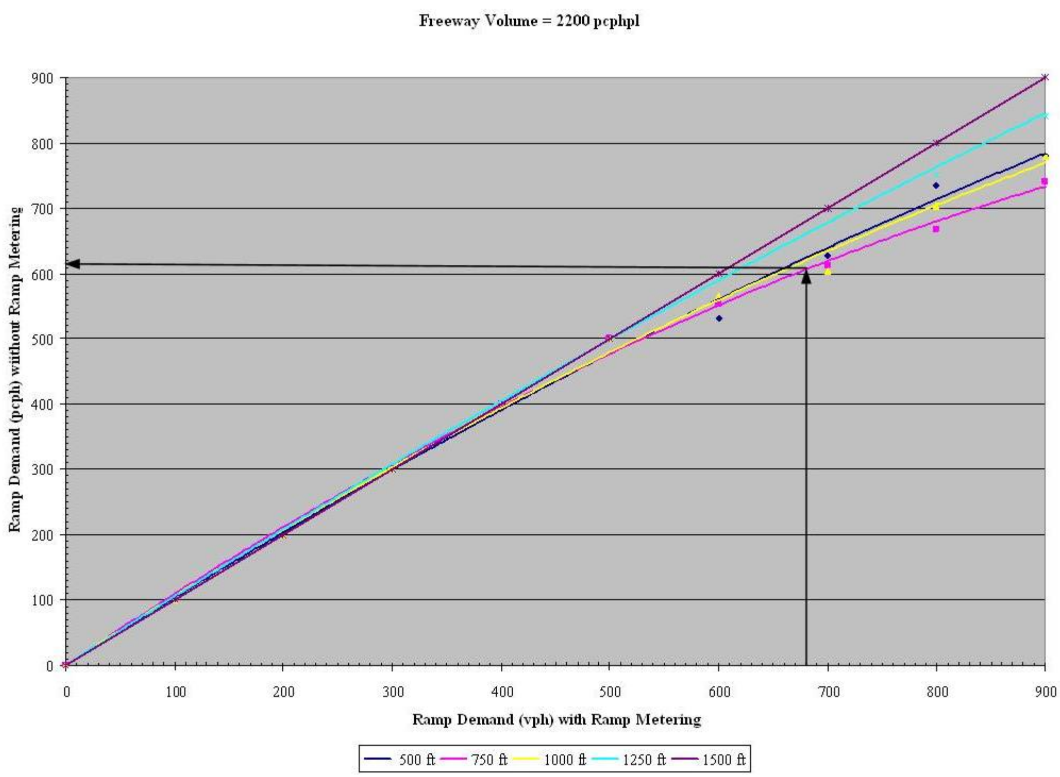

Figure 16-11. Illustration of Use of Ramp Demand Curves to Determine Amount of Traffic to Be Diverted by Managed Ramp Strategy.

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Table 16-6. Summary of "Best Fit" Regression Equation for Estimate Non-Meter Ramp Demand to Obtain Equivalent Operations with Ramp Metering

Freeway Demand Level	Ramp Acceleration Lane Length	"Best-Fit" Regression Equation	R-Squared Value
1800	500	$y = -0.000119117647058832x^2 + 1.06379411764706x$	0.9977
1900	500	$y = -0.000244875222816403x^2 + 1.11855169340464x$	0.9959
2000	500	$y = -0.000213179590017834x^2 + 1.10635398841354x$	0.9969
	750	$y = -0.000390485739750451x^2 + 1.16794162210339x$	0.9951
	1000	$y = -0.000290987076648850x^2 + 1.10454344919786x$	0.9984
	1250	$y = -0.000156818181818900x^2 + 1.07731818181819x$	0.9986
2100	500	$y = -0.000143538324420683x^2 + 1.01472459893048x$	0.9936
	750	$y = -0.000462577985739756x^2 + 1.20355102495544x$	0.9934
	1000	$y = -0.000242535650623890x^2 + 1.09952094474154x$	0.9970
	1250	$y = -0.000185160427807494x^2 + 1.09471925133690x$	0.9974
2200	500	$y = -0.000212455436720150x^2 + 1.06207798573976x$	0.9967
	750	$y = -0.000348919340463463x^2 + 1.12882865418895x$	0.9981
	1000	$y = -0.000260594919786101x^2 + 1.08922972370767x$	0.9974
	1250	$y = -0.000146167557932272x^2 + 1.07087344028521x$	0.9987
2300	500	$y = 0.0000681595365418855x^2 + 0.878904188948312x$	0.9936
	750	$y = -000224821746880575x^2 + 1.02514527629234x$	0.9948
	1000	$y = -0.000224721479500894x^2 + 1.03409157754011x$	0.9964
	1250	$y = -0.0001373217468805770x^2 + 1.03739527629234x$	0.9986
2400	500	$y = 0.0000656417112299412x^2 + 0.850622994652412x$	0.9946
	750	$y = 0.000140318627450974x^2 + 0.785703431372553x$	0.9814
	1000	$y = -0.000260238413547245x^2 + 1.08385360962567x$	0.9981
	1250	$y = -0.00016468360071302x^2 + 1.0703453654189x$	0.9988

Table 16-6 shows the "best fit" regression equations and the regression correlation coefficient (R-Squared value) for each line shown in Figure 16-4 through Figure 16-10. Individuals can use these equations to estimate the non-metered ramp demand that would produce an equivalent level of operations on a freeway segment, if the ramp were metered. Based on these equations, Table 16-7 and Table 16-8 show the amount of demand that must be diverted away from a ramp by a managed lane strategy to achieve an equivalent level of operation on the freeway segment if ramp meters were to be deployed at the ramp. This table provides estimates of demand only where the performance of the freeway was measured to be statistically significant when ramp metering was used compared to when it was not used. This table shows that a managed lane strategy needs to be able to divert approximately 10 to 20 percent of the initial demand from the ramp in order to produce the same effect on freeway performance as installing a ramp meter.

Table 16-7. Percentage of Demand That Must Be Diverted from Ramp by Managed Lanes Strategies.

Freeway Demand Level	Ramp Acceleration Lane Length	Ramp Demand (pcph) with Metering	Equivalent Ramp Demand (pch) without Metering	Diverted Demand (pchp)	Percent Diverted Demand
1800	500	900	861	39	4.34%
1900	500	900	808	92	10.18%
2000	500	800 900	714 785	86 115	10.70% 12.83%
	750	900	735	165	18.35%
	1000	900	758	115	15.73%
	1250	900	843	57	6.38%
2100	500	600 700 800 900	557 640 720 797	43 60 80 103	7.14% 8.57% 10.01% 11.45%
	750	700 800 900	616 667 709	84 133 191	12.03% 16.65% 21.28%
	1000	900	793	107	11.88%
	1250	800	757	43	5.34%
2200	500	600 700 800 900	561 639 714 784	39 61 86 116	6.54% 8.66% 10.79% 12.91%
	750	600 700 800 900	552 619 680 733	48 81 120 167	8.05% 11.54% 15.03% 18.52%
	1000	700 800 900	635 705 769	65 95 131	9.32% 11.92% 14.53%
	1250	900	845	55	6.07%
2300	500	400 500 600 700	362 456 552 649	38 44 48 51	9.38% 8.70% 8.02% 7.34%
	750	500 600 700 800 900	456 534 607 676 741	44 66 93 124 159	8.73% 10.97% 13.22% 15.47% 17.72%
	1000	500 600 700 800 900	461 540 614 683 749	39 60 86 117 151	7.83% 10.07% 13.22% 15.47% 17.72%
	1250	700	659	41	5.87%

Table 16-8. Percentage of Demand That Must Be Diverted from Ramp by Managed Lanes Strategies (Cont.).

Freeway Demand Level	Ramp Acceleration Lane Length	Ramp Demand (pcph) with Metering	Equivalent Ramp Demand (pch) without Metering	Diverted Demand (pchp)	Percent Diverted Demand
2400	500	400	351	49	12.31%
		500	442	58	11.66%
		600	534	66	11.00%
		700	628	72	10.34%
	750	500	428	72	14.41%
		600	522	81	13.01%
		700	619	82	11.61%
		800	718	79	10.20%
		900	821	43	8.80%
	1000	600	557	43	7.23%
		700	631	69	9.83%
		800	701	99	12.43%
		900	765	135	15.04%
	1250	900	830	70	7.79%

Although, ramp meters have been shown to be an effective tool at helping to maintain efficient traffic flow on a segment of freeway, many agencies are hesitant to install ramp meters because of potential negative public opinion. Managed lane strategies offer the potential to manage traffic demand on a facility. The purpose of this study was to assess the feasibility of using managed lanes strategies applied to a ramp as an alternative to installing a ramp meter. Specifically, the research team wanted to determine the amount of traffic that needed to be diverted away from an entrance ramp, presumably by a managed lane strategy, to achieve an equivalent level of operation on a freeway segment that used ramp metering.

Using simulation, we compared the performance of a freeway segment with and without ramp metering. We used two measures to assess the performance of the freeway: average running speed, and throughput. Our simulation studies showed that ramp metering was able to maintain higher average running speeds and allow more throughput in a section of freeway than if ramp metering was not used in the segment. We then used the results of this analysis to determine what level of demand on a non-metered ramp would produce the same performance on the freeway that used ramp metering. We found that, on average, a managed lane strategy needs to be able to produce a 10 to 20 percent reduction in ramp demand to achieve the same level of operation on a freeway segment than if ramp metering was used on the same segment. Additional research is needed to determine which managed lane strategies would be most effective at achieving this level of demand reduction.

Section 4 – Incident and Special Event Management

The incentive for considering ramp management strategies in support of incident or special event management is to provide insight on freeway dynamics and the relationship between single versus multiple vehicle restrictions in concurrence with ramp management. The intent is to assess whether or not ramp management restrictions are a viable option in support of congestion management as they relate to accidents and special events.

Currently, operational strategies that support incident management include total ramp closure and Intelligent Transportation Systems (ITS) where travelers receive information on lane closures either pre-trip or en route. Although this document does not address advanced warning of congestion and its impact on ramp management, it may give insight to Traffic Management Centers (TMC) on how a facility currently operates in support of an accident and how pre-trip and/or en route information may or may not improve travel time for travelers. Modeling each ramp management scenario can give transportation agencies insight on how various combinations of strategies operate and which could possibly be the most viable option given the mix and percentage of vehicles currently using the facility. Operational strategies that support special events also include ITS technologies that give en route information pertaining to specific congestion locations. Regulating the amount of flow through a specific exit ramp could benefit not only freeway mainlanes but also overall network performance.

Performance Measures for Incident Management

In the context of managed ramps in support of incident management, the ultimate effectiveness of ramp management is gauged not only by the balance of traffic flow around the incident area, but also the flow of traffic in the surrounding areas. Volume and speed are two measures of effectiveness agencies can use to gauge the performance of various ramp management strategies for the purpose of incident management.

Volume

As with any freeway facility, hourly volumes are dynamic and are constantly changing. Volume comparison can validate how traffic is diverted in and around the incident location. Lower volume through the incident location means that the freeway travel time has significantly increased and caused vehicles to find alternate paths.

Speed

Speed is also an appropriate performance measure for assessing the effectiveness of ramp management strategies for incident management purposes. The distribution of speed along a corridor shows how a facility operates during periods of congestion caused by an incident. The volume on a freeway facility in conjunction with the number of vehicles entering at merge points can cause variations in speed. The higher the freeway speed, the more inclined vehicles are to use freeway ramps to enter the facility.

Network Performance

A comparative analysis can also be performed for ramp management strategies for incident management. Overall performance measures included average overall travel time and average stop time. It must be noted that the network performance of these scenarios includes all data collected within the entire defined network. The defined network can include the freeway facility, frontage roads, all ingress and egress points as well as all surrounding arterials.

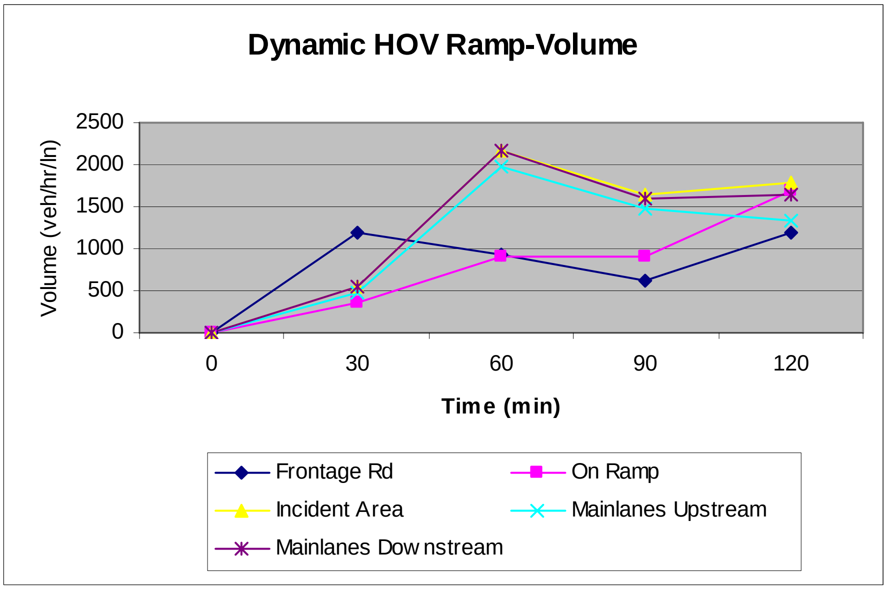
Viable Strategies for Incident Management

A number of managed ramp strategies have the potential to improve freeway operations in the case of incidents. Of the potential strategies considered, HOV ramps, ramp closure, and variable pricing have the greatest potential to reduce the impact of incidents on freeway operations when compared to truck restrictions and no ramp management.

HOV Ramp

The dynamic HOV ramp strategy consists of closing a designated freeway ramp to trucks and SOV vehicles simultaneously during the defined accident time intervals. Only HOVs are allowed to utilize the designated managed ramp during the defined accident time interval. Therefore, approximately 70 percent of traffic is diverted away from entrance ramps during incident time intervals. This result is consistent with vehicles rerouting their trips based on congestion levels and travel time.

Figure 16-12 shows performance levels for both volume and speed when the designated on-ramp is managed with truck and SOV restrictions. The dynamic HOV ramp shows considerably lower travel speeds and higher hourly volumes on the frontage road when compared to the baseline model. Incident area hourly volume for the dynamic HOV ramp on the freeway mainlane incident area approaches a saturation level of 2200 vehicles per hour in the open lane. This result would indicate that less turbulence at the on-ramp merge area allows greater flow of traffic to push through the incident area.



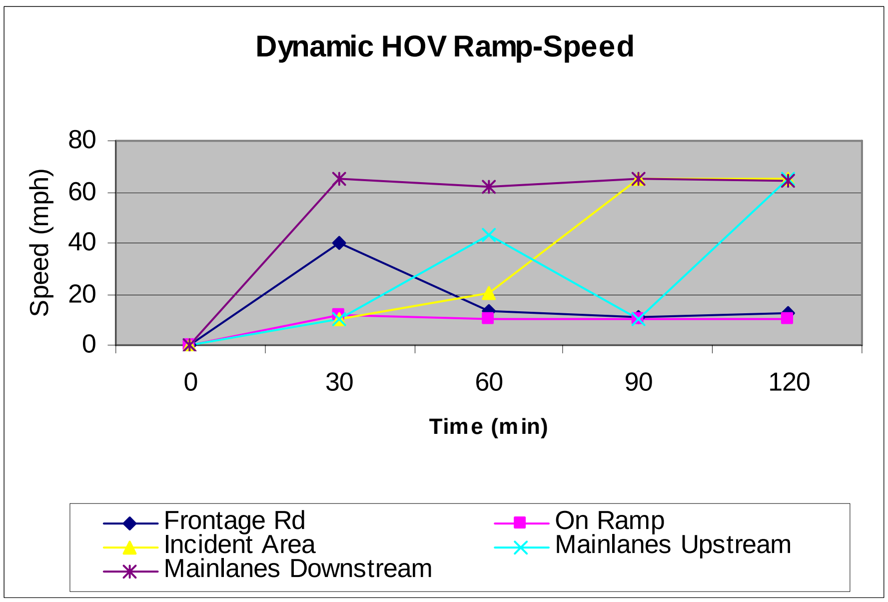
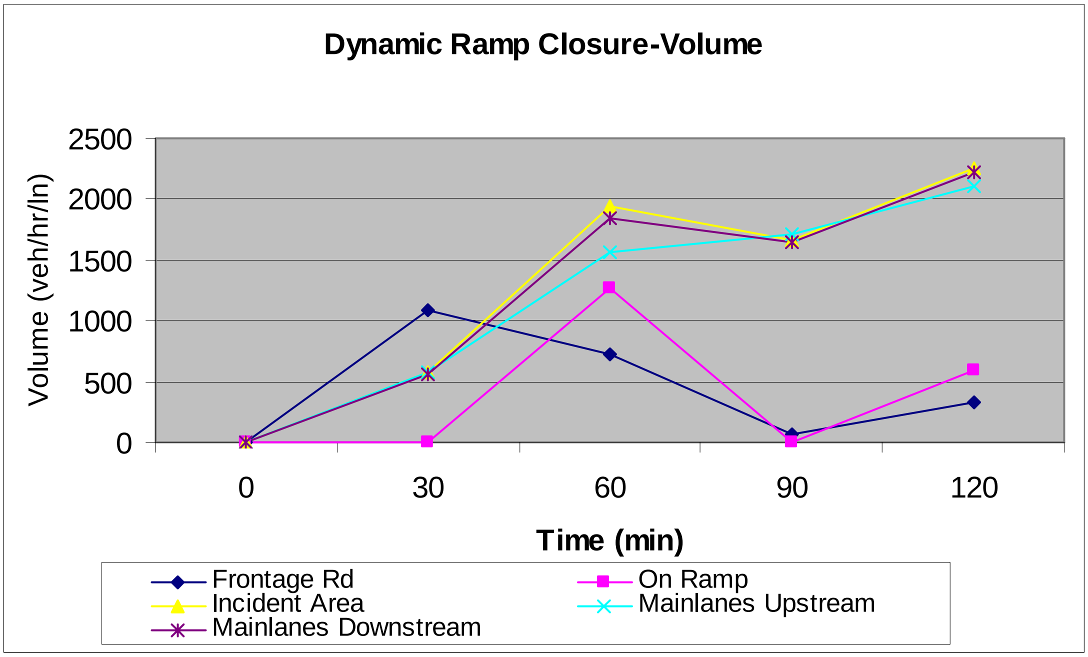


Figure 16-12. Dynamic HOV Ramp Performance Measures.

Dynamic Ramp Closure

The dynamic ramp closure strategy restricts all vehicles from entering the managed freeway on ramp during the simulated incident intervals. All vehicles must either bypass the managed entrance ramp to an upstream or downstream entrance, or reroute to shortest path based on travel time. Speed on the frontage road remains relatively consistent ranging from 36 to 40 miles per hour (mph). However, hourly traffic volume on the frontage road between 30 minutes and 90 minutes decreases to virtually zero. Researchers interpret from this decrease that the majority of vehicles using the managed entrance ramp divert away from the freeway altogether. Figure 16-13 is a graphical representation of the performance measures defined including speed and volume. Dynamic ramp closure has the potential to have a vast improvement on entrance ramp and frontage road travel speeds when compared to a baseline model. Volume on freeway mainlanes in the incident area are also higher during the periods of dynamic closure, allowing more mainlane vehicles to push through the only open lane.



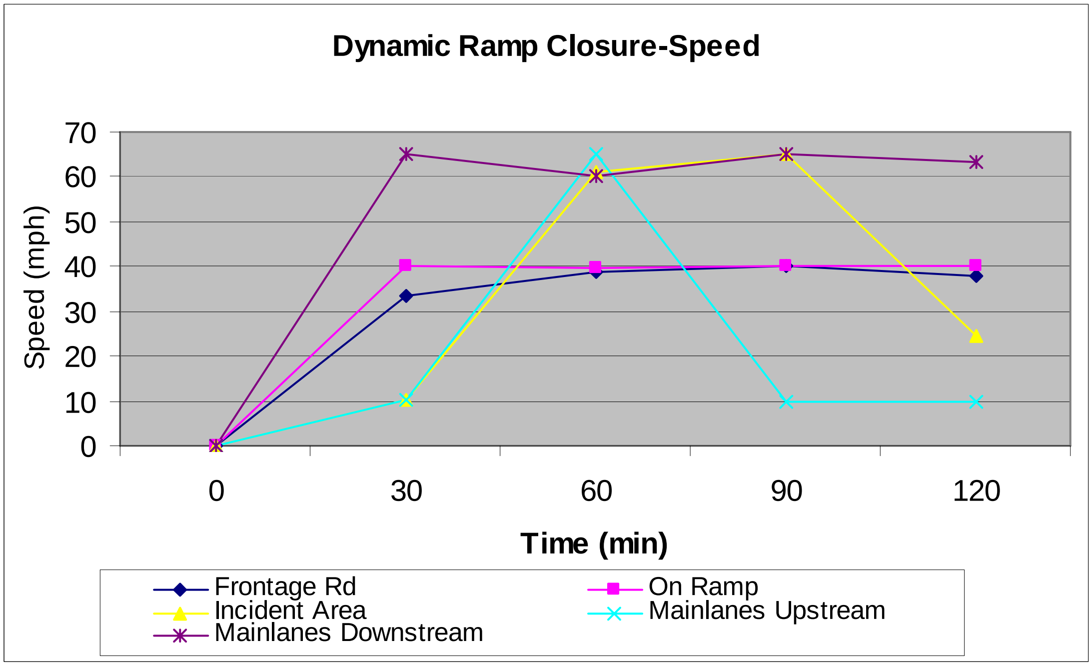


Figure 16-13. Dynamic Ramp Closure Performance Measures.

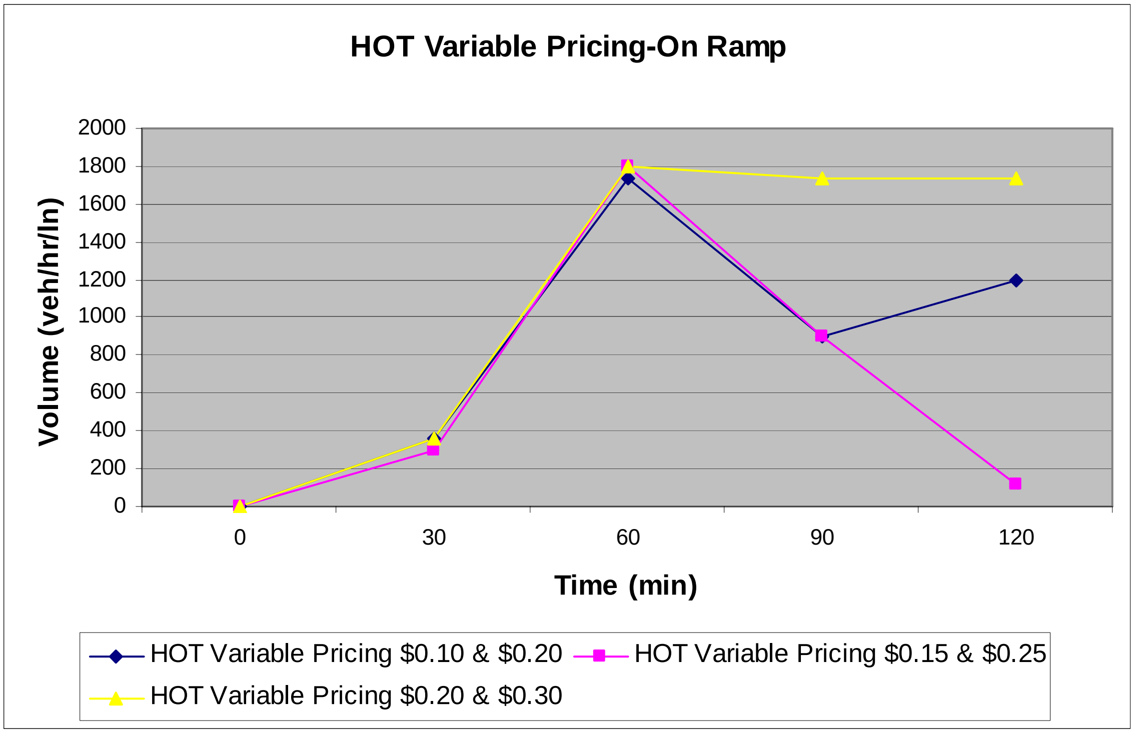
Dynamic Variable Pricing (HOT)

The dynamic variable pricing strategy consists of three different high-occupancy toll (HOT) models, each with different tolling rates. Tolling charges are implemented on a specified managed ramp simultaneously and continue for the duration of an incident. Toll charges are assessed to SOV vehicles and trucks. HOV vehicles can enter the managed ramp without charge. It must be noted that toll charges can be altered at various rates for SOV, HOV and trucks. It must further be noted that tolling intervals can be varied with sensitivity analysis to help relieve congestion caused by the shockwave of an accident. Table 16-9 shows the tolling rates used for each of the three defined HOT scenarios.

Table 16-9. High Occupancy Toll Rates-Incident Management.

Scenario	SOV	Truck	HOV
1	$0.10	$0.20	$0.00
2	$0.15	$0.25	$0.00
3	$0.20	$0.30	$0.00

HOT tolling scenarios show how sensitive drivers are to tolling rates. The managed ramp has higher volumes with a higher toll rate. This result is indicative of the fact that truck traffic composes 10 percent of all traffic and often has a higher value-of-time. This result also indicates the driver’s willingness to pay additional toll charges in order to save travel time. Since the managed ramp is immediately upstream of the incident, additional volume flow at this junction creates a bottleneck location where there is only one lane of traffic open. Therefore, the scenario with the highest toll rate attracts drivers to the managed ramp, and decreases freeway volume on the freeway mainlanes upstream of the incident, as shown in Figure 16-15. On-ramp volumes are considerably higher for tolling scenarios when compared to a baseline model. The tolling rate of $0.20 for cars and $0.30 for trucks has the highest on-ramp entry volume of the three tolling scenarios.



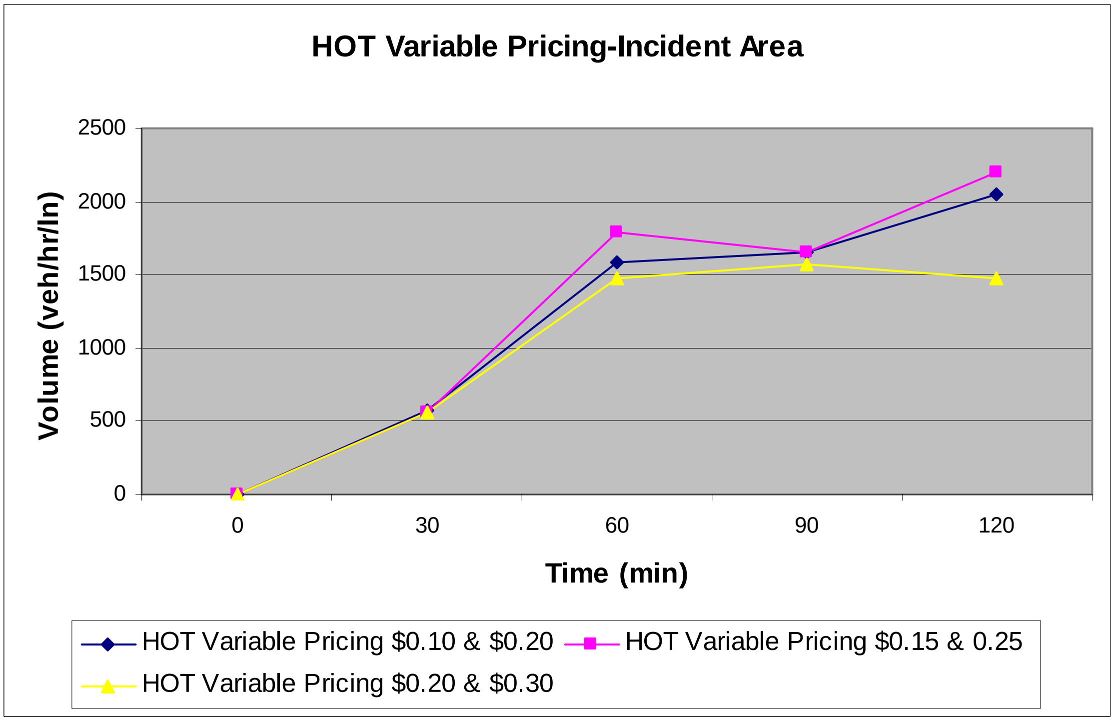
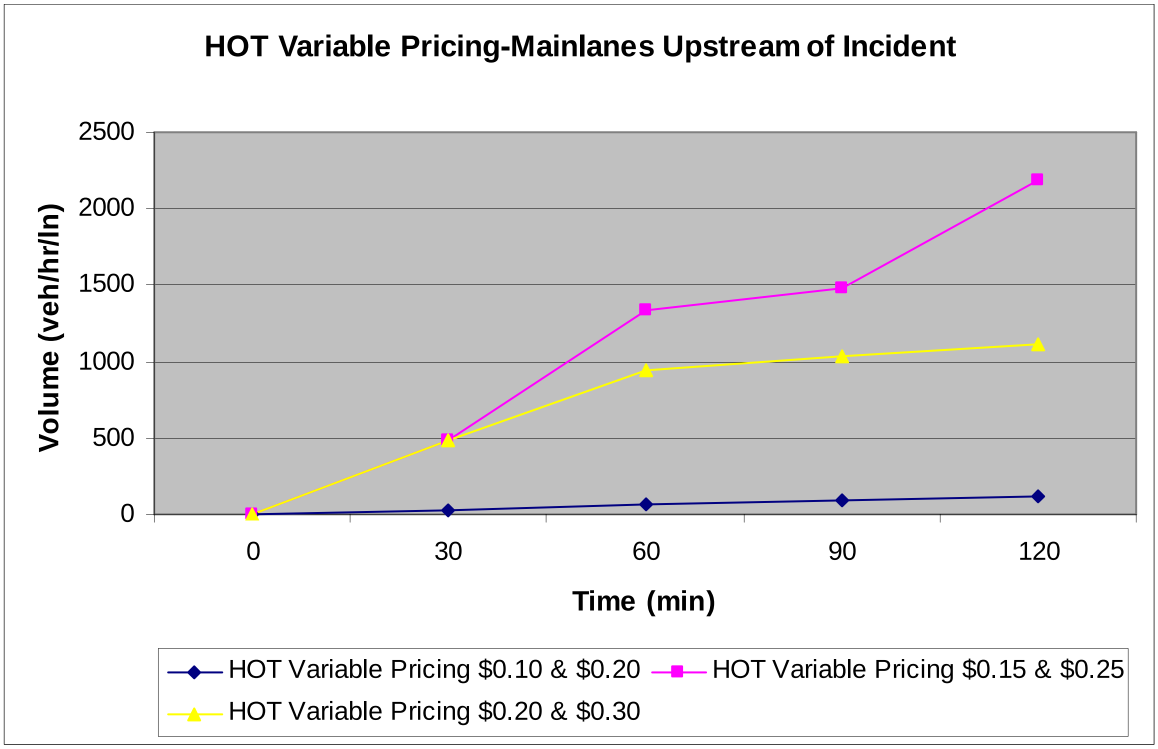


Figure 16-14. Tolling Scenarios – Volume.



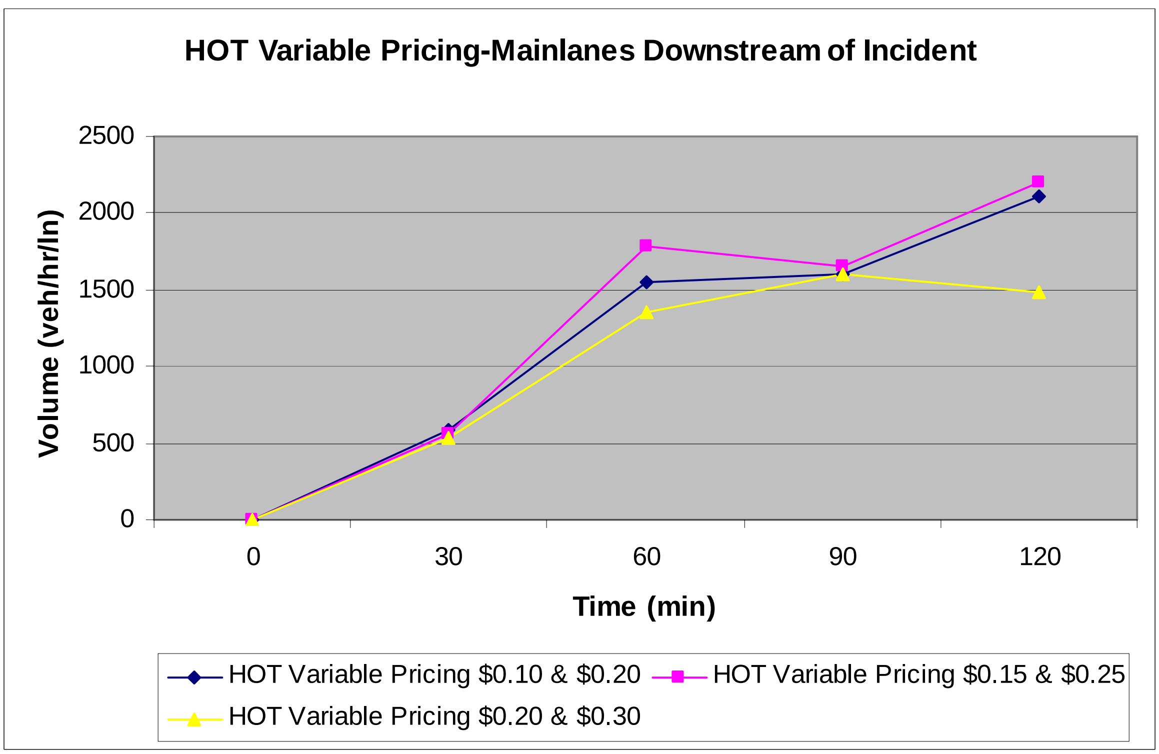


Figure 16-15. Tolling Scenarios – Volume (Contined).

A comparative analysis of six potential ramp management strategies for incident management as well as a baseline model provides insight into those strategies that might have the most benefits to the motoring public. Measures of effectiveness for freeway mainlanes in and around an incident area would be inconclusive since freeway capacity is reduced by 75 percent. In order to get an accurate assessment of how each ramp strategy performs, a system-wide network performance analysis is needed. Such an analysis shows that when the freeway ramp is closed dynamically during the duration of an incident, overall average travel time ranks better than all other alternatives, as shown in Figure 16-16.

Total ramp closure creates a better balanced flow of traffic on the open freeway mainlane and therefore reduces the overall travel time. Figure 16-17 illustrates that the highest variable pricing rate has the highest the average stop time. This outcome is proof of the fact that price elasticity dictates routing decisions for motorists (*7*).

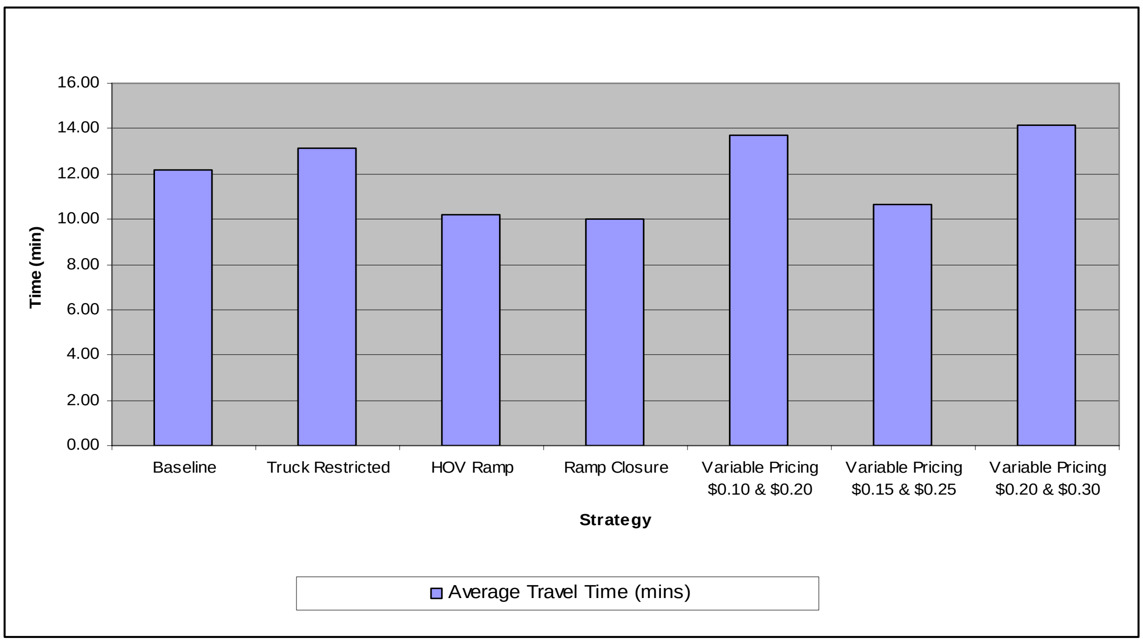


Figure 16-16. Comparative Analysis of Average Network Performance – Incident Management.

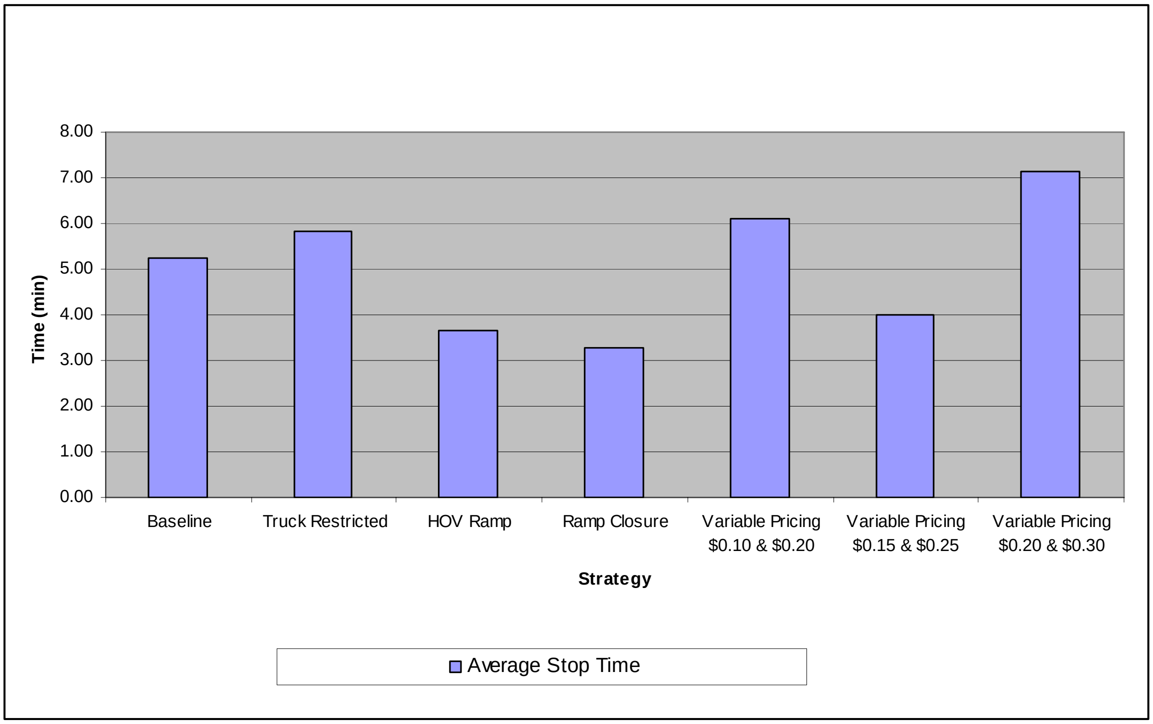


Figure 16-17. Comparative Analysis of Average Stop Time – Incident Management.

Incident Management Strategy Comparison

Ramp closure in response to a freeway incident has the most potential for providing optimal results when comparing average travel time and overall average travel times for all vehicles in the network. Restricting trucks from entering a freeway facility in response to an incident can actually be more detrimental to overall system performance. Despite the fact that a typical traffic stream includes only 10 percent of trucks, they are much larger to maneuver. Restricting trucks from entering a freeway can create havoc on the frontage and adjacent arterial roads. However, certain pricing schemes may actually perform worse than truck restrictions, indicating that price elasticity plays a major role in traffic diversion. When toll rates are high, vehicles immediately search for alternate paths downstream of the incident. When toll rates are low, vehicles flood the managed ramps and actually create bottleneck situations in and around the incident area. Therefore, sensitivity analysis with a well calibrated model is needed before optimal results can be obtained when analyzing pricing as a ramp management strategy.

Performance Measures for Special Event Management

In the context of managed ramps in support of special event management, the ultimate effectiveness of ramp management is gauged not only by the balance of traffic flow around the defined exit ramp, but also the flow of traffic on adjacent freeway mainlanes. For special event management, performance measures agencies can evaluate effectiveness using queue length, delay, speed, and travel time.

Queue Length

During special events, traffic converges on a destination in a short time period. As a result, queuing can propagate rather quickly on freeway exit ramps. This condition can lead to rear-end collisions, congested traffic areas, and bottleneck areas on adjacent freeway mainlanes. For this reason, queue length is an appropriate performance measure. The ability to estimate the propagation of vehicle spillback by managing the exit ramp of a special event area can give stakeholders insight into which type of vehicles to restrict or give accessibility. Queue length is typically measured from the stop bar of a terminal intersection.

Delay

Delay is one of the most scrutinized performance measures by travelers. When vehicles are destined to a special event, delay becomes even more critical. Any change in traffic congestion can have major impacts on vehicle delay. Consequently, delay is another appropriate performance measure for ramp management for special event purposes. Delay is measured from upstream freeway mainlanes to exit ramp.

Speed

Speed changes in and around a freeway exit ramp are dynamic and can vary greatly due to any disruption of traffic flow. Freeway exit ramps that experience heavy volumes in short time periods can easily alter the speed of freeway mainlanes. This imbalance of speed can increase the chances of collisions. Speed on freeway mainlanes adjacent to exit ramp is an appropriate performance measure to assess the impact of managed ramps for special events.

Travel Time

Off ramp queuing and speed changes around a special event area can affect travel time for vehicles bypassing the event. Peak hour congestion combined with a special event can compound the problem and increase travel time dramatically. Therefore, travel time is an additional performance measure for this ramp management strategy. Travel time is measured on a 4-mile section of a freeway adjacent to a special event venue.

Viable Strategies for Special Event Management

Two managed ramp strategies for special event management have the most potential to improve freeway operations: venue-destined vehicle restrictions and total closure. Both of these strategies have the potential to alleviate problems when too many vehicles utilize a single exit ramp to access a special event venue.

Venue-Destined Vehicle Restrictions

The first ramp management strategy is to dynamically restrict venue-destined vehicles from entering the venue from the closest freeway exit that creates problems. When queuing reaches the midpoint of the exit ramp, the venue-destined vehicles are automatically rerouted and forced to continue on the freeway facility to the next available exit. The goal is to prevent the queued vehicles from spilling back onto the freeway mainlanes. As the queue dissipates, venue-destined vehicles are allowed to utilize the exit ramp again. Output performance measures are compared to a base case (do nothing) model and consist of ramp queue length, average freeway travel time on a predefined section, average speed upstream of the exit ramp, and average delay measured at the terminal intersection.

Ramp Closure

The second strategy is to restrict all vehicles from exiting at the problem exit ramp when spillback onto freeway mainlanes starts to occur. As with the venue-destined vehicle restriction strategy, all vehicles are automatically rerouted and forced to continue on the freeway facility and bypass the exit ramp. Performance measures for all vehicles restricted are identical to the venue-destined vehicle restriction.

Special Event Management Strategy Comparison

When both scenarios are compared to a base case model, significant impacts are noticeable. A comparative analysis of average freeway speed drops below 15 mph when no ramp management strategies are implemented. Restricting venue-destined vehicles and restricting all vehicles considerably increases freeway speeds to approximately 50 mph. Speeds for ramp managed scenarios fluctuate between the two as shown in Figure 16-18.

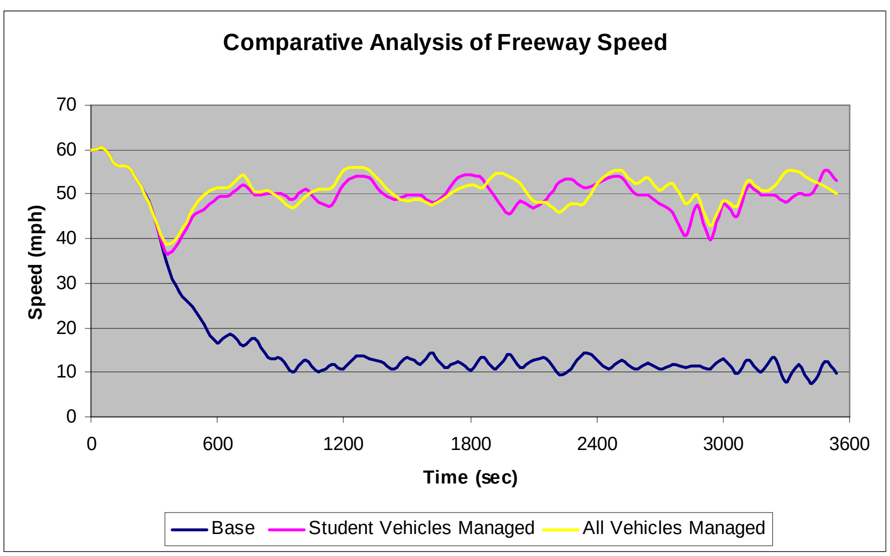


Figure 16-18. Comparative Analysis of Freeway Speed-Special Event Management.

If ramp storage from the stop bar at a terminal intersection is approximately 900 ft to the loop detector, queue length exceeds the storage capacity in the base model and continues to spill back for the duration of the special event. Both ramp management scenarios drastically reduce the queue length. The length of the queue fluctuates but stays relatively short and does not surpass the storage capacity of the off-ramp, as shown in Figure 16-19.

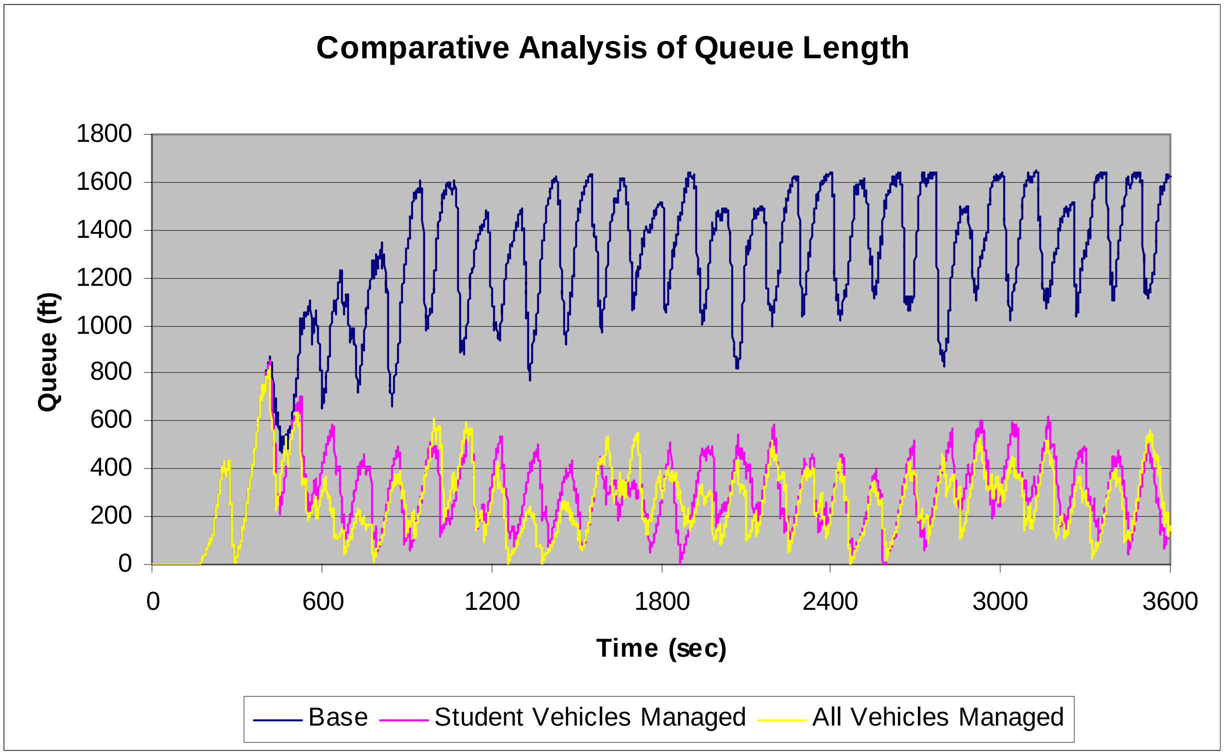


Figure 16-19. Comparative Analysis of Queue Length-Special Event Management.

Modeling shows that ramp closure performs the best when compared to venue-destined vehicle restrictions. Significant improvements to speed, queue length, delay, and travel time are apparent in simulation models. This brings forth the question of how dynamic restrictions and closures can be implemented. It must be noted that in reality, all traffic does not obey messages placed on dynamic message signs (DMS), which can be a useful tool to implementing these strategies. Therefore, it is important to consider the optimal upstream placement of DMS to maximize traffic flow or minimize traffic disruption caused by off-ramp queue spillback resulting from congestion from special events.

Section 5 – Managed Lanes Facility Preference

One particular motivation for managing ramps is in support of managed lanes that exist within an expressway corridor. Often the management of these ramps is less visible than directly managed ramps and the strategies are as subtle as ramp location to "feed" eligible vehicles to the managed portion of the facility. As an example, visualize a medially located managed lane along an expressway corridor through an industrial portion of a city. The managed lane permits only trucks and there are expressway general-purpose entrance/exit ramp pairs every half mile. Several ramps are available for trucks to enter the expressway, but trucks are managed by having them enter the expressway at a ramp a mile upstream from the location where a slip ramp provides access from the expressway general-purpose lanes into the barrier-separated truck-only managed lane. If this control was not applied, trucks entering at the first ramp upstream of the managed entrance would have insufficient distance to weave to the managed lane entrance without adversely affecting general-purpose lane speed.

Since this portion of the managed ramp guidelines focuses on expressway access ramps that support managed lanes within the expressway corridor, the management techniques deployed at the ramp are linked to the function and restriction of the managed lanes. Typical forms of managed lanes in Texas include HOV lanes, express (limited access) lanes, and tolled lanes, though some research in the state has been directed to investigating the potential for truck-only managed lanes (*8*).

The motivation for a detailed examination of operations issues associated with managing ramps to support an expressway's managed lanes function(s) is to provide reasonable design values for ramp placement given the geometric and traffic demand environment of the expressway facility, the type of managed lanes in the corridor, and the type of controls placed on the ramp. It is additionally desired that the use of any procedure developed for this purpose would either directly or indirectly indicate whether the type of management strategy being considered for a ramp was viable in terms of not adversely affecting quality of flow on the expressway.

Performance Measures for Managed Lane Facility Preference

In the context of managed ramps that support managed lanes within an expressway corridor, the efficacy of ramp management is ultimately gauged by the relative success of the managed lanes themselves. In turn, objectives for managed lanes depend heavily on the communities in which projects are found. Texas experience to date has deployed managed lanes to varying degrees to increase average vehicle occupancy (Houston and Dallas HOV lanes); increased expressway safety (Houston, Austin, Dallas/Fort Worth, San Antonio truck lane restrictions); generated revenue from the sale of excess capacity for more reliable travel times (Houston HOT lanes); and facilitated long-distance trips (express lanes with restricted access in many cities).

Speed

At the heart of any given managed lanes strategy is the explicit goal of maintaining high speed for the managed lanes (*9*). In essence, while the goal of the overall managed lane is linked to community and stakeholder needs and objectives, the performance of the managed lane is judged by its ability to maintain quality, higher-speed travel. As a result, speed is the primary indicator of the level of performance for managed ramps scenarios supporting managed lanes. The use of speed as a performance indicator has the additional benefit of being readily and directly understood by the motoring public, unlike more industry-specific terms such as density and flow rate.

Speed Differential and Safety

One of the primary contributing factors to safety issues arising along higher-speed roadways is speed differential. In the case of uncongested expressway traffic, the most readily identifiable locations where speed differentials occur are in the vicinity of entrance and exit ramps, where motorists are either attempting to decelerate to exit ramp speed or accelerate from entrance ramps in order to match pace with through vehicles on the expressway. Weaving situations offer additional complexity that the driver must negotiate as they contend with gap searching and acceptance across multiple lanes and possible speed differentials between weaving and expressway through traffic.

Traffic engineering research shows that crash potential increases as the speed differential increases (*10*). Figure 16-20 demonstrates this phenomenon, which relates speed differential and crashes for both full access-controlled expressway ("Freeway" in the figure) and non-access controlled arterial roadways. Essentially, as the speed differential increases the crash rate increases at an exponential rate. The impact on safety resulting from speed differentials is further documented in national practices and standards for roadway design (*11*), from which Figure 16-21 is extracted. Figure 16-20 and Figure 16-21 are notably consistent in associating lower speed differentials with lower crash rates and indicating a speed differential of approximately 10 mph as the transition point above which the crash rate or ratio begins to increase rapidly with increasing speed differential.

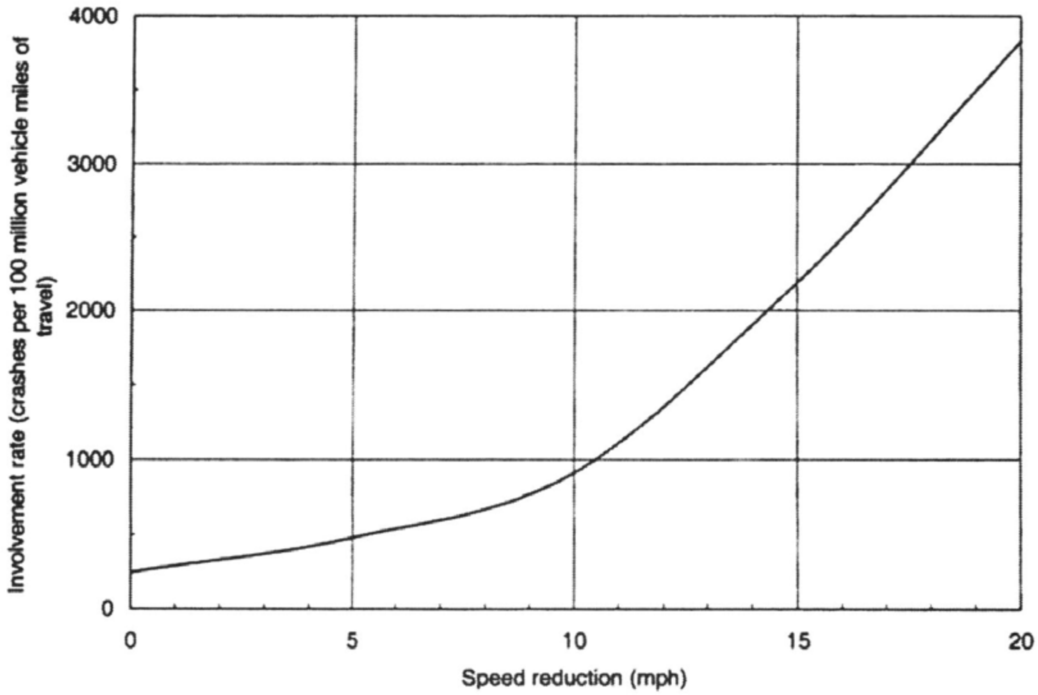


Figure 16-20. Crash Rate as a Function of Speed Differential (Adapted from *10*).

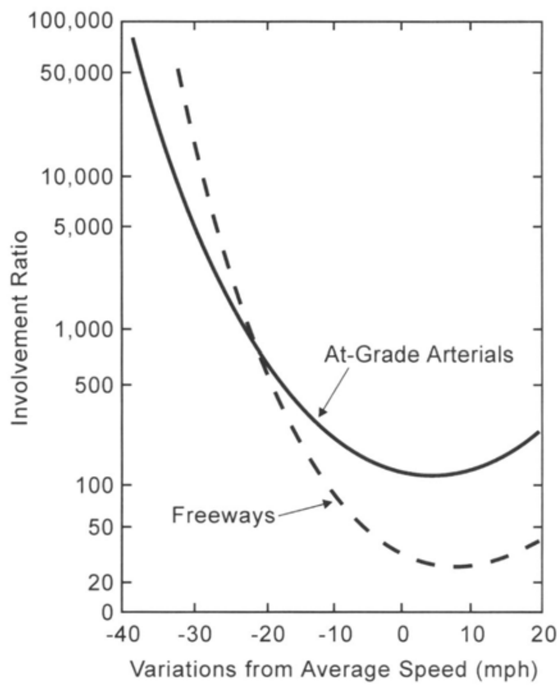


Figure 16-21. Crash Involvement Rate of Trucks for Which Running Speeds Are Reduced Below Average Running Speed of All Traffic (*11*).

Speed and speed differential can be used in several ways in the course of analysis performed on the simulation output data from ramp modeling to support managed lanes. Only those conditions with speed differentials of less than 10 mph are considered desirable and viable for design. Simulation results should be subjected to two tests: speed differential between approaching expressway traffic and traffic within the managed ramp weaving area, and speed differential between expressway through (i.e., non-weaving) and ramp-to-managed lanes (weaving) traffic. If either speed differential is observed to be in excess of 10 mph, that scenario is not recommended as a potential managed ramp design condition.

Managed Lane Merging Conditions

Several figures illustrate a more complete visual example of the potential conditions under which access to a managed lanes facility is provided downstream of a general-purpose ramp. Figure 16-22 presents the case where an intermediate exit ramp is found between the managed entrance ramp and the managed lanes access ramp. The managed ramp itself features a forced merge condition onto the expressway through lanes. Figure 16-23 illustrates the ramp merge condition where an acceleration lane is provided. Figure 16-24 shows a full auxiliary lane. Note that since no downstream intermediate ramp is shown in this example the auxiliary lane becomes a full lane addition onto the expressway.

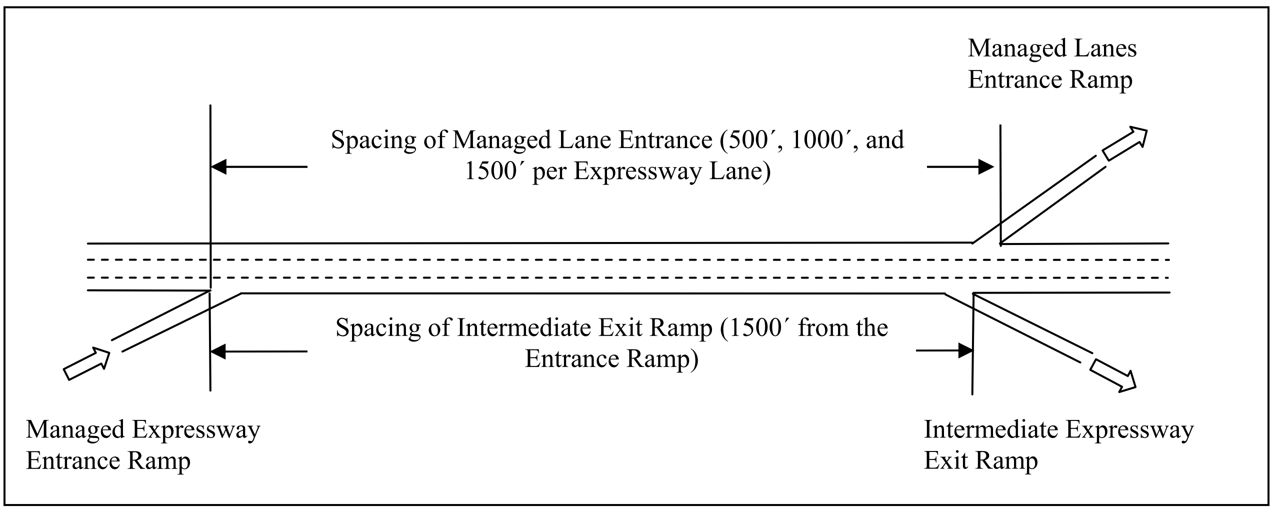


Figure 16-22. Expressway with Forced Merge Ramp (with Intermediate Ramp).

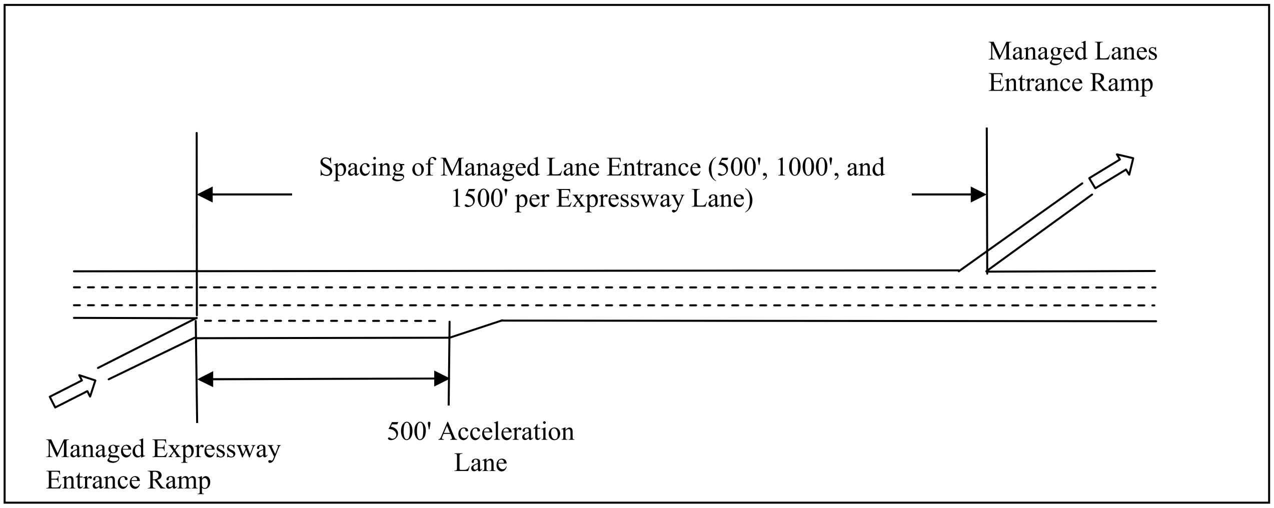


Figure 16-23. Expressway with Acceleration Lane Ramp Merge (without Intermediate Ramp).

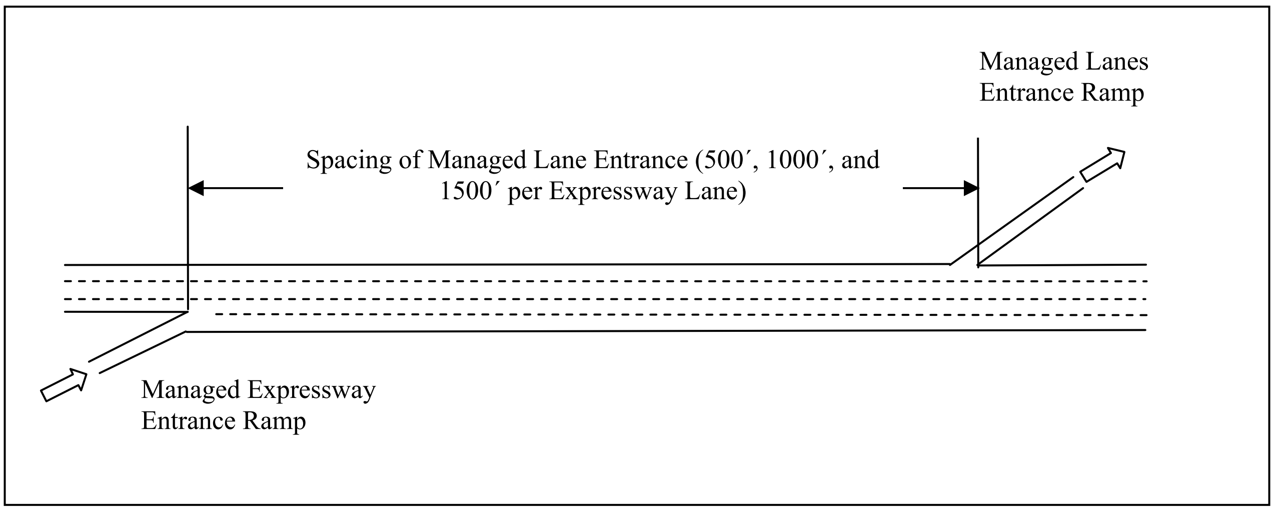


Figure 16-24. Expressway with Full Auxiliary Lane Ramp Merge (without Intermediate Ramp).

Viability of Managed Facility Preference

As noted previously, only those conditions with speed differentials of less than 10 mph are considered desirable and viable for providing managed ramp preference for vehicles destined for a managed lanes facility. The following sections discuss the overall impacts of various factors on the ability to maintain speed differentials of less than 10 mph for this purpose. Each discussion presents information related to the three merging conditions noted above.

Proportion of Trucks on the Expressway

The vehicle mix on the expressway mainlanes can be divided into three categories: no trucks (90 percent auto, and 10 percent bus); normal mix (90 percent auto, 5 percent bus, and 5 percent truck); and high truck volume (80 percent auto, 5 percent bus, and 15 percent trucks). Figure 16-25 shows expressway mainlane speeds and ramp weaving speeds under the three ramp merge conditions and for the percentage of truck traffic on the expressway. As the expressway truck percentage increases, expressway through lane speeds and ramp weaving speeds decrease for all ramp merge conditions. Expressway mainlane speeds and ramp weaving speeds are higher where the ramp merge features an auxiliary lane.

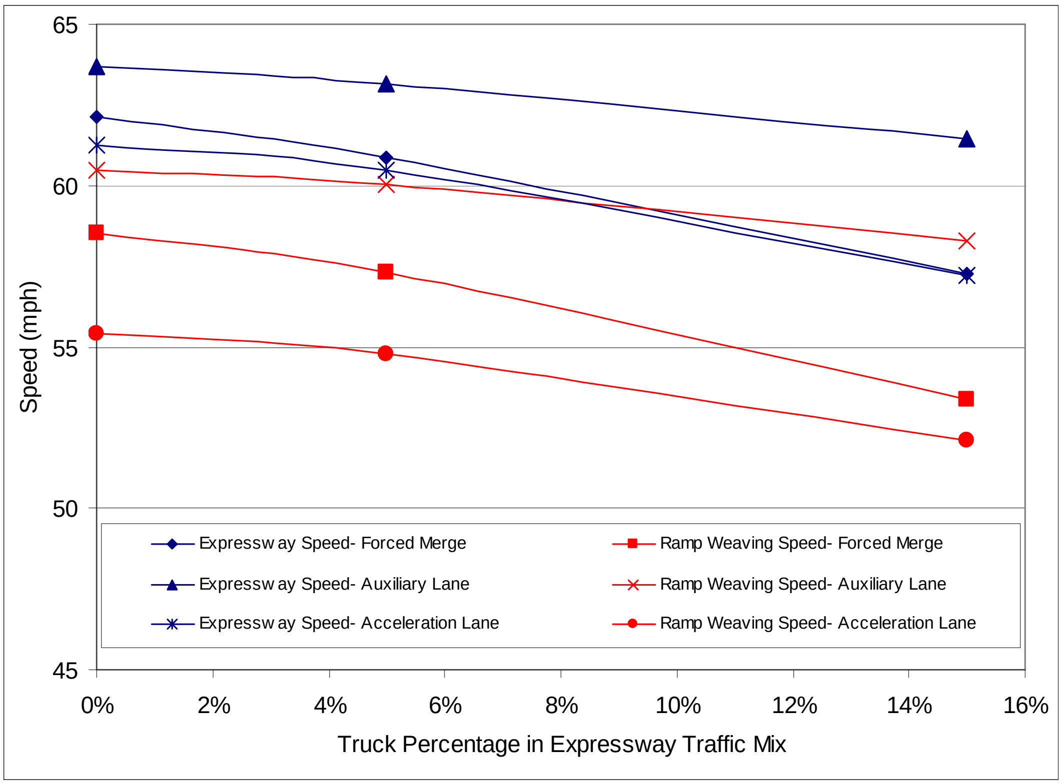


Figure 16-25. Expressway and Ramp Weaving Speeds with Different Expressway Truck Mixes.

Space between Managed Ramp to Managed Lanes Access Point

Different ramp spacings of 500 ft, 1000 ft, and 1500 ft per expressway lane also impact the operations of the freeway when managing ramps for managed lanes facility preference. Figure 16-26 shows expressway mainlane speeds under various ramp merge conditions and ramp spacings. Mainlane speeds are observed to increase with spacing increases between the managed ramp and the managed lane access ramp. Ramp weaving speeds and ramp spacing per expressway mainlane for all three ramp merge conditions are shown in Figure 16-27. Ramp weaving speeds also increase with an increase in spacing entry ramp to expressway and entry ramp to the managed lane.

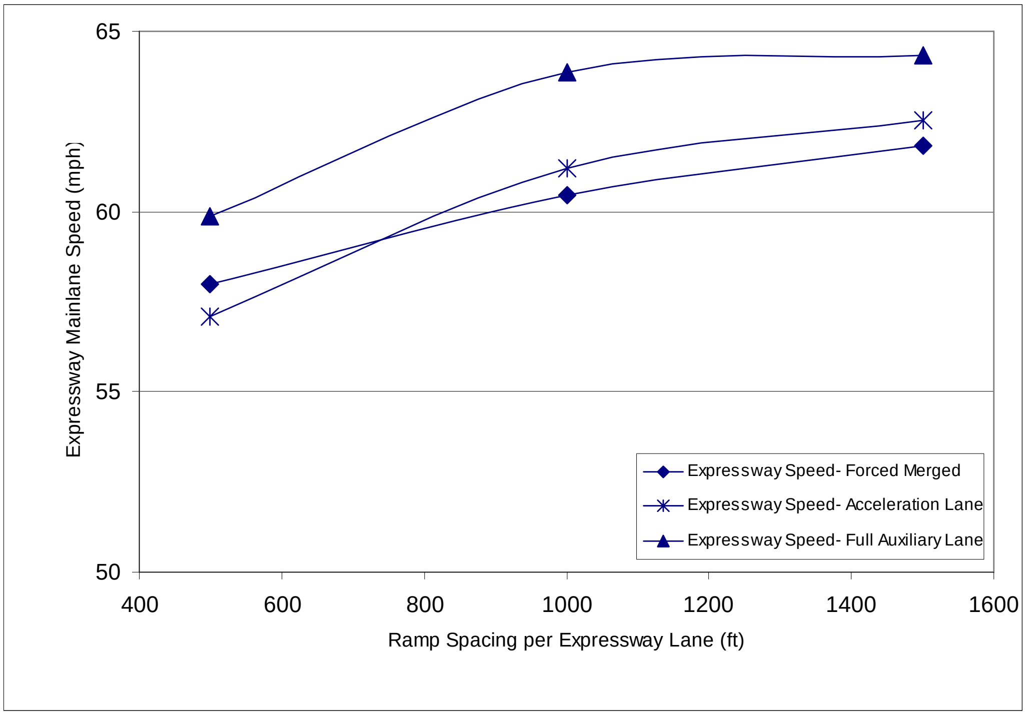


Figure 16-26. Expressway Mainlane Speeds with Different Ramp Conditions and Ramp Spacing.

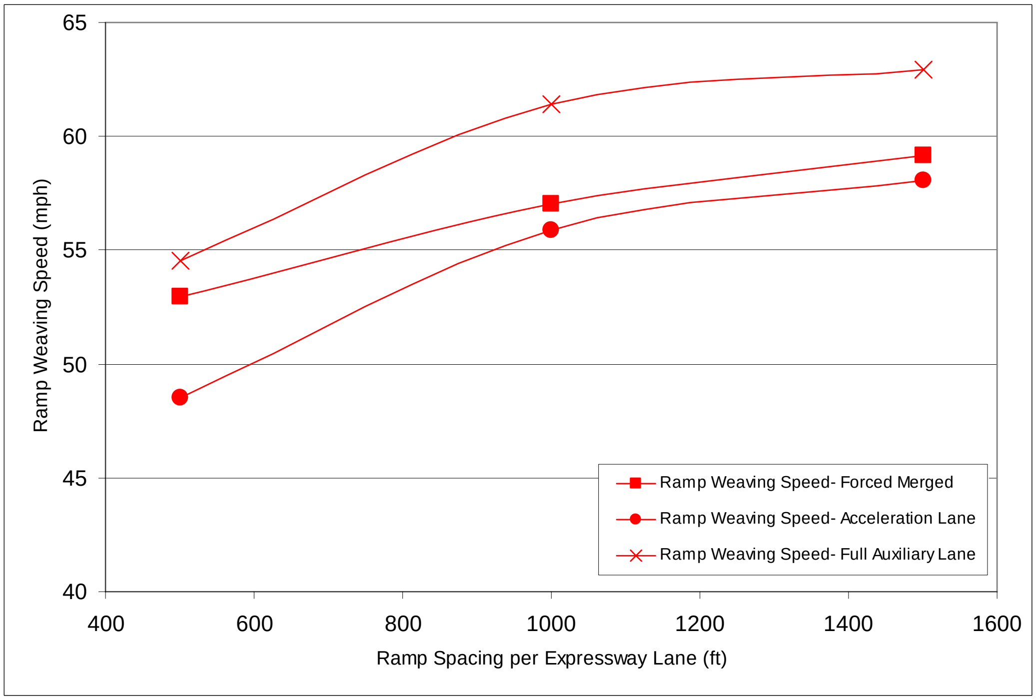


Figure 16-27. Ramp Weaving Speeds with Different Ramp Conditions and Ramp Spacing.

Proportion of Automobiles on the Ramp

Four managed ramp vehicle mixes provide insight into the impact of these vehicle mixes on freeway operations when managed at the ramp. These vehicle mixes include: all automobiles (100 percent auto); normal mix (90 percent auto, 5 percent bus, and 5 percent truck), HOV/HOT/SOV and buses only (85 percent auto and 15 percent bus); and trucks only (100 percent truck). Expressway mainlane speeds are observed to increase with an increase in the proportion of automobiles found in the ramp traffic mix. Similarly, ramp weaving speeds increase with an increase in the ramp auto proportion. Expressway mainlane speeds and ramp weaving speeds, broken down by the three ramp merge conditions, are shown in Figure 16-28 and Figure 16-29, respectively.

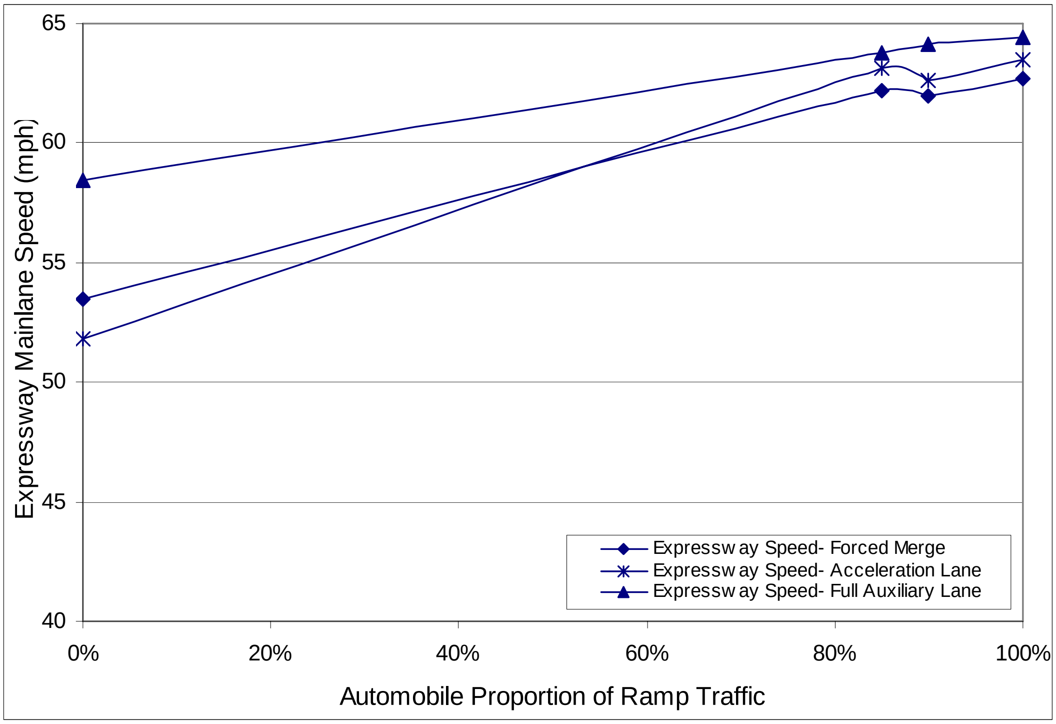


Figure 16-28. Expressway Mainlane Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

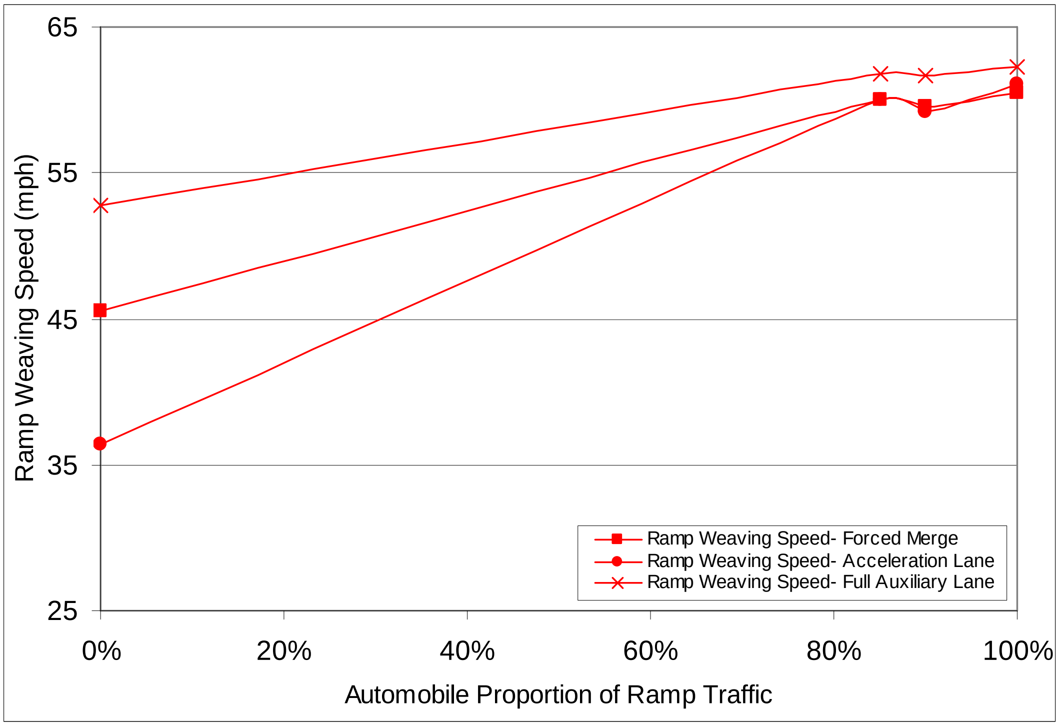


Figure 16-29. Ramp Weaving Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

Figure 16-30 and Figure 16-31 show expressway mainlane speeds and ramp weaving speeds under the three ramp spacing conditions, respectively. Expressway speeds and ramp weaving speeds both increase with increases in weaving distance and increase in the proportion of automobiles found on the ramp.

The "truck only" ramp vehicle mix performs better with full auxiliary lane than the other two types of ramp merge conditions. The speed difference is approximately 7 mph between full auxiliary lane and acceleration lane ramp merge conditions for a ramp composition of 100 percent trucks. The speed difference reduced to approximately 1 mph for a ramp featuring only automobiles in the vehicle mix. Expressway mainlane speed was approximately 52 mph with 100 percent trucks on the ramp and the speed increased to approximately 64 mph with 100 percent automobiles on the ramp for a ramp with an acceleration lane. The differential of ramp weaving speed between two ramp conditions, full auxiliary lane, and acceleration lane, is approximately 17 mph for 100 percent trucks on the entrance ramp. The speed differential of ramp weaving speed for these two ramp merge conditions is approximately 1 mph if 100 percent autos are found on the ramp.

Full auxiliary lanes yield higher ramp weaving speeds for both 100 percent truck and 100 percent auto vehicle mixes on the entrance ramp. The difference in the ramp weaving speed between the acceleration lane and forced merge ramp condition is greater when the ramp serves 100 percent truck traffic. Ramp weaving speed differentials are observed to decrease as the truck proportion on the ramp traffic decreases. The difference is marginal when truck proportion in traffic mix reaches zero, e.g., 100 percent automobiles on the ramp.

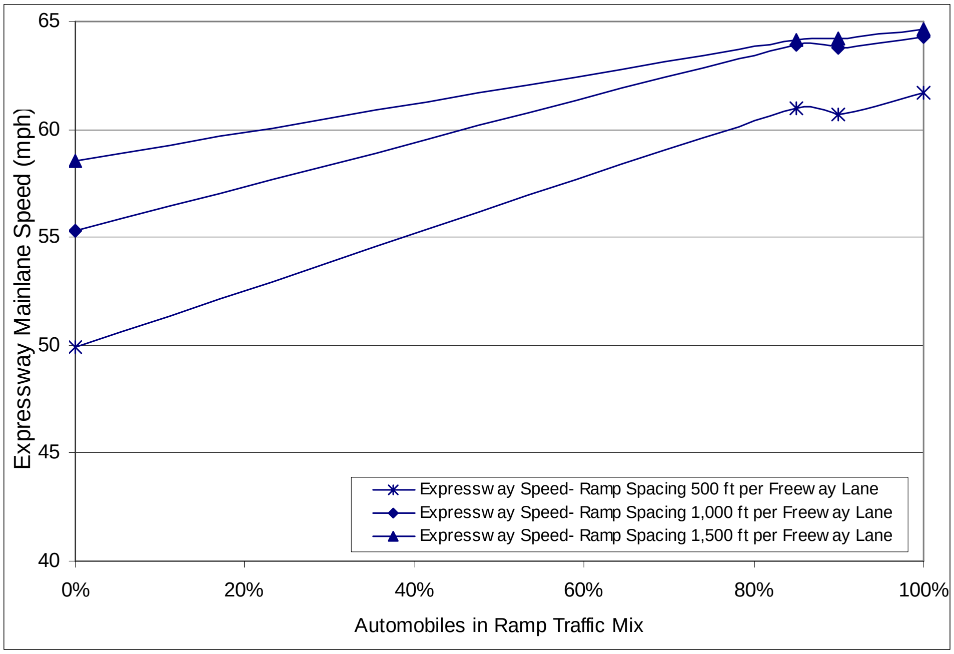


Figure 16-30. Expressway Mainlane Speeds with Varying Automobile Proportions and Ramp Spacing.

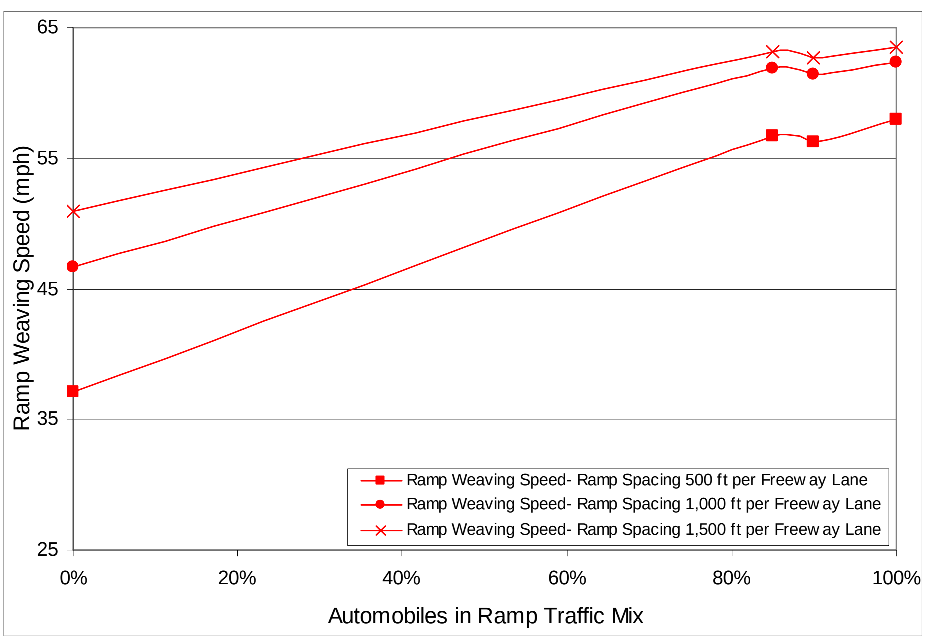


Figure 16-31. Ramp Weaving Speeds with Varying Automobile Proportions and Ramp Spacing.

Expressway Volume Level

Two typical volume expectations for expressway traffic conditions are either nominal (1000 vehicles per hour per lane [vphpl]) or higher volume (1400 vehicles per hour per lane) flow levels. As expected, expressway mainlane and ramp weaving speeds are greater when the volume level is less demanding in terms of volume-to-capacity ratio. Figure 16-32 shows both expressway mainlane and ramp weaving speeds with different ramp merge conditions and expressway flow levels.

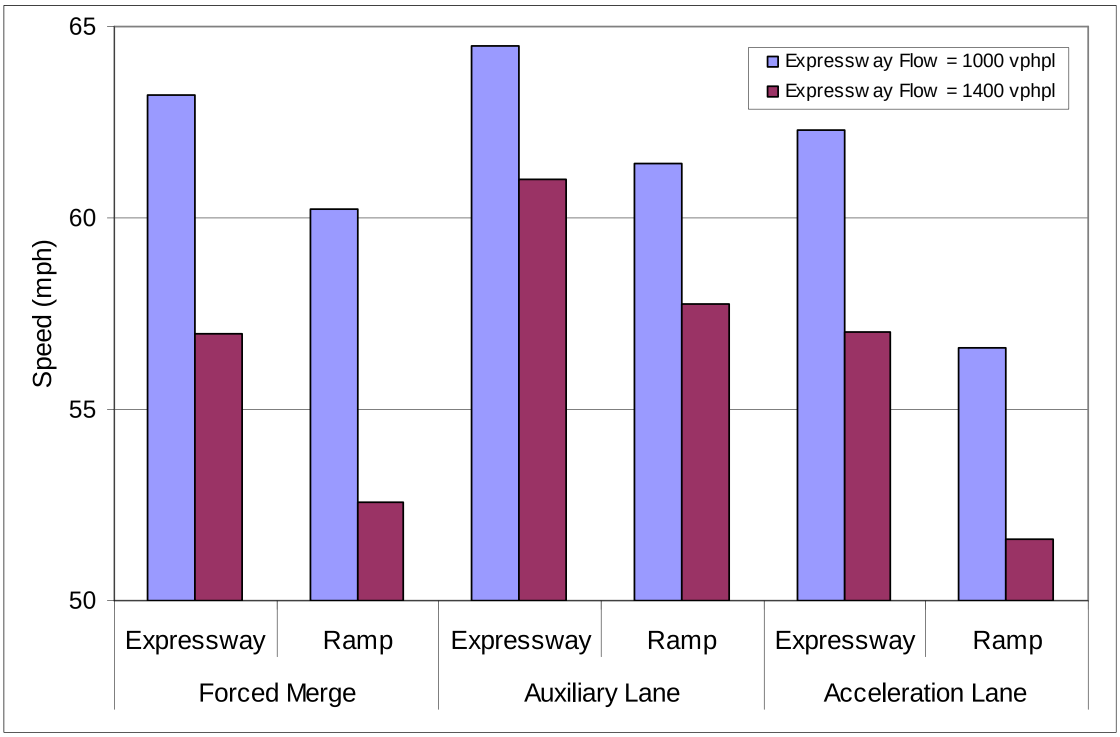


Figure 16-32. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Expressway Flow Levels.

Presence of an Intermediate Ramp

The presence of an intermediate ramp between the expressway's managed entrance ramp and the entrance ramp to the managed lanes decreases the expressway mainlane and ramp weaving speed. Both expressway mainlane and ramp weaving speeds are lower for all ramp merge conditions in the presence of intermediate ramps. Figure 16-33 illustrates expressway mainlane and ramp weaving speeds with and without the intermediate ramp and across different ramp merge conditions.

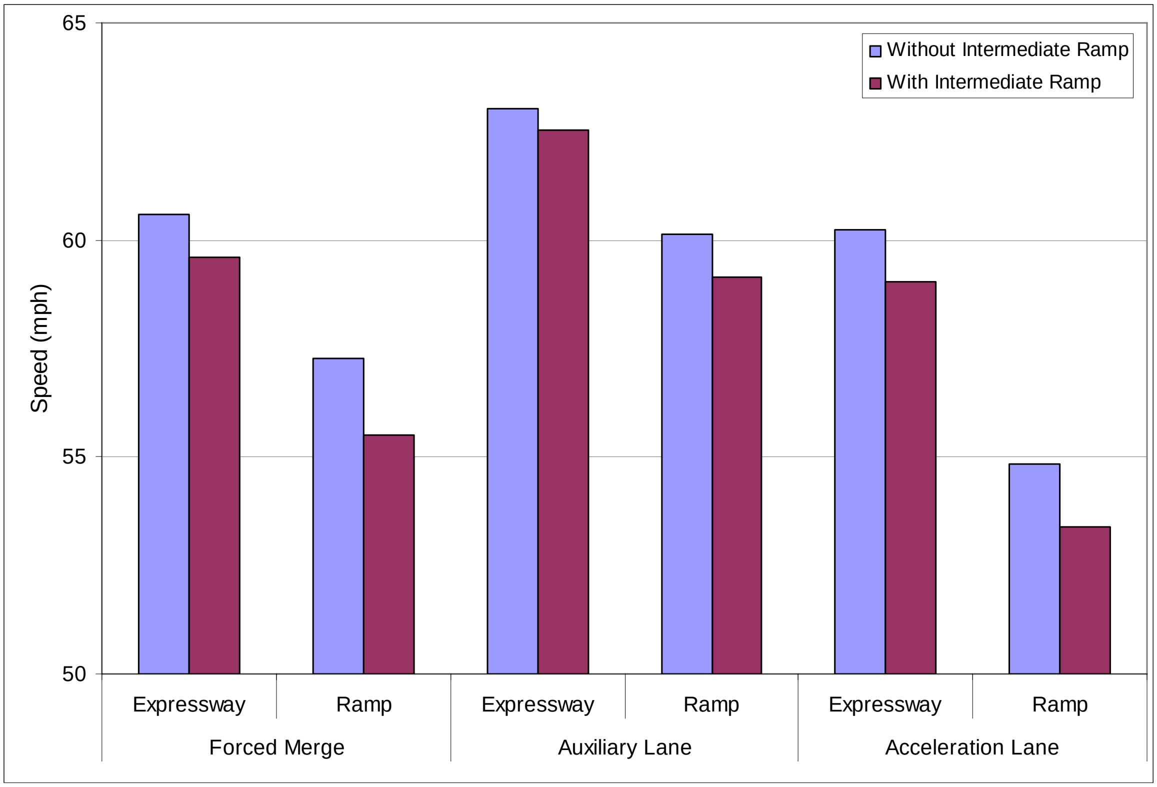


Figure 16-33. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Intermediate Ramp Scenarios.

Entry Ramp Flow Level

Two typical levels of managed ramp flow can impact operations, those levels being 375 and 750 vehicles per hour per lane. Figure 16-34 shows the extent to which higher ramp flows have an impact on freeway and ramp weaving speed performance. The output is also organized to demonstrate the differences ramp merge conditions have under the different ramp flow scenarios.

Proportion of Ramp Traffic Weaving to Reach the Managed Lane

To ascertain the impact that different quantities of weaving traffic from the managed ramp to the managed lanes access point had on overall operations, cases are designed with 25 percent and 50 percent of ramp traffic weaving to reach the managed lane. Figure 16-35 illustrates the significance of the weaving traffic proportion on expressway mainlane and ramp weaving speeds and which organizes results by managed ramp merge condition.

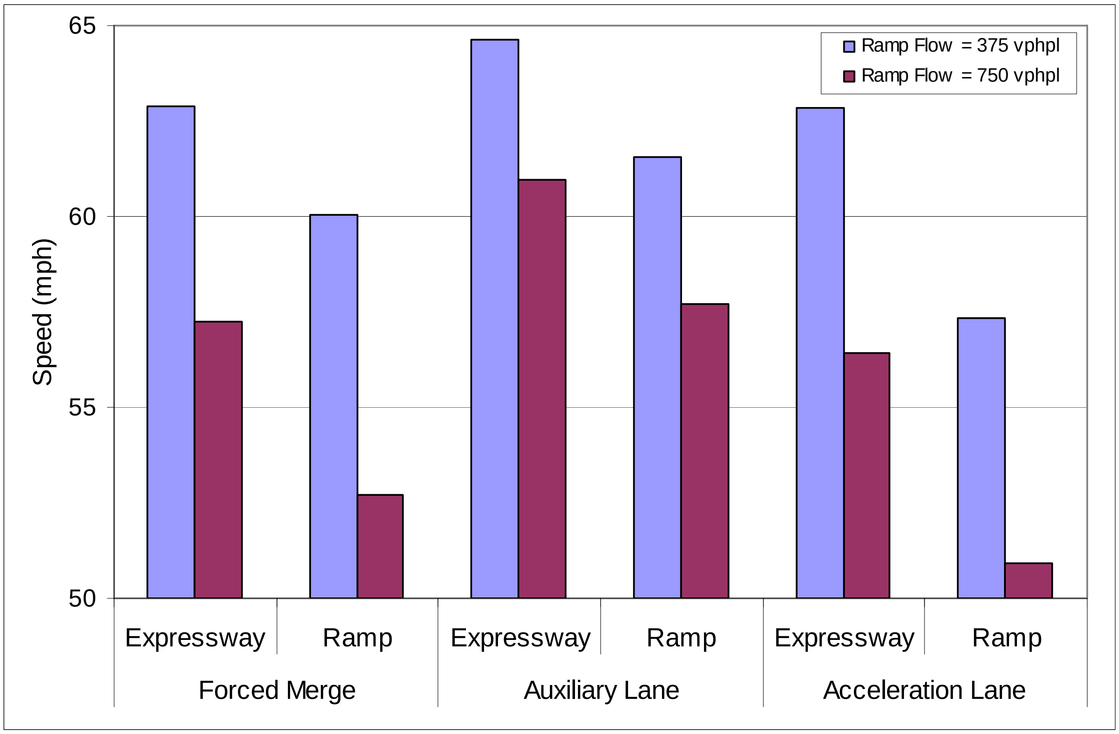


Figure 16-34. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Ramp Flow Levels.

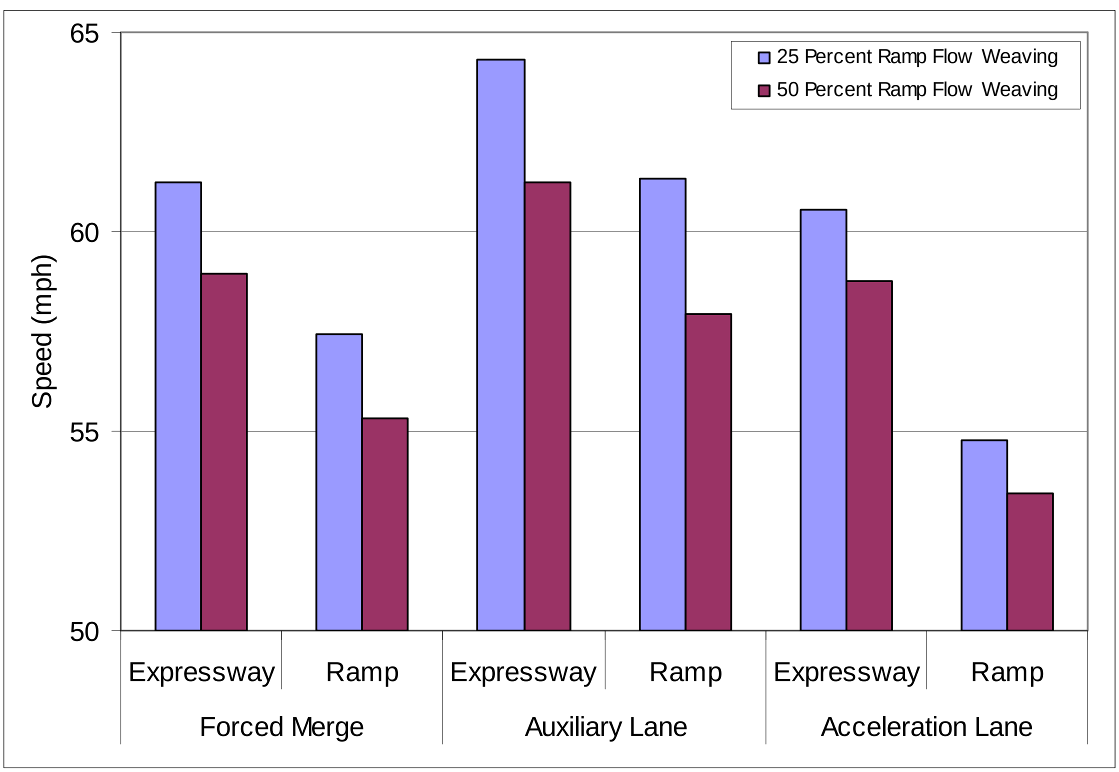


Figure 16-35. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Proportions of Ramp Traffic Weaving to the Managed Lane.

Design Values for Managed Ramp Scenarios

This section of the handbook is designed to guide one in using simulation results to produce and refine design values for most of the possible managed ramp design conditions one encounters. Three example applications are outlined to step the user through the process of applying the expressway and weaving speeds found throughout the many tables of Appendix D to one's unique needs.

Application 1: Truck-Only Managed Ramp

Managed ramp condition: Trucks only to allow for usage of upstream entrance into "Truck Only" lane on left-hand side of expressway mainlanes.

Freeway Conditions:

- No. of expressway mainlanes: Three (3)
- Vehicle mix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: moderate expressway volume (1000 vphpl);
- Assume there is no intermediate ramp between entrance ramp and entry into trucks only lane (managed lane) upstream

Entrance Ramp Conditions:

- Ramp merge condition: acceleration lane
- Vehicle mix/user group: trucks only
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 50 percent

<u>Determine: Recommended spacing of managed lane entrance upstream of freeway entrance ramp (see Figure 16-36).</u>

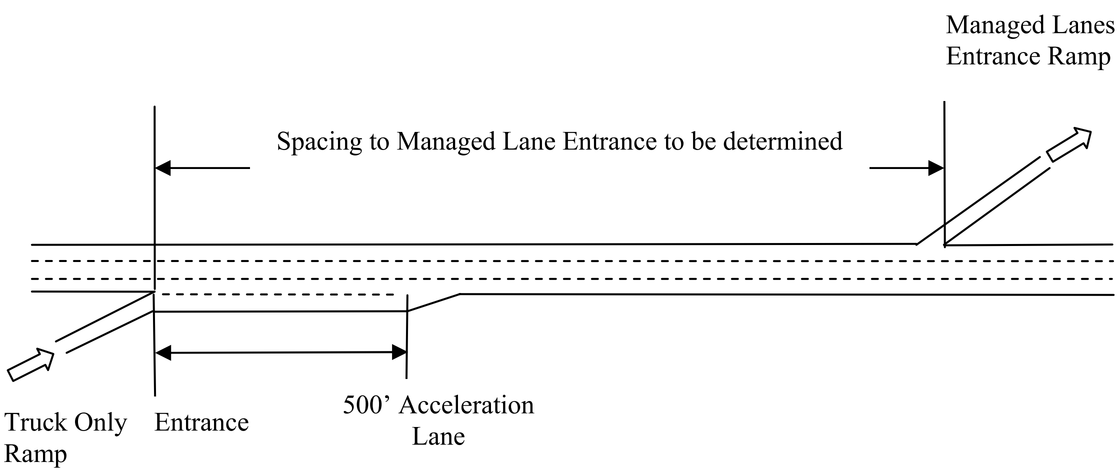


Figure 16-36. Truck-Only Managed Ramp Example.

Approach:

- Relevant Tables: Table D-7, Table D-9, and Table D-11
- Referring to Ramp Merge Conditions – Acceleration Lane, without Intermediate Ramp:
  - Ramp Condition of "No Auto" and 375 vph representing moderate ramp volume (or 375 vphpl). The volume accessing the managed lane is 188 vph (or 50 percent).
  - Expressway Condition of Three lanes. Under 3-lane expressway condition identify the column with "5% truck" and 3000 vph.

For 500 ft per expressway lane spacing (Table D-7).

> The results from Table D-7 show speeds of expressway vehicles as 60 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 41 mph. Even though expressway speeds were still reasonably high, there is a 19 mph speed differential in speeds between these two vehicle groups. This difference is above the threshold of 10 mph speed differential imposed for safety reasons.

Similarly, looking up Table D-9 for a 1000 ft per expressway lane spacing

> The results from Table D-9 show speeds of expressway vehicles as 61 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 47 mph. There is a 14 mph speed drop in speeds between these two vehicle groups. Even though this provides a safer operating scenario than with the 500 ft per lane spacing, it still does not meet our criteria of a less than 10 mph speed differential.

Similarly, looking up Table D-11 for a 1500 ft per expressway lane spacing

> The results from Table D-11 show speeds of expressway vehicles as 64 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 53 mph. There is an 11 mph speed drop in speeds between these two vehicles. Even though this provides a safer operating scenario than with both the 500 and 1000 ft per lane spacing, it is still not considered a "safe enough" operating scenario using a threshold of a 10 mph speed difference.

The engineer will therefore have to consider a minimum spacing of 1500 ft per lane between the managed ramp and the entrance to the managed lane downstream.

Consider a scenario where you had four expressway mainlanes instead of three:

Then from Table D-7 again; looking in the column under the Expressway conditions with four expressway mainlanes and 5 percent trucks with 4000 vph (representing nominal expressway flow) we get the following:

Expressway vehicle speeds 57 mph, ramp weaving traffic speeds 39 mph – an 18 mph drop in speeds.

Table D-9 for a 1000 ft per lane spacing results in a 63 mph and 50 mph – a 13 mph drop in speeds

Table D-11 for a 1500 ft per lane spacing results in a 64 mph and 54 mph - a 10 mph drop in speeds.

Again, just as in the case of the three-lane expressway configuration, a minimum of 1500 ft per lane spacing needs to be used to accommodate the "Truck Only" managed ramp.

Application 2: Weaving Distance Required for Auto-Only Managed Ramp

Managed ramp condition: Only auto – trucks excluded due to grade or other geometric considerations

Expressway Conditions:

- No. of expressway mainlanes: Three (3)
- Vehicle mix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: moderate expressway volume (1000 vphpl);
- Assume there is an intermediate ramp between the managed entrance ramp and entry into managed lane upstream

Entrance Ramp Conditions:

- Ramp merge condition: forced merge
- Vehicle mix/user group: auto only
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 25 percent

<u>Determine: Distance downstream to locate entry into managed lane to allow for vehicles using auto only managed ramp access to managed lane (see Figure 16-37).</u>

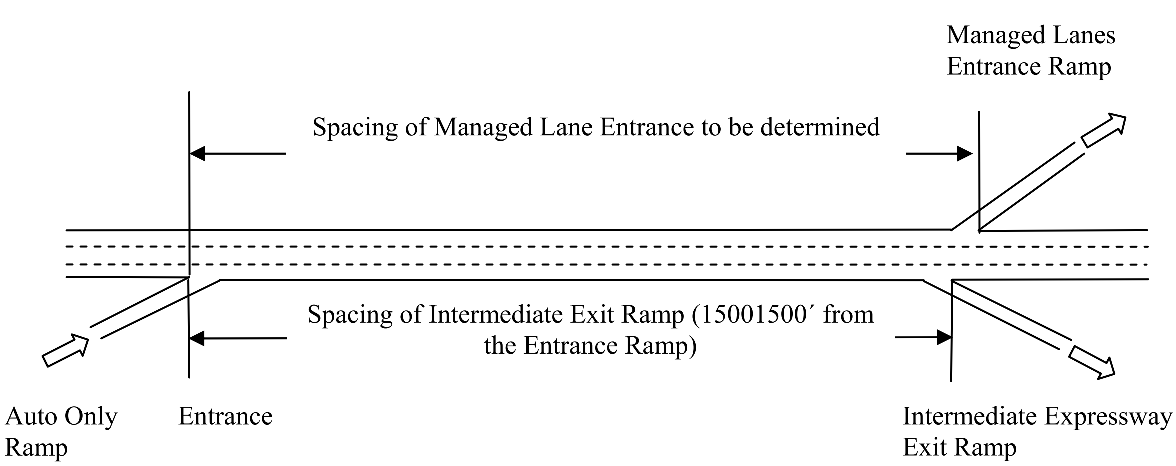


Figure 16-37. Auto-Only Managed Ramp Example.

Approach

- Relevant Tables: Table D-2, Table D-4, and Table D-6.
- Referring to Ramp Merge Conditions – Forced Merge, with Intermediate Ramp:
  - Ramp condition of "All Auto" and 375 vph representing moderate ramp volume (or 375 vphpl). The volume accessing the managed lane is 94 vph (or 25 percent).
  - Expressway condition of three lanes. Under 3-lane expressway condition identify the column with "5% truck" and 3000 vph (nominal expressway flow of 1000 vphpl).

The results from Table D-2 show speeds of expressway vehicles as 66 mph with speeds of weaving traffic from the expressway entrance ramp to the managed lane as 64 mph. Both expressway vehicles and weaving ramp vehicles maintained reasonably high speeds. There is just a 2 mph speed drop in between these two traffic flows. This is below the threshold of 10 mph speed differential and is considered an acceptable operating scenario.

Thus, a minimum of 500 ft per lane spacing for the conditions outlined above provides for a safe operating environment for both weaving and expressway traffic.

Consider a scenario where the managed ramp is at a flow level of 750 vphpl and all other factors remain the same as in the case above:

Referring again to Table D-2, we look across the row with "All Auto" and this time with the 750 vph volume. We select a 188 vph weaving volume, and since all expressway conditions remain the same we get a result of 64 mph for expressway mainlanes traffic and 62 mph for managed ramp weaving traffic. Again both speeds are appreciably high and there is only a 2 mph drop in speeds – an acceptably safe operating environment. Thus, just as in the case with moderate ramp volumes, a minimum of 500 ft per lane spacing should be enough to provide a reasonably safe weaving environment.

Application 3: HOV/HOT/SOT Managed Ramp

Managed ramp condition: High-occupancy vehicles (HOV)/High-occupancy toll (HOT)/Single-occupant toll (SOT) and buses only entrance ramp (85 percent auto and 15 percent bus);

Expressway conditions:

- No. of expressway mainlanes: Three (3)
- Vehicle nix : normal mix on expressway mainlanes (90 percent auto, 5 percent bus, and 5 percent truck)
- Volume: high expressway volume (1400 vphpl)
- Assume there is an intermediate ramp between managed entrance ramp and entry into HOV/HOT/SOT lane

Entrance Ramp Conditions:

- Ramp merge condition: full auxiliary lane

- Vehicle mix/user group: high-occupancy vehicles (HOV)/high-occupancy toll (HOT)/single-occupancy toll (SOT) and buses only on ramp (85 percent auto and 15 percent bus)
- Moderate volume on ramp (375 vphpl)
- Percent of ramp traffic accessing managed lanes assumed to be 50 percent

Determine: Distance downstream to place entrance into HOV/HOT/SOT Lane (see Figure 16-38).

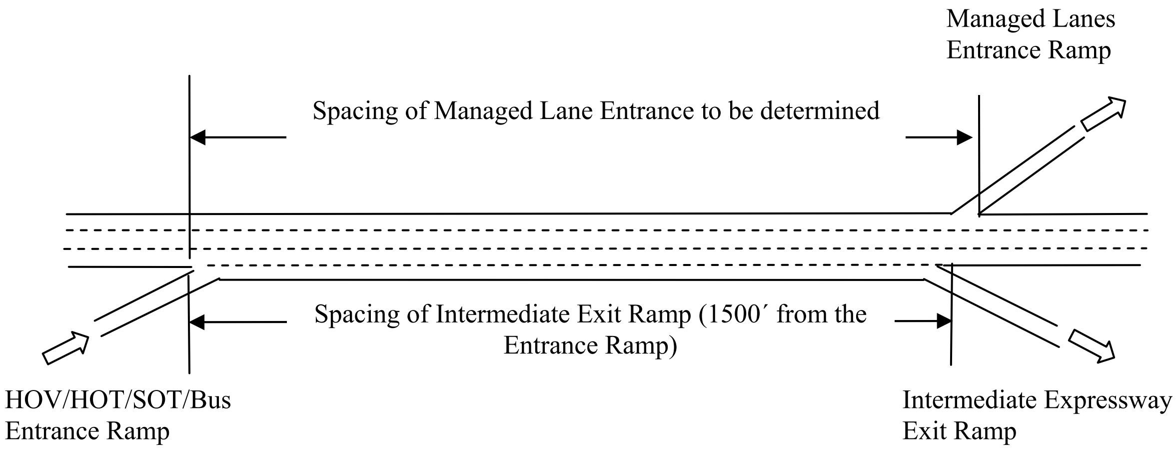


Figure 16-38. HOV/HOT/SOT/Bus Managed Ramp Example.

Approach

- Relevant Tables: Table D-14, Table D-16, and Table D-18
- Referring to Ramp Merge Conditions – Full Auxiliary Lane, with Intermediate Ramp
  - Ramp Condition: Look across "85% Auto" and 375 vph representing moderate ramp volume (375 vphpl). The volume accessing the managed lane is 188 vph.
  - Expressway Condition: Under 3-lane expressway condition identify the column with "5% truck" and 4,200 vph (1400 vphpl).

Table D-14 shows speeds of expressway vehicles as 63 mph with speeds of weaving traffic from the managed ramp to the managed lane as 60 mph. Both expressway vehicles and weaving ramp vehicles maintained reasonably high speeds. There is just a 3 mph speed drop in speeds between these two flows. This is below the threshold of 10 mph speed differential and is considered a safe operating scenario.

Thus, a minimum of 500 ft per lane spacing for the conditions outlined above provides for safe operating environment for both weaving and expressway traffic.

Consider a scenario where there is a heavy truck percentage on the expressway mainlanes. All ramp conditions remain the same, but under the 3-lane expressway condition identify the column with "15% truck" and 4200 vph (1400 vphpl)

Referring again to Table D-14, we look across the row with “85% Auto” and 375 vph representing moderate ramp volume. The volume accessing the managed lane is 188 vph.

Under the 3-lane expressway condition with “15% truck” and 4200 vph, we maintain the 25 percent weaving volume (188 vph), and since all expressway conditions remain the same we get a result of 61 mph for expressway mainlanes traffic and 57 mph for managed ramp weaving traffic. We observe that both speeds have dropped from the previous scenario with the weaving speeds much lower than the assumed free-flow speeds on the expressways (about 65 mph). However, there is only a 5 mph difference in speeds from expressway mainlane vehicles and the managed ramp to managed lane weaving vehicles. This difference in speeds is considered as acceptable and below the 10 mph threshold set.

Thus even with the increase in truck traffic on the expressway mainlanes, a minimum of 500 ft per lane spacing can be used to provide a reasonably safe weaving environment.

Section 6 – Ramp Safety

The incentive for considering ramp management strategies to support ramp safety is to alleviate congestion and improve the safety conditions at entrance ramps that have less than ideal geometric design features. One typical example of such a ramp is the Paisano Drive entrance ramp on westbound Interstate 10 in El Paso, Texas. At this particular location, the freeway mainlanes upstream of the entrance ramp continuously experience heavy traffic congestion. The Paisano Drive ramp has a relatively high grade and a short acceleration lane. The on-ramp is approximately 2800 ft upstream of the IH-10/US 54 interchange. Vehicles destined for either US 54 north or Juarez, Mexico, begin to merge to the far right lane where the Paisano Drive on-ramp enters IH-10 creating a bottleneck location.

The ramp management strategy for ramp safety is intended to identify vehicle restrictions that have the potential to improve safety for the freeway mainlanes. The freeway mainlanes are analyzed to evaluate driving behavior from vehicle merging into the far right lane with vehicles entering the facility through a specific entrance ramp that may present safety problems. Regulating the amount of flow through problematic entrance ramps could improve the safety for the vehicles on the freeway mainlanes upstream and downstream of the merge/weave area.

Performance Measures for Ramp Safety

Assessing the impacts of managed entrance ramp strategies for ramp safety purposes consists of analyzing traffic performance and safety conditions both upstream and downstream of a designated ramp. When trying to analyze how "safe" a freeway segment is, three specific performance measures provide insight into the assessment. The most critical performance measure is acceleration/deceleration. Greater rates of change of vehicle speeds indicate a tremendous amount of turbulence on the freeway. When speed begins to drop and density increases, a greater potential for a freeway incident exists.

Acceleration and Speed

The acceleration of the vehicles plays an important role when determining if the driving conditions are adequate on the freeway. Higher deceleration rates that vehicles experience increase the risk of rear-end collisions from trailing vehicles. An analysis of acceleration/deceleration can be made for the far right lane of the freeway as well as all general-purpose lanes of a freeway facility. Speed is also measured both upstream and downstream of the designated entrance ramp. Speed measurements can be taken for the far right lane of a freeway as well as an average for all freeway mainlanes.

Density

Another measurement to be analyzed is density of the freeway mainlanes. Density measures how compact vehicles are spaced together on a freeway segment. Density is obtained only for the freeway mainlanes (as a whole) and not for the individual first lane of the freeway. The upstream and downstream density of the designate entrance ramp is also acquired for comparison purposes and safety issues.

Viable Strategies for Ramp Safety

The explicit goal of managing ramps to enhance ramp safety is to try and maintain high speed in designated freeway sections with ramp management strategies (*9*). Previous research has shown that large fluctuations in speed greatly increase the potential for crashes (*10*). As a result, various combinations of vehicle restriction scenarios can be modeled to determine which ones performed the best when assessing optimal safety conditions on a freeway corridor. Two managed ramp strategies for ramp safety have the most potential to improve freeway operations: automobile restrictions and total closure.

Automobile Restrictions

The first ramp management strategy with the potential to improve operations as they relate to ramp safety is restricting automobiles from using a designated entrance ramp. All the vehicles traveling on the freeway mainlanes upstream of an entrance ramp targeted for ramp management decelerate to provide adequate gaps for vehicles entering the freeway. This behavior can be a safety issue because it interrupts the mainlane flow of the freeway with vehicles entering at the entrance ramp. The flow of mainlane traffic is dependent upon the inflow rate of vehicles entering the freeway. As various vehicle classes are restricted from the entrance ramp, speed increases upstream of the entry point.

Speed is most influenced when no restriction is placed on the entrance ramp since all vehicles are allowed access to the freeway. As various vehicle classes are restricted, freeway mainlane speed increases. With a typical vehicle mix composed of 90 percent automobiles, their restriction from an entrance ramp has the most influence on mainlane speed other than total ramp closure. Restricting only cars from entering a facility also causes the least amount of speed acceleration and deceleration fluctuation for vehicles traveling upstream of the managed entrance ramp.

Safety issues more frequently occur in the right lane since vehicles using the entrance ramp affect the flow on the freeway. Thus, it is important to analyze in depth the right lane traffic because this is where entering vehicles have the greatest effect on the freeway traffic flow. The traffic flow on the far rightmost lane is influenced the greatest when no vehicles are restricted. Allowing all vehicles to enter the freeway facility greatly impacts speed on the far right freeway merge lane. Only allowing trucks and/or buses access shows to have the highest travel speeds on the far right lane upstream of the managed ramp. As congestion builds on the model network, speeds for trucks and buses using the ramp level out at 32 mph. Allowing cars to enter the freeway decreases the average speed on the far right lane upstream of the managed entrance ramp to approximately 27 mph.

When no vehicles are restricted from entering the freeway, overall mainlane speed downstream of the weave/merge area created by the managed ramp dropped to approximately 50 mph. When cars are restricted independently or in juxtaposition with other vehicle classes, average speed on all mainlanes ranges from 60 to 62 mph, an occurrence that is more apparent when analyzing average acceleration downstream of the managed entrance ramp. The car-restricted management strategy shows the acceleration to level off at approximately 1 ft/sec^2. This means that there is less fluctuation of the overall traffic speeds and vehicles are flowing smoother when compared to other scenarios. When restrictions of large traffic compositions are regulated from entering the freeway, there is less fluctuation in speeds. Hence, restricting the highest number of vehicles (i.e., automobiles) creates less disruption of freeway mainlanes.

The right lane can be analyzed independently since this lane has the greatest amount of turbulence caused by the merging and weaving of vehicles. Since cars compose the highest volume (90 percent), freeway access poses the greatest variability of speed. Vehicle restrictions that include automobiles have better performance than other scenarios with speed distributions ranging from 53 to 60 mph. The same pattern emerges when analyzing the average acceleration and deceleration. Restricting cars from entering the freeway allows the downstream vehicles traveling in the far right lane to maintain a more constant speed. Having a constant speed in a merge area provides for smoother transition and flow of vehicles and ultimately provides a safer environment for motorists.

Ramp Closure

The second and more restrictive ramp management strategy with the potential to improve ramp safety is total ramp closure. In terms of speed performance, closing the entire entrance ramp proves to be the most optimal. However, total ramp closure does show to have a greater range of acceleration variability. Acceleration in the far right lane also has the greatest range of variability when all vehicles were restricted from entering the freeway facility because mainlane traffic speeds up when passing the on-ramp without disruption.

Ramp Safety Strategy Comparison

When comparing all vehicle restrictions at a managed entrance versus the base case “do nothing” scenario, density decreases by 17 percent in the rightmost lane. This decrease represents the highest density reduction compared to other possible scenarios shown in Figure 16-39. This lane also has the highest increase in speed of 21 percent when compared to all other scenarios, as shown in Figure 16-40.

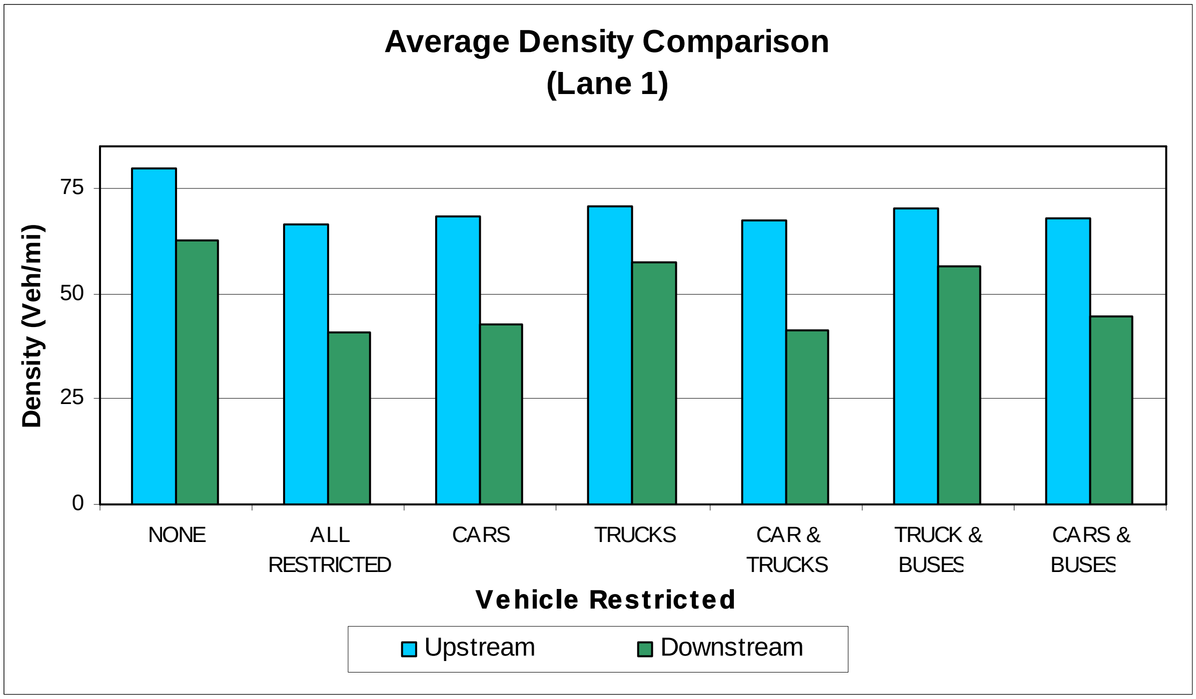


Figure 16-39. Average Density Comparison for Lane 1- Upstream and Downstream.

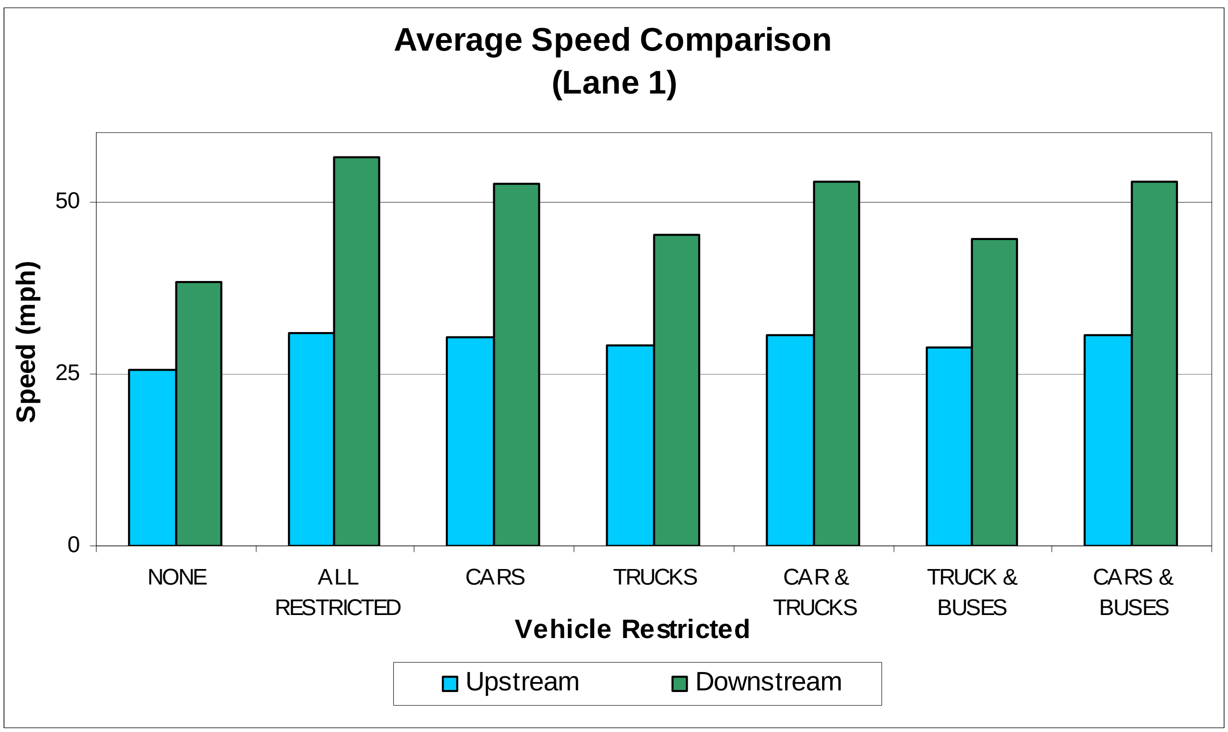


Figure 16-40. Average Speed Comparison for Lane 1- Upstream and Downstream.

When ramp closure is not an option, the most ideal ramp management strategy consists of car and truck restrictions with a 15.4 percent decrease in density followed by car and bus restrictions with a 15.3 percent density reduction. Restricting only cars reduces density by

14.7 percent when compared to the base case scenario. Restricting only cars also increases speed in the far right lane by almost 20 percent. All scenarios that restrict cars independently or in conjunction with other vehicle classes show a 20 percent increase in upstream mainlane speed and approximately 15 percent decrease in density. Ramp management scenarios that do not restrict cars from entering the freeway show significantly poorer performance measures when compared to no vehicles restricted. Truck-only restrictions decrease density in the far right lane by 11 percent.

For the downstream analyses, there was a considerable difference in density compared to the upstream lanes due to the spillback created by vehicles entering the facility. The performance measures followed the same general patterns as the upstream mainlanes. Total ramp closure decreased density on the far right lane by 35 percent when compared to "do nothing," as shown in Figure 16-39. Speed also increased significantly on the far right lane as Figure 16-40 illustrates. Speed is consistently similar for restriction of cars, cars and trucks, and cars and buses, each with an average speed increase of 37 percent when compared to no vehicle restrictions.

The main improvement in density and speed is observed in lane one. The subsequent lanes—lanes two, three, and four—have less significant change as compared to lane one, but following the same pattern as lane one. Lane four has some variation since it is the farthest lane from the effect from the managed entrance ramp.

Figure 16-41 shows the average stopped delay per vehicle and the respective type of restriction on a managed entrance ramp. The base case scenario is also shown for comparison purposes. In addition, the average delay accounts for the whole network performance. When no vehicles are restricted from the on-ramp the average stopped delay is higher. However, when restricting certain vehicle types, the stopped delay decreases. Aside from the base case scenario, the highest stopped delay per vehicle shows when only trucks are restricted. However, when cars and buses are restricted the stopped delay reduces considerably (16.93 sec) when compared to the base case scenario (24.64 sec). Since buses have a slower acceleration rate, restricting such vehicle types improves the safety and congestion conditions on the IH-10 corridor.

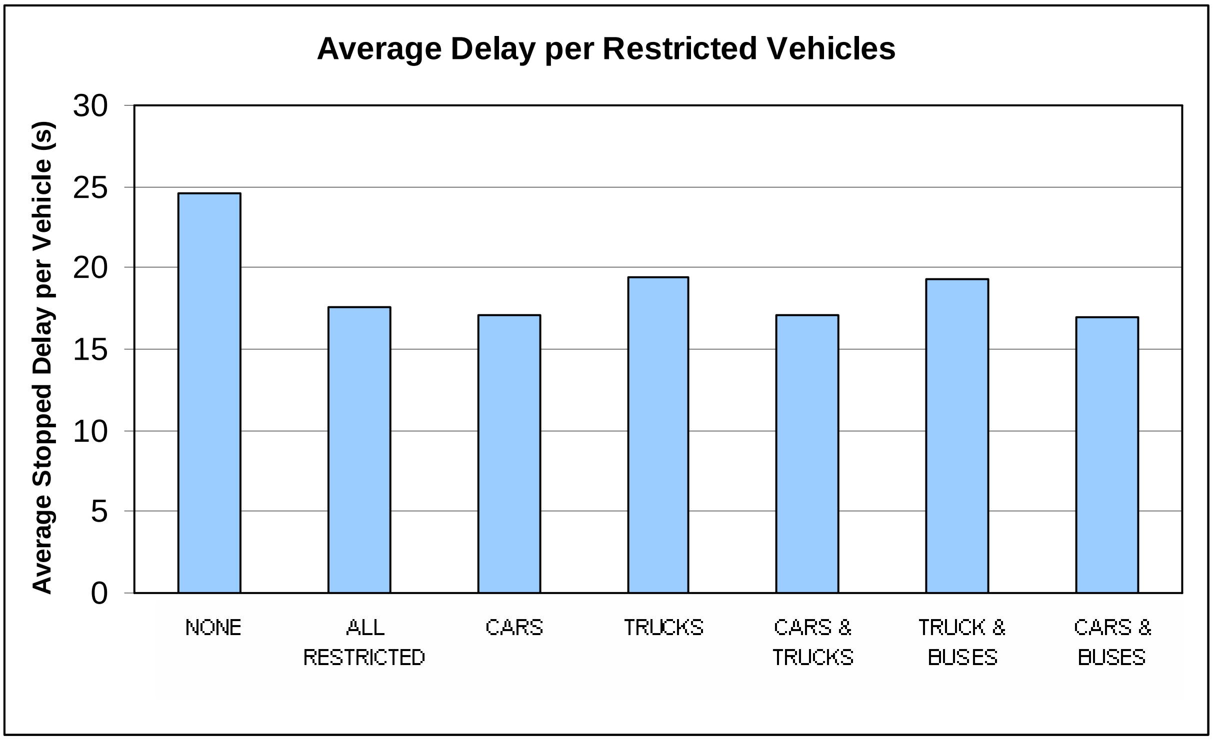


Figure 16-41. Average Stopped Delay per Vehicle in Seconds.

Section 7 – Related Issues

A number of related issues are important when considering managed ramp operational strategies for implementation. These issues include, but are not limited to, public and agency input, pricing as an option, decision-making needs and traffic control devices, enforcement, environmental justice, evaluation and monitoring, interoperability, and outreach and marketing. The following sections highlight these issues within the managed ramps context, thereby illustrating the need for transportation agencies to carefully consider them throughout the project development process.

Public and Agency Input

It goes without saying that public and agency input is critical to the development of any project involving managed ramps. This input should be part of every step in the project development process. Without it, the project may not necessarily reflect the goals and objectives of the region and its residents, increasing the risk of opposition to efforts to improve the transportation system. The Metropolitan Planning Organization (MPO) and transportation agency should engage the public and other stakeholder groups by establishing communication, sharing information, gathering feedback, and enhancing their participation in the planning and project development process.

Through consensus building, project managers can realize project delivery in a more timely fashion. Generally speaking, the public may not fully understand the true costs of transportation, or the current state of transportation finance. Therefore, it is useful to educate the public regarding the financial constraints of the potential transportation investments. Scenario planning and visualization tools can also be useful to work with the public to raise awareness and reach consensus.

The managed ramps concept complicates this involvement process by generating a need for public education. The MPO must thoroughly communicate the concept and the various potential strategies it might include. Also, the MPO should include such aspects of managed ramps as goals, objectives, operations, and potential revenue use, when considering them for the transportation plan. Public involvement can help ensure that an MPO considers all of the social, economic, and environmental consequences of their transportation investment decisions as they relate to managed ramps. It gains buy-in from the public and develops an environment of cooperation and collaboration with participating stakeholders that can smooth the way for project development in the future.

Pricing as an Option

Pricing is one of the methods by which an agency may be able to achieve ramp management within the region. Whether implemented alone (value priced or toll ramps) or with an occupancy component (HOT lanes), pricing can be a tool for preserving the operational integrity of a freeway. However, pricing is not without its challenges. In addition to the overall operational strategies, agencies must face such issues as identifying and selecting pricing alternatives, assessing the level and use of revenues, and determining public and political acceptance (*12*). With all of these challenges and their far-reaching ramifications, agencies and stakeholders need to determine whether ramp pricing will be an option at the regional level. While ramp pricing may not be appropriate for every corridor, having pricing in the toolbox of feasible alternatives increases the potential viability of projects and can serve as a means to manage ramp demand as well as make them feasible financially (*12*).

Decision-Making Needs and Traffic Control Devices

An implied goal of the managed ramps concept is to manage freeway access based on designated user groups or operational limitations at ramps. These choices can vary by time of day or possibly in response to changing traffic conditions on the general-purpose lanes in the corridor or region. The extent to which travelers can and will accommodate such operational flexibility hinges on their getting the right information at the right time and in the right format so that they can make effective decisions pertaining to their trip. Figure 16-42 illustrates the types of managed ramps-centered knowledge a driver needs and how it varies by familiarity with a facility.

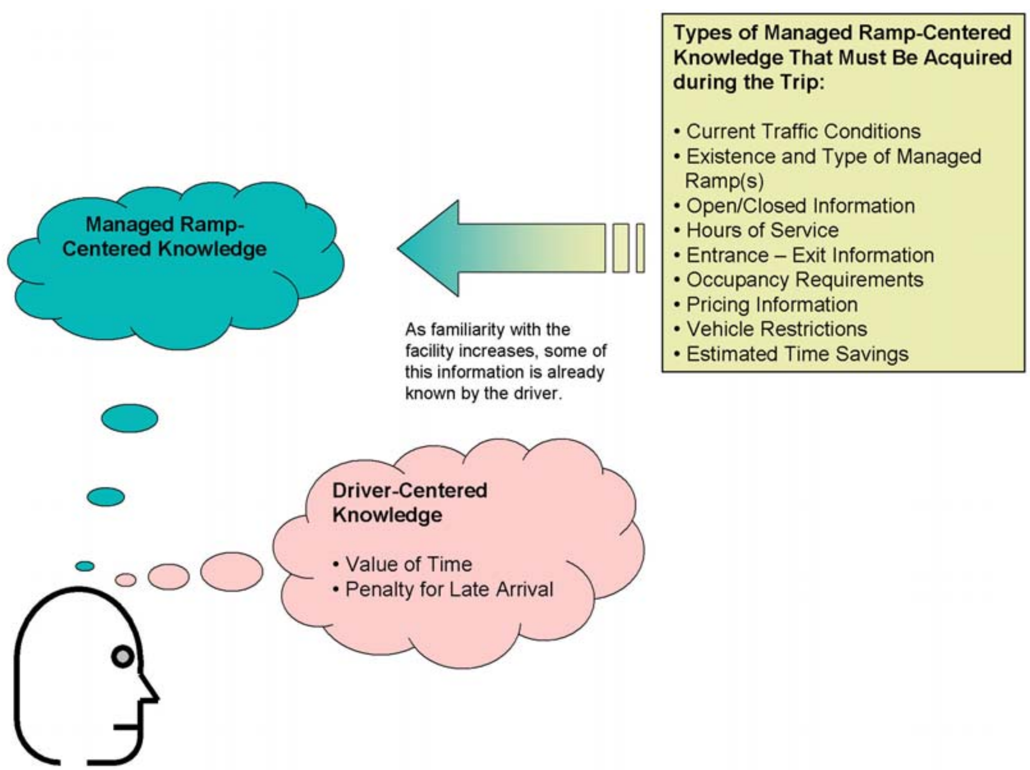


Figure 16-42. Driver Information Needs (Adapted from *13*).

Determination of who the target audience really is (familiar, semi-familiar, or unfamiliar) can help determine how much information must be presented within a corridor regarding the managed ramps and/or a managed lanes facility. This step needs to happen early in the design process so that designers can make rational decisions about what levels of information they need to present.

Designers and operators of managed ramps must consider traffic control device needs early in the planning process as well. The initial costs of communicating with drivers include the right-of-way for signing and supporting structures; the cost of the structures; the cost of dynamic message signs and accompanying power and communications; the cost of designing, fabricating, and installing static signs including any lane closures required; and the cost of pavement markings including standard lane striping plus any horizontal signs and symbols required or desired to augment guide or warning information contained in the signs (*14*). The ongoing costs of communication include maintenance of signs and markings, communications fees such as monthly cell phone charges for wireless networks, and maintenance of power supplies and other electronic components of dynamic message signs.

Beyond the cost of traffic control, early consideration of driver information needs in the planning process will assure that an operating scheme is not implemented that requires overly complex signs (*14*). Variable tolls based on occupancy or time of day with dynamic pricing based on current conditions can result in complex toll schedules. Conventional toll roads often have a full menu of prices posted at toll plazas. With vehicles moving at slow speeds, and in most cases stopping completely, it is safe to present this large amount of information. But with electronic toll collection at high speed, it becomes dangerous to overload drivers with complex toll rules. For such complex operations, planners may have to accept that "one big sign" is not appropriate.

If the managed ramps will have a subscription-based pricing system, communication with subscribers through the mail or other means can allow agencies to provide the full toll schedule off-road. If a wider audience is anticipated, other methods of presenting the information must be considered such as the use of multiple, sequential signs. Another strategy might be to present a small amount of information that applies to the largest number of users, such as the minimum toll for a passenger vehicle. Other mechanisms, such as two-way transponders, which would present information in-vehicle, are on the horizon and may lessen the need for numerous traffic control devices in the future.

In addition to operating strategies, planners need to consider traffic control devices in the geometric design as well. Considering traffic control early in the process can ensure that the necessary infrastructure is in place to meet the information needs of a facility to maximize driver comprehension and utilization of the system.

Enforcement

A freeway facility with managed ramps requires effective enforcement policies and programs to operate successfully. Agencies employ various strategies on managed ramps to regulate demand, and those actions require enforcement to maintain the integrity of the facility. The enforcement strategy chosen for managed ramps may be similar to those of managed lanes, such as: routine enforcement, special enforcement, selected enforcement, or self-enforcement (*15*). Routine enforcement would use existing freeway patrols to monitor managed ramps while special enforcement would use dedicated equipment and manpower specifically to monitor the managed ramps. Selective enforcement is a combination of the two strategies and may be appropriate for specific events or concerns, such as the opening of new managed ramps or to combat high violation rates. The last enforcement strategy relies on the concept of self-enforcement, which involves promoting citizen monitoring and self-regulation by users of the managed ramps and the motorists in adjacent general-purpose lanes. Experience has shown that the best compliance rates yield from routine and special enforcement led by dedicated or semi-dedicated law enforcement personnel combined with automated enforcement techniques (*16*).

Enforcement of vehicle-occupancy requirements, use by authorized vehicles, or proper toll collection is critical to protecting eligible vehicles' travel time savings and safety. As these operating strategies are combined, enforcement becomes even more difficult. Visible and effective enforcement promotes fairness and maintains the integrity of the managed lanes facility to help gain acceptance among users and non-users. Furthermore, fines for violating managed ramps operational conditions should be high enough to discourage willful violation and minimize the need for dedicated enforcement (*17*). Currently, fines for HOV and HOT lane violations in the U.S. can range from $45 for a first offense to over $1000 for repeat offenders and/or license points (*17*). Development of enforcement policies and programs ensures that all appropriate agencies are involved in the process and have a common understanding of a project and the need for enforcement (*15*). Participation from enforcement agencies, the courts and legal system, state departments of transportation, and transit agencies is critical for enforcement success.

Enforcement also impacts the design of managed ramps. For example, traditional enforcement on managed ramps often requires dedicated enforcement areas, which would most likely be located immediately adjacent to the managed ramp and allow enforcement personnel to monitor the facility, pursue violators, and apprehend violators to issue appropriate citations. They also serve as a safe environment for enforcement personnel to perform their duties. However, recent advances in automated enforcement technology may lower the number of dedicated enforcement areas needed in the future, thereby shifting the focus of design to proper placement of electronic equipment (*15*). Planning for enforcement from the beginning can ensure that the facility is designed properly to accommodate it and preserve the integrity of the system and the fairness to users.

Environmental Justice

Environmental justice is an increasingly important element of policymaking in transportation. It is fundamentally about fairness toward the disadvantaged and the concept of environmental justice requires that transportation plans be fully inclusive. This requirement means that plans may not disproportionately impact minority and low-income communities or areas, and must allow these groups to fully share in the benefits of transportation infrastructure implementation (*18*). These strategies that are intended to expand access for low-income and minority populations to transportation programs are mandated by the Civil Rights Act of 1964, Executive Order 12898 issued in 1994, and U.S. DOT Order 5680.2 issued in 1997 (*19*).

Environmental justice is closely intertwined with the planning and project development processes. As agencies develop their regional plan and identify projects that could incorporate managed ramps, they should consider the impacts they may have on these groups. Examples of planning to meet environmental justice standards include placement of highways, providing access to transit for transportationally disadvantaged people, emphasizing pedestrian plans, and enhancing streetscapes and sidewalks. Involving the impacted groups in the planning process through meaningful public involvement, as discussed previously, is critical to ensuring environmental justice (*20*).

Evaluation and Monitoring

Successful monitoring and evaluation programs generally consist of the following six indistinct and overlapping steps:

- setting goals and objectives that reflect the program or system's desired performance and are consistent with agency or regional priorities;
- identifying appropriate performance metrics to accurately evaluate attainment of the goals and objectives;
- identifying required data and sources to support calculation of the performance measures;
- defining appropriate evaluation methods within the constraints of data availability and staff training;
- defining an appropriate schedule for ongoing, periodic monitoring of the system; and
- reporting the results in a usable and easily understood format (*21*).

The performance of managed ramps, documented through a comprehensive evaluation and monitoring program, should play a central role in the traditional long-range, short-range, and operations level transportation planning process.

Performance measures, derived from goals and objectives set earlier in the planning and project development processes and related to mobility and congestion, reliability, accessibility, safety, environmental impact, system preservation, or organizational efficiency, help gauge progress toward performance "targets" for managed ramps. Subsequently, these performance measures, and their relation to the performance targets, are used to direct resources and activities (i.e., projects, programs, and policies) and focus public discussions around alternative investment strategies. Because of their potential to influence resource allocations and the subsequent success of managed ramps, it is important for the performance measures to address all aspects of managed ramps activities. A primary function of managed ramps may be to reduce congestion through improvements in vehicle throughput or effective capacity. To maintain this primary functionality, the planning process must also consider activities such as facility maintenance and incident management. Adequately monitoring and evaluating these "support" functions, in terms of both product or outcome and process, will help to ensure appropriate resource allocations in these areas. Incident management activities, in particular, may require additional resources not traditionally or immediately available within departments of transportation (i.e., properly equipped incident response vehicles, specialized training, etc.).

The continued deployment of ITS technologies has the potential to make a vast amount of data available to support planning and operational efforts at all levels. Planning for managed ramp evaluation and monitoring can ensure an agency has the appropriate infrastructure, policies, and procedures in place, prior to implementation, to ensure the effective operation of managed ramps within the region.

Interoperability

Bringing managed ramps to completion is a complex process of planning, design, and daily operation. These on-going operations include, at a minimum, management, enforcement, incident detection, revenue collection, and enforcement. Often, managed ramps may be cross-cutting, not only in the use of multiple operating concepts to achieve goals, but also because it can involve multiple agencies and vehicle user groups.

These types of interactions all point to a level of interoperability that creates operational challenges. As a definition, interoperability can best be expressed as "the ability of a system to use the parts, information, or equipment of another system." The complex nature of a managed lanes facility calls for a complete understanding of major relationships within managed lanes, their scope, and the critical issues associated with each relationship or area of interoperability (*22*).

In general, interoperability within the context of managed ramps can exist at three levels: at the agency level, at the facility level, and/or at the equipment level. The level at which interoperability exists helps determine the interactions agencies should consider in the planning and project development processes. For example, agency level interactions typically consist of long-term planning or design coordination, as well as broad-scale agreements for creating similar policies and procedures for operating managed ramps. Agency level interactions will also typically examine the use of managed ramps in more of a regional context, as one method of accomplishing regional transportation goals. In sharp contrast to that high-level planning and interaction, coordination at the equipment level is meant to ensure that data elements from one system can be transmitted, received, and understood by another system, regardless of their eventual use in both systems. In the middle of the two endpoints are the facility level interactions, which typically would occur in areas such as geometric design, traffic control devices, enforcement, and more (*22*). While facility level interactions can certainly be planning oriented, they are typically more corridor specific, focusing on the components or operations of an individual facility, rather than the focus of regional goals performed at the agency level.

The development of any cross-cutting facility, like managed ramps, must be supported by all of the involved agencies and must support the broad-based transportation goals of the region.

Outreach and Marketing

Public acceptance plays a critical role in the success of any project. Marketing a new product or concept can be challenging. Effective marketing campaigns must consider the goals of the managed ramps project and tailor the message to meet those goals. Several different techniques can be used to communicate with the public depending on the message that is to be delivered and the objectives. Likewise, a message may be tailored to particular audiences. It is important that the public, or the audience, be correctly defined. Audiences will depend on the nature or scope of the managed ramps project and may change throughout the different phases of the project. Additionally, once the managed ramps project is operational, conveying information to the users should continue to ensure they are fully aware of potential changes in operational conditions and to maintain their trust in the project and compliance with regulations governing its use.

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APPENDIX F: MANAGED LANES HANDBOOK APPENDIX D

Appendix D –Managing Ramps for Managed Lanes Facility Preference

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Table D-1. Ramp Merge Conditions- Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(63)	66(64)	64(61)	66(63)	65(61)	66(63)	65(62)	65(62)	63(59)
		188 vph	66(64)	65(63)	66(64)	65(62)	65(63)	63(61)	66(63)	65(62)	66(62)	63(60)	65(61)	59(55)
	750 vph	188 vph	66(64)	63(60)	65(63)	62(59)	65(63)	55(49)	65(62)	64(60)	65(63)	63(59)	65(62)	56(52)
		375 vph	65(63)	62(59)	65(62)	58(56)	63(60)	43(38)	64(61)	60(56)	64(60)	57(52)	63(59)	40(33)
90% Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(62)	66(63)	63(60)	66(62)	65(61)	66(63)	64(61)	65(62)	63(59)
		188 vph	66(64)	65(62)	66(63)	64(62)	66(63)	62(59)	66(62)	64(60)	65(62)	63(59)	65(61)	60(56)
	750 vph	188 vph	65(63)	62(59)	65(63)	60(57)	65(62)	40(34)	65(62)	62(57)	65(62)	62(58)	64(61)	49(43)
		375 vph	64(62)	60(57)	63(61)	53(49)	62(59)	40(35)	64(60)	57(52)	64(60)	55(50)	61(57)	40(33)
85% Auto	375 vph	94 vph	66(64)	65(62)	66(64)	65(62)	66(63)	64(62)	66(63)	65(62)	66(63)	65(62)	65(62)	63(59)
		188 vph	66(64)	65(62)	66(64)	64(62)	65(63)	62(60)	66(63)	64(60)	65(62)	62(57)	65(62)	60(56)
	750 vph	188 vph	65(63)	62(59)	65(63)	63(60)	65(63)	44(40)	65(62)	63(59)	65(62)	62(59)	64(61)	46(40)
		375 vph	65(62)	59(56)	64(62)	56(54)	63(60)	37(32)	64(60)	59(55)	64(60)	55(51)	62(58)	39(33)
No Auto	375 vph	94 vph	65(59)	60(55)	65(60)	60(51)	64(58)	50(43)	64(58)	61(54)	65(59)	59(51)	64(58)	53(45)
		188 vph	62(56)	53(45)	62(58)	49(41)	60(53)	36(29)	62(57)	53(45)	62(55)	47(37)	62(56)	38(29)
	750 vph	188 vph	42(31)	39(26)	46(36)	36(26)	43(34)	35(25)	59(49)	46(31)	57(45)	43(29)	54(47)	38(27)
		375 vph	37(28)	39(26)	36(27)	32(25)	33(25)	31(25)	44(35)	38(26)	40(31)	36(26)	37(28)	36(26)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-2. Ramp Merge Conditions- Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	65(62)	66(64)	64(61)	66(63)	61(58)	66(62)	64(61)	65(63)	63(59)	65(62)	54(51)
		188 vph	66(64)	65(62)	66(63)	63(60)	65(62)	59(57)	65(62)	63(59)	65(62)	61(58)	65(61)	51(47)
	750 vph	188 vph	65(63)	60(56)	64(62)	55(51)	64(61)	41(34)	65(62)	61(56)	65(61)	60(56)	64(60)	44(35)
		375 vph	65(62)	58(55)	64(61)	55(52)	62(60)	39(32)	64(60)	58(52)	64(60)	52(45)	62(58)	41(33)
90% Auto	375 vph	94 vph	66(64)	65(62)	66(64)	63(59)	65(63)	61(58)	65(63)	64(60)	65(62)	62(58)	65(61)	53(48)
		188 vph	66(64)	64(61)	65(63)	63(59)	65(62)	59(56)	65(62)	63(60)	65(62)	61(56)	64(61)	51(45)
	750 vph	188 vph	65(63)	59(54)	65(62)	51(44)	63(60)	40(32)	65(61)	61(56)	64(60)	55(50)	64(60)	43(34)
		375 vph	64(61)	55(51)	63(60)	63(60)	60(57)	38(31)	63(59)	57(52)	63(58)	48(40)	60(55)	41(32)
85% Auto	375 vph	94 vph	66(64)	64(61)	66(64)	63(59)	65(63)	62(59)	66(63)	64(60)	65(62)	62(58)	65(62)	58(54)
		188 vph	66(64)	64(62)	65(63)	63(60)	65(63)	57(55)	65(61)	63(59)	65(61)	62(58)	64(60)	50(46)
	750 vph	188 vph	65(62)	60(57)	65(62)	53(47)	64(62)	41(34)	65(61)	61(57)	65(61)	58(53)	64(60)	44(36)
		375 vph	64(62)	55(49)	64(60)	45(39)	61(58)	40(33)	64(59)	57(52)	63(59)	51(45)	60(56)	41(34)
No Auto	375 vph	94 vph	64(58)	60(52)	64(58)	49(38)	62(56)	40(30)	64(58)	59(49)	64(58)	53(42)	63(55)	43(31)
		188 vph	62(56)	51(42)	61(55)	41(32)	58(52)	36(28)	61(54)	52(42)	62(54)	42(30)	59(50)	38(28)
	750 vph	188 vph	45(32)	40(25)	43(31)	38(25)	37(27)	37(26)	55(43)	46(28)	54(41)	44(28)	47(34)	41(27)
		375 vph	38(27)	37(25)	36(26)	35(25)	34(25)	33(24)	46(35)	41(27)	42(30)	40(27)	41(30)	38(26)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-3. Ramp Merge Conditions- Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(63)	63(60)	66(63)	62(60)	65(63)	58(54)	66(65)	66(65)	66(65)	66(65)	66(65)	65(63)
		188 vph	65(62)	61(58)	65(62)	59(56)	64(61)	54(51)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	65(62)	61(58)	64(61)	58(56)	63(60)	45(43)	66(65)	65(63)	66(65)	65(63)	66(65)	63(60)
		375 vph	62(59)	54(51)	61(58)	48(46)	59(57)	30(29)	66(64)	64(61)	66(64)	62(60)	65(63)	56(54)
90% Auto	375 vph	94 vph	65(62)	63(60)	65(62)	62(59)	65(63)	60(56)	66(65)	66(64)	66(65)	66(64)	66(65)	65(62)
		188 vph	65(61)	61(58)	65(61)	59(56)	64(60)	51(49)	66(65)	65(64)	66(65)	65(64)	66(65)	63(61)
	750 vph	188 vph	64(61)	59(56)	64(60)	56(54)	62(59)	43(40)	66(65)	65(63)	66(64)	65(62)	66(64)	60(59)
		375 vph	62(59)	48(45)	60(57)	42(41)	57(55)	29(28)	66(64)	63(61)	66(64)	62(59)	65(63)	53(51)
85% Auto	375 vph	94 vph	66(63)	63(59)	65(62)	62(59)	66(63)	58(54)	66(65)	66(65)	66(65)	66(64)	66(65)	64(62)
		188 vph	65(61)	61(58)	64(62)	60(57)	64(60)	52(50)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	64(61)	59(56)	63(60)	56(52)	62(59)	41(39)	66(65)	65(63)	66(65)	65(63)	66(64)	61(59)
		375 vph	61(58)	52(50)	60(57)	40(40)	58(55)	27(26)	66(64)	64(62)	66(64)	63(60)	65(63)	56(53)
No Auto	375 vph	94 vph	64(58)	57(49)	64(57)	57(48)	63(55)	42(37)	66(63)	65(61)	66(63)	63(58)	66(63)	59(54)
		188 vph	60(53)	43(37)	59(53)	29(26)	59(52)	24(21)	65(62)	62(59)	65(63)	60(55)	64(61)	49(43)
	750 vph	188 vph	53(44)	43(30)	49(39)	38(28)	43(35)	39(30)	64(59)	55(39)	63(59)	51(38)	63(59)	48(36)
		375 vph	24(23)	24(20)	27(24)	23(21)	23(22)	23(21)	58(52)	44(33)	58(53)	42(32)	51(44)	39(32)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-4. Ramp Merge Conditions- Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)	66(65)	65(63)	66(65)	65(63)	66(65)	62(60)
		188 vph	66(65)	66(64)	66(65)	65(63)	66(65)	63(61)	66(65)	65(64)	66(65)	64(63)	66(64)	61(59)
	750 vph	188 vph	66(65)	65(63)	66(65)	63(61)	65(64)	52(47)	66(65)	65(62)	66(64)	63(61)	65(64)	53(48)
		375 vph	66(65)	64(62)	65(64)	62(60)	65(63)	53(49)	66(64)	64(62)	65(64)	63(61)	65(63)	52(46)
90% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	65(63)	66(65)	65(63)	66(65)	65(63)	66(65)	65(63)	66(65)	62(60)
		188 vph	66(65)	65(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(63)	66(65)	65(63)	65(64)	61(59)
	750 vph	188 vph	66(64)	63(59)	66(65)	60(57)	65(64)	48(43)	66(64)	64(62)	66(64)	62(60)	65(64)	52(46)
		375 vph	65(64)	64(61)	65(64)	56(52)	65(63)	49(44)	66(64)	64(61)	65(63)	63(60)	65(63)	52(45)
85% Auto	375 vph	94 vph	66(66)	66(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(63)	66(65)	65(63)	66(64)	62(60)
		188 vph	66(65)	66(64)	66(65)	65(63)	66(65)	64(63)	66(65)	65(64)	66(65)	64(63)	66(64)	61(59)
	750 vph	188 vph	66(65)	65(63)	66(64)	61(59)	65(64)	49(45)	66(64)	64(62)	62(59)	63(61)	65(64)	54(49)
		375 vph	66(64)	64(62)	66(64)	59(56)	65(63)	49(44)	66(64)	64(62)	65(64)	63(61)	65(63)	52(47)
No Auto	375 vph	94 vph	66(63)	63(57)	66(63)	64(59)	65(62)	51(42)	66(62)	64(59)	66(62)	62(58)	65(61)	58(50)
		188 vph	66(62)	63(58)	65(62)	62(58)	65(61)	54(46)	65(61)	61(54)	65(60)	60(54)	65(61)	52(45)
	750 vph	188 vph	56(43)	51(35)	52(40)	49(35)	51(40)	46(35)	63(54)	57(39)	60(48)	53(37)	56(44)	51(37)
		375 vph	55(44)	49(35)	57(47)	47(34)	49(40)	44(33)	60(53)	53(36)	57(47)	51(36)	52(41)	49(35)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-5. Ramp Merge Conditions- Forced Merge, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(64)	66(66)	66(64)	66(65)	65(64)	66(65)	64(63)
	750 vph	188 vph	66(66)	66(65)	66(65)	65(64)	66(65)	64(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	62(61)	66(65)	65(63)	66(65)	64(63)	66(65)	59(57)
90% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(64)	66(65)	66(64)	66(65)	65(64)	66(65)	63(62)
	750 vph	188 vph	66(65)	66(64)	66(65)	65(64)	66(65)	59(56)	66(65)	65(64)	66(65)	65(64)	66(65)	62(60)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	60(58)	66(65)	65(63)	66(64)	63(61)	66(65)	56(55)
85% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(66)	66(65)	66(65)	65(65)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(66)	66(64)	66(65)	66(64)	66(65)	64(63)
	750 vph	188 vph	66(65)	65(64)	66(65)	65(64)	66(65)	62(60)	66(65)	65(64)	66(65)	65(64)	66(65)	63(62)
		375 vph	66(65)	65(64)	66(65)	64(63)	66(65)	59(57)	66(65)	65(63)	66(65)	65(63)	66(64)	58(57)
No Auto	375 vph	94 vph	66(64)	65(63)	66(64)	66(63)	66(64)	65(63)	66(64)	65(62)	66(64)	65(61)	66(64)	62(59)
		188 vph	66(64)	65(62)	66(64)	64(61)	66(64)	60(57)	66(64)	63(60)	66(64)	60(56)	65(63)	56(52)
	750 vph	188 vph	64(60)	56(41)	60(50)	54(43)	60(52)	51(40)	65(62)	57(43)	65(61)	55(41)	64(60)	52(40)
		375 vph	63(58)	52(39)	59(52)	50(39)	53(44)	48(38)	62(57)	62(57)	60(55)	47(36)	53(49)	44(35)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-6. Ramp Merge Conditions- Forced Merge, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	65(64)	59(58)	65(64)	56(56)	63(63)	43(41)
		188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	65(64)	59(58)	64(64)	54(56)	62(62)	44(42)
	750 vph	188 vph	66(65)	65(64)	66(65)	64(62)	66(65)	57(53)	64(64)	56(55)	63(63)	52(50)	60(60)	44(38)
		375 vph	66(65)	65(64)	66(65)	64(62)	66(65)	55(50)	64(63)	56(54)	63(63)	51(49)	61(61)	44(39)
90% Auto	375 vph	94 vph	66(65)	66(65)	66(66)	65(64)	66(65)	65(64)	65(64)	58(57)	64(64)	55(54)	62(62)	43(40)
		188 vph	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	65(64)	58(56)	64(63)	54(53)	62(62)	43(41)
	750 vph	188 vph	66(65)	64(62)	66(65)	61(58)	66(65)	54(47)	64(63)	55(52)	63(63)	50(47)	61(60)	43(38)
		375 vph	66(65)	64(62)	66(65)	62(59)	66(65)	53(46)	47(40)	54(52)	63(62)	48(45)	60(60)	44(39)
85% Auto	375 vph	94 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	65(65)	59(58)	64(64)	56(56)	63(63)	43(41)
		188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	65(64)	59(58)	64(64)	56(55)	63(63)	43(41)
	750 vph	188 vph	66(65)	65(63)	66(65)	63(62)	66(65)	53(48)	64(63)	56(54)	63(63)	52(50)	61(61)	43(39)
		375 vph	66(65)	65(64)	66(65)	62(60)	65(65)	58(54)	64(63)	56(54)	63(63)	51(49)	61(61)	44(39)
No Auto	375 vph	94 vph	66(63)	65(61)	66(64)	64(60)	66(63)	56(47)	64(59)	52(41)	63(58)	45(35)	61(56)	42(33)
		188 vph	66(64)	64(59)	66(63)	64(59)	65(63)	56(48)	63(59)	50(38)	62(58)	45(35)	60(55)	40(31)
	750 vph	188 vph	60(50)	56(39)	61(52)	53(38)	55(44)	51(38)	59(52)	48(34)	58(51)	44(32)	51(41)	41(32)
		375 vph	59(47)	55(38)	60(51)	53(39)	58(49)	51(38)	56(48)	45(31)	55(46)	42(31)	47(38)	40(31)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-7. Ramp Merge Conditions- Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(61)	66(62)	65(61)	66(62)	64(59)	66(62)	65(60)	66(62)	63(59)	66(61)	62(58)
		188 vph	66(62)	64(60)	66(62)	64(60)	66(62)	62(56)	66(62)	64(60)	65(61)	63(58)	65(60)	58(53)
	750 vph	188 vph	65(61)	62(57)	65(61)	60(55)	64(60)	54(50)	65(61)	63(58)	65(61)	60(55)	65(61)	53(49)
		375 vph	64(60)	57(52)	64(59)	54(51)	60(56)	34(35)	64(59)	56(51)	63(59)	51(46)	60(55)	36(36)
90% Auto	375 vph	94 vph	66(61)	65(60)	66(61)	65(60)	66(60)	64(57)	66(61)	65(59)	65(61)	64(60)	65(61)	61(55)
		188 vph	65(59)	63(58)	65(59)	63(57)	65(59)	58(52)	65(60)	63(57)	65(60)	61(56)	64(59)	57(52)
	750 vph	188 vph	64(58)	61(55)	64(59)	60(54)	64(58)	43(40)	64(59)	61(55)	65(59)	58(51)	63(57)	45(42)
		375 vph	62(56)	53(48)	61(55)	59(51)	59(53)	31(33)	62(56)	54(48)	62(55)	49(44)	58(53)	34(34)
85% Auto	375 vph	94 vph	66(61)	65(59)	66(62)	65(60)	65(60)	64(57)	66(62)	65(60)	66(61)	64(59)	66(61)	63(58)
		188 vph	66(61)	64(59)	65(60)	63(58)	65(60)	60(55)	66(61)	64(59)	65(59)	59(54)	65(60)	56(52)
	750 vph	188 vph	65(60)	60(54)	64(59)	60(54)	64(59)	53(48)	65(60)	62(56)	65(60)	60(54)	64(59)	52(48)
		375 vph	63(57)	56(51)	62(56)	59(53)	61(55)	31(33)	63(57)	55(49)	62(56)	49(44)	60(54)	35(35)
No Auto	375 vph	94 vph	60(41)	53(35)	59(41)	51(35)	59(41)	40(30)	61(42)	54(34)	60(40)	53(35)	58(40)	46(32)
		188 vph	56(38)	44(32)	60(41)	42(30)	53(38)	32(25)	57(38)	47(32)	57(39)	44(30)	54(36)	35(28)
	750 vph	188 vph	40(26)	28(19)	37(25)	27(19)	29(20)	26(18)	48(30)	35(22)	45(29)	32(21)	41(26)	31(21)
		375 vph	29(21)	24(18)	26(20)	23(18)	25(19)	24(18)	41(28)	28(20)	38(26)	28(20)	32(23)	27(20)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-8. Ramp Merge Conditions- Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(60)	66(61)	64(60)	65(61)	60(56)	65(62)	64(60)	66(62)	62(57)	65(59)	56(50)
		188 vph	65(61)	63(58)	65(61)	63(59)	65(60)	59(54)	65(62)	62(56)	65(61)	59(54)	64(59)	56(50)
	750 vph	188 vph	65(60)	61(57)	64(61)	56(52)	63(58)	36(36)	65(60)	59(53)	65(60)	57(52)	63(58)	44(41)
		375 vph	63(57)	57(52)	63(58)	50(46)	62(56)	34(36)	62(57)	53(48)	63(58)	48(43)	61(55)	36(35)
90% Auto	375 vph	94 vph	66(60)	63(58)	65(60)	63(57)	65(58)	60(55)	65(61)	63(58)	65(61)	62(56)	65(59)	56(50)
		188 vph	65(60)	62(56)	64(59)	62(57)	64(58)	55(51)	65(59)	61(54)	64(59)	59(53)	63(58)	56(51)
	750 vph	188 vph	63(56)	58(51)	63(58)	53(48)	62(56)	34(35)	64(58)	59(51)	64(57)	53(47)	63(56)	40(38)
		375 vph	60(54)	52(48)	62(55)	46(43)	58(52)	32(33)	62(55)	52(46)	61(55)	47(42)	56(49)	35(35)
85% Auto	375 vph	94 vph	66(60)	64(59)	65(60)	64(59)	65(60)	60(54)	65(61)	64(59)	65(61)	61(56)	65(60)	55(49)
		188 vph	65(60)	63(57)	65(60)	62(56)	64(59)	59(53)	65(62)	62(56)	64(59)	59(54)	64(58)	53(48)
	750 vph	188 vph	64(59)	58(52)	64(58)	54(49)	64(58)	35(35)	65(59)	59(53)	64(59)	54(49)	63(57)	42(39)
		375 vph	63(56)	54(48)	62(56)	48(44)	60(54)	33(34)	63(57)	53(47)	63(57)	48(43)	60(53)	35(35)
No Auto	375 vph	94 vph	59(40)	51(34)	57(39)	43(29)	56(39)	33(26)	61(39)	53(33)	60(40)	46(30)	58(39)	37(26)
		188 vph	55(38)	45(31)	53(37)	39(28)	51(35)	31(25)	57(38)	49(32)	56(38)	43(30)	54(37)	36(27)
	750 vph	188 vph	33(22)	28(19)	31(21)	28(19)	28(19)	27(18)	44(26)	36(21)	41(25)	35(21)	38(23)	33(21)
		375 vph	27(20)	25(18)	26(20)	24(18)	25(19)	24(18)	39(26)	32(20)	36(23)	31(20)	33(22)	30(20)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-9. Ramp Merge Conditions- Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(64)	66(63)	66(64)	65(62)
		188 vph	66(64)	66(64)	66(65)	66(64)	66(64)	65(63)	66(65)	66(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	65(63)	66(64)	65(62)	66(63)	65(62)	66(65)	65(64)	66(64)	65(62)	66(64)	62(60)
		375 vph	66(64)	65(63)	66(64)	65(62)	66(64)	56(55)	66(64)	65(62)	66(64)	64(62)	65(63)	59(56)
90% Auto	375 vph	94 vph	66(64)	66(63)	66(63)	66(63)	66(63)	65(62)	66(64)	66(64)	66(64)	66(63)	66(63)	65(63)
		188 vph	66(63)	65(62)	66(64)	66(63)	66(63)	65(61)	66(64)	65(62)	66(64)	65(62)	66(63)	63(60)
	750 vph	188 vph	66(62)	65(61)	66(63)	64(59)	66(62)	62(58)	66(64)	65(62)	66(63)	64(60)	66(63)	61(58)
		375 vph	66(63)	64(60)	66(62)	63(59)	65(61)	55(53)	66(63)	63(60)	65(63)	63(59)	65(62)	57(53)
85% Auto	375 vph	94 vph	66(64)	66(63)	66(64)	66(63)	66(64)	66(63)	66(65)	66(64)	66(64)	66(64)	66(64)	65(62)
		188 vph	66(64)	66(63)	66(64)	66(63)	66(64)	65(63)	66(64)	66(63)	66(64)	65(63)	66(64)	64(61)
	750 vph	188 vph	66(64)	65(62)	66(63)	65(62)	66(63)	61(57)	66(64)	65(62)	66(64)	65(62)	66(63)	61(58)
		375 vph	66(63)	65(61)	66(63)	64(61)	65(63)	59(57)	66(63)	64(61)	66(63)	63(59)	65(62)	57(54)
No Auto	375 vph	94 vph	63(48)	59(44)	63(49)	56(42)	62(47)	53(40)	64(52)	61(46)	64(52)	60(46)	63(49)	55(43)
		188 vph	62(48)	57(42)	61(47)	56(43)	60(47)	50(39)	63(50)	58(44)	63(50)	57(44)	61(48)	49(39)
	750 vph	188 vph	51(37)	40(26)	49(36)	38(26)	43(30)	36(25)	57(42)	46(30)	57(41)	44(29)	53(38)	41(28)
		375 vph	47(34)	35(25)	47(35)	34(25)	41(29)	35(25)	55(41)	36(26)	52(38)	35(25)	49(36)	33(24)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-10. Ramp Merge Conditions- Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(64)	66(63)	66(64)	65(63)	66(64)	63(62)	66(65)	66(63)	66(64)	65(63)	66(64)	63(61)
		188 vph	66(64)	66(64)	66(64)	65(63)	66(64)	63(60)	66(65)	65(63)	66(64)	65(63)	66(64)	62(59)
	750 vph	188 vph	66(64)	65(62)	66(64)	63(61)	66(63)	51(49)	66(64)	65(63)	66(64)	64(62)	65(63)	55(53)
		375 vph	66(64)	64(61)	66(63)	63(60)	65(63)	52(51)	66(64)	64(61)	66(64)	63(61)	65(62)	58(56)
90% Auto	375 vph	94 vph	66(64)	65(63)	66(64)	65(61)	66(63)	63(59)	66(64)	65(62)	66(64)	65(62)	66(63)	62(60)
		188 vph	66(64)	65(62)	66(63)	65(62)	66(63)	62(59)	66(64)	65(62)	66(63)	65(62)	65(63)	62(59)
	750 vph	188 vph	66(62)	64(60)	65(62)	62(57)	65(61)	47(45)	66(63)	64(61)	66(63)	63(59)	65(62)	49(46)
		375 vph	65(62)	63(58)	65(62)	60(57)	65(61)	49(47)	66(63)	63(60)	65(63)	62(58)	65(61)	53(50)
85% Auto	375 vph	94 vph	66(64)	66(63)	66(64)	65(63)	66(63)	64(61)	66(65)	65(63)	66(64)	65(62)	66(63)	61(59)
		188 vph	66(64)	66(63)	66(64)	65(63)	66(64)	65(61)	66(64)	65(63)	66(64)	65(63)	66(64)	62(59)
	750 vph	188 vph	66(63)	64(61)	66(63)	62(59)	65(62)	51(50)	66(64)	64(61)	66(63)	63(60)	65(63)	52(50)
		375 vph	66(63)	64(60)	66(63)	61(58)	65(62)	49(48)	66(63)	64(60)	66(63)	63(59)	65(62)	50(48)
No Auto	375 vph	94 vph	62(48)	58(41)	62(48)	55(40)	61(47)	49(37)	64(50)	60(45)	63(51)	58(44)	62(48)	51(39)
		188 vph	62(47)	55(41)	62(48)	56(43)	61(48)	45(35)	63(50)	59(44)	63(51)	56(43)	62(49)	47(36)
	750 vph	188 vph	47(31)	42(26)	48(34)	40(25)	41(28)	38(25)	58(42)	47(29)	55(38)	43(28)	53(38)	42(27)
		375 vph	48(33)	40(25)	42(28)	39(25)	39(27)	37(25)	54(39)	44(27)	52(37)	41(27)	49(35)	41(27)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-11. Ramp Merge Conditions- Acceleration Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	66(64)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	66(64)	66(65)	64(62)
	750 vph	188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	64(62)	66(65)	66(64)	66(65)	65(64)	66(64)	63(61)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(64)	64(62)	66(65)	65(63)	66(65)	65(63)	66(64)	60(57)
90% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(65)	66(64)	66(64)	65(63)
		188 vph	66(65)	66(64)	66(64)	66(64)	66(64)	65(64)	66(65)	66(64)	66(65)	66(64)	66(64)	63(60)
	750 vph	188 vph	66(64)	65(62)	66(64)	65(62)	66(64)	63(60)	66(64)	65(63)	66(64)	65(62)	66(64)	62(60)
		375 vph	66(63)	65(62)	66(64)	65(62)	66(63)	60(57)	66(64)	65(62)	66(64)	63(61)	66(63)	60(57)
85% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(65)	66(63)	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(64)	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)
	750 vph	188 vph	66(65)	66(64)	66(64)	65(63)	66(64)	64(62)	66(65)	65(63)	66(64)	65(63)	66(64)	62(59)
		375 vph	66(64)	65(63)	66(64)	65(62)	66(64)	62(60)	66(64)	65(63)	66(64)	63(61)	66(64)	60(57)
No Auto	375 vph	94 vph	64(53)	61(49)	64(53)	59(47)	63(51)	58(47)	65(63)	63(52)	65(55)	62(52)	64(54)	59(49)
		188 vph	63(52)	60(47)	64(53)	58(47)	62(51)	53(41)	65(62)	61(50)	64(54)	60(49)	64(54)	56(46)
	750 vph	188 vph	55(41)	48(32)	53(40)	45(32)	47(34)	43(31)	61(48)	51(35)	60(48)	49(34)	58(47)	47(33)
		375 vph	55(42)	43(30)	51(38)	43(30)	47(35)	42(30)	58(46)	37(28)	57(45)	40(29)	54(42)	39(29)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-12. Ramp Merge Conditions- Acceleration Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(65)	65(63)	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	66(65)	65(63)	66(65)	64(62)	66(64)	53(53)	66(65)	65(63)	66(65)	65(63)	66(64)	58(57)
		375 vph	66(65)	65(63)	66(64)	64(63)	65(64)	50(51)	66(64)	65(63)	66(64)	64(62)	65(64)	54(54)
90% Auto	375 vph	94 vph	66(64)	66(64)	66(64)	66(64)	66(64)	65(63)	66(65)	66(64)	66(65)	65(63)	66(64)	63(61)
		188 vph	66(65)	66(63)	66(64)	65(63)	66(64)	64(62)	66(64)	66(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	64(62)	66(64)	64(60)	65(63)	55(53)	54(53)	65(62)	66(64)	63(61)	65(63)	55(54)
		375 vph	66(63)	64(61)	66(64)	63(61)	65(62)	56(54)	54(53)	64(62)	66(64)	63(60)	65(63)	53(52)
85% Auto	375 vph	94 vph	66(65)	66(64)	66(65)	66(64)	66(64)	65(64)	66(65)	66(64)	66(65)	65(64)	66(64)	64(63)
		188 vph	66(65)	66(64)	66(65)	66(64)	66(64)	65(63)	66(65)	65(64)	66(65)	65(63)	66(64)	63(61)
	750 vph	188 vph	66(64)	64(62)	66(64)	64(61)	66(64)	52(52)	66(64)	65(63)	66(64)	64(62)	66(64)	54(53)
		375 vph	66(64)	65(62)	66(64)	63(61)	65(63)	55(54)	66(64)	65(62)	66(64)	63(60)	65(63)	54(53)
No Auto	375 vph	94 vph	64(52)	61(46)	64(52)	59(45)	63(51)	50(40)	65(55)	62(49)	64(53)	60(48)	64(54)	51(41)
		188 vph	63(51)	60(46)	63(51)	58(45)	63(51)	50(39)	65(55)	62(50)	64(54)	59(47)	63(53)	52(42)
	750 vph	188 vph	52(36)	49(31)	49(35)	47(31)	47(33)	44(31)	60(46)	53(34)	58(44)	51(34)	54(39)	49(34)
		375 vph	53(38)	47(31)	49(34)	46(31)	47(33)	44(31)	58(43)	50(33)	57(43)	49(33)	53(38)	47(33)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-13. Ramp Merge Conditions- Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(63)	65(62)	66(62)	65(62)	66(63)	65(62)	66(62)	65(62)	66(63)	65(61)	66(63)	65(61)
		188 vph	65(62)	65(61)	65(62)	64(61)	66(63)	62(58)	65(61)	63(59)	65(61)	62(57)	64(60)	61(56)
	750 vph	188 vph	65(62)	64(62)	65(62)	64(61)	65(62)	63(59)	65(61)	63(59)	65(61)	63(59)	64(60)	61(58)
		375 vph	64(60)	61(56)	63(60)	59(56)	63(59)	63(59)	63(58)	59(54)	62(57)	55(50)	62(56)	48(44)
90% Auto	375 vph	94 vph	66(63)	65(62)	66(62)	65(61)	66(63)	65(61)	66(62)	65(61)	66(61)	64(61)	66(62)	64(60)
		188 vph	65(62)	64(61)	65(61)	63(60)	65(62)	63(59)	65(60)	63(59)	65(61)	63(59)	64(60)	60(55)
	750 vph	188 vph	65(62)	64(61)	65(62)	63(59)	65(61)	62(59)	65(60)	63(59)	65(61)	62(58)	64(60)	60(55)
		375 vph	64(60)	57(52)	63(58)	58(54)	61(56)	49(45)	63(58)	58(52)	63(58)	55(49)	60(54)	44(41)
85% Auto	375 vph	94 vph	66(62)	65(62)	66(63)	65(62)	66(62)	65(62)	66(63)	65(61)	66(62)	65(61)	66(63)	62(55)
		188 vph	65(62)	64(61)	65(62)	64(60)	65(62)	63(59)	65(61)	63(59)	65(60)	62(57)	65(60)	52(43)
	750 vph	188 vph	65(62)	64(60)	65(62)	63(60)	65(62)	62(59)	65(61)	62(58)	65(61)	63(59)	64(60)	59(54)
		375 vph	63(59)	58(54)	63(58)	58(53)	62(57)	53(50)	63(57)	56(51)	62(57)	56(50)	60(54)	47(43)
No Auto	375 vph	94 vph	65(57)	63(55)	65(58)	63(55)	65(57)	62(54)	65(57)	62(53)	65(57)	62(52)	65(57)	61(51)
		188 vph	62(54)	58(49)	62(53)	54(44)	61(53)	51(42)	62(52)	56(46)	63(54)	55(46)	61(52)	52(43)
	750 vph	188 vph	62(53)	56(48)	62(54)	53(45)	61(53)	49(42)	63(54)	55(45)	62(55)	53(44)	62(52)	45(37)
		375 vph	48(40)	30(26)	46(38)	28(24)	36(31)	24(22)	52(42)	33(27)	52(43)	29(25)	46(37)	25(23)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-14. Ramp Merge Conditions- Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(62)	65(62)	66(63)	64(60)	66(63)	64(61)	65(62)	64(59)	65(61)	63(57)	65(61)	59(54)
		188 vph	66(62)	63(60)	65(62)	63(60)	65(60)	63(58)	65(60)	62(57)	65(60)	61(56)	63(58)	56(49)
	750 vph	188 vph	65(62)	63(60)	65(62)	63(60)	65(61)	60(56)	64(60)	61(55)	64(60)	61(55)	63(59)	57(53)
		375 vph	63(59)	60(56)	63(58)	57(53)	61(57)	51(48)	63(58)	55(49)	62(56)	53(48)	60(54)	42(39)
90% Auto	375 vph	94 vph	66(63)	65(61)	66(62)	64(61)	65(60)	64(60)	65(61)	64(59)	65(62)	63(58)	64(59)	61(56)
		188 vph	65(61)	63(58)	65(61)	63(59)	64(60)	61(57)	64(60)	62(56)	64(60)	61(55)	63(58)	55(49)
	750 vph	188 vph	65(61)	63(60)	65(61)	62(58)	65(61)	58(55)	65(61)	61(54)	64(59)	59(53)	63(58)	52(45)
		375 vph	63(59)	57(53)	62(58)	56(51)	62(58)	48(44)	62(56)	54(48)	61(55)	51(45)	59(52)	42(38)
85% Auto	375 vph	94 vph	66(62)	65(62)	66(62)	65(61)	66(63)	63(60)	65(61)	63(57)	65(61)	63(58)	65(60)	59(53)
		188 vph	65(61)	63(60)	65(61)	63(60)	65(61)	61(57)	64(60)	62(56)	64(59)	60(54)	63(59)	56(49)
	750 vph	188 vph	65(61)	63(59)	65(61)	62(59)	64(60)	60(56)	64(60)	61(55)	64(59)	59(53)	63(58)	54(47)
		375 vph	63(59)	58(53)	62(58)	57(53)	60(56)	49(45)	62(56)	55(48)	62(57)	51(45)	58(52)	42(38)
No Auto	375 vph	94 vph	65(56)	62(52)	64(55)	62(53)	64(55)	59(50)	64(53)	60(48)	64(54)	60(50)	63(54)	53(42)
		188 vph	62(51)	58(49)	61(52)	53(43)	61(52)	49(38)	62(51)	53(40)	62(52)	54(42)	60(49)	43(33)
	750 vph	188 vph	61(52)	52(42)	59(50)	46(37)	58(50)	37(28)	61(51)	44(32)	61(50)	42(32)	58(46)	35(27)
		375 vph	45(37)	31(25)	43(34)	30(24)	38(32)	26(23)	52(41)	33(25)	51(40)	30(24)	44(35)	28(23)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-15. Ramp Merge Conditions- Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(64)	66(64)	66(64)	66(65)	66(64)	66(65)	65(64)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(63)	66(64)	64(62)	66(63)	64(61)
	750 vph	188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	66(64)	66(65)	65(63)	66(64)	65(63)	66(63)	63(61)
		375 vph	66(65)	65(65)	66(64)	65(64)	65(64)	63(62)	65(63)	63(59)	65(63)	62(59)	65(62)	57(55)
90% Auto	375 vph	94 vph	66(66)	66(65)	66(65)	66(65)	66(66)	66(65)	66(64)	66(64)	66(65)	66(64)	66(64)	65(63)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(62)	66(63)	65(62)	66(64)	63(60)
	750 vph	188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(63)	66(65)	65(64)	66(64)	65(62)	66(64)	64(61)
		375 vph	66(64)	65(63)	65(64)	65(63)	65(63)	63(62)	65(62)	62(58)	64(61)	61(57)	64(61)	55(52)
85% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(63)	66(65)	65(64)	66(64)	65(64)
		188 vph	66(65)	66(65)	66(65)	66(65)	66(65)	66(64)	66(64)	65(63)	66(64)	64(61)	66(64)	64(62)
	750 vph	188 vph	66(65)	66(65)	66(65)	66(65)	66(64)	65(64)	66(64)	65(63)	66(64)	65(63)	66(65)	63(61)
		375 vph	66(65)	65(64)	66(64)	65(64)	65(63)	62(60)	65(63)	62(59)	64(62)	59(56)	64(62)	56(55)
No Auto	375 vph	94 vph	66(64)	66(63)	66(64)	66(64)	66(64)	65(63)	66(62)	65(61)	66(62)	64(59)	66(62)	63(57)
		188 vph	65(62)	64(60)	65(63)	64(62)	65(62)	61(57)	65(59)	61(56)	65(59)	59(52)	64(59)	58(50)
	750 vph	188 vph	65(62)	64(61)	65(63)	64(60)	64(62)	62(61)	65(60)	61(56)	65(60)	59(54)	64(60)	54(46)
		375 vph	62(60)	51(43)	61(57)	46(44)	59(55)	36(33)	59(53)	46(42)	58(52)	39(33)	54(50)	23(24)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-16. Ramp Merge Conditions- Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1000 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	65(63)	66(65)	63(62)
		188 vph	66(65)	66(64)	66(65)	66(65)	66(64)	65(64)	66(65)	65(63)	66(64)	64(62)	66(63)	62(59)
	750 vph	188 vph	66(66)	66(65)	66(65)	65(65)	66(65)	64(62)	66(64)	64(63)	66(64)	64(62)	65(64)	61(59)
		375 vph	66(65)	65(64)	66(64)	65(63)	65(64)	63(62)	65(63)	63(60)	65(63)	63(60)	65(62)	59(57)
90% Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(64)	65(63)	66(65)	65(64)	66(63)	63(59)
		188 vph	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	65(63)	66(64)	64(61)	65(63)	63(60)
	750 vph	188 vph	66(65)	66(64)	66(65)	65(63)	66(64)	64(63)	66(64)	65(62)	66(64)	64(62)	65(63)	61(57)
		375 vph	66(64)	65(63)	66(64)	64(62)	65(64)	63(60)	65(62)	63(60)	65(62)	62(59)	64(62)	59(56)
85% Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(64)	66(65)	65(62)	66(64)	65(63)	66(65)	65(63)	66(64)	63(61)
		188 vph	66(65)	66(65)	66(65)	66(64)	66(64)	64(63)	66(64)	65(64)	66(64)	64(61)	65(63)	62(60)
	750 vph	188 vph	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(63)	65(62)	66(64)	64(61)	65(63)	61(59)
		375 vph	66(65)	65(63)	65(64)	64(63)	65(64)	63(62)	65(63)	63(60)	65(63)	62(60)	64(62)	58(56)
No Auto	375 vph	94 vph	66(63)	65(61)	66(62)	65(62)	65(63)	64(60)	66(59)	64(56)	65(61)	63(58)	65(59)	60(52)
		188 vph	65(63)	64(61)	65(62)	63(59)	65(61)	62(56)	64(59)	62(54)	65(59)	60(53)	64(60)	58(48)
	750 vph	188 vph	65(62)	62(57)	65(62)	62(57)	64(59)	58(52)	64(59)	58(49)	64(59)	57(46)	63(57)	53(45)
		375 vph	62(57)	55(49)	61(58)	49(42)	59(55)	44(38)	61(54)	50(41)	60(52)	46(38)	57(49)	37(31)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-17. Ramp Merge Conditions- Full Auxiliary Lane, without Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	67(66)	66(66)	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	64(63)
	750 vph	188 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)	66(65)	64(62)
		375 vph	66(65)	65(65)	66(65)	66(65)	66(65)	65(64)	65(64)	64(62)	65(64)	63(61)	65(63)	59(57)
90% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(66)	66(65)	66(65)	65(64)
		188 vph	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(63)
	750 vph	188 vph	66(66)	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	63(61)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	64(63)	65(63)	63(61)	65(63)	62(60)	65(62)	59(57)
85% Auto	375 vph	94 vph	66(66)	66(66)	67(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(65)	66(65)	65(64)
		188 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(63)	66(64)	64(63)
		375 vph	66(65)	65(64)	66(65)	65(64)	66(65)	63(62)	65(63)	63(61)	65(63)	62(60)	65(62)	57(55)
No Auto	375 vph	94 vph	66(65)	66(65)	66(65)	66(65)	66(64)	65(64)	66(63)	65(62)	66(62)	65(62)	66(62)	64(60)
		188 vph	66(64)	65(63)	66(64)	65(63)	66(64)	63(61)	65(61)	63(59)	65(62)	62(58)	64(60)	60(56)
	750 vph	188 vph	66(64)	65(64)	65(63)	65(63)	65(63)	63(60)	65(61)	62(57)	65(62)	62(57)	65(61)	57(53)
		375 vph	63(60)	55(51)	63(60)	52(49)	61(58)	42(39)	60(54)	49(44)	61(56)	46(42)	57(52)	31(30)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds

Table D-18. Ramp Merge Conditions- Full Auxiliary Lane, with Intermediate Ramp, and Managed Lane Ramp Spacing 1500 feet per Expressway Lane.

Ramp Conditions			Expressway Conditions (number of expressway mainlanes)											
			Three						Four					
			No Truck		5% Truck		15% Truck		No Truck		5% Truck		15% Truck	
Traffic Mix	Volume	Volume Accessing Managed Lanes	3,000 vph	4,200 vph	3,000 vph	4,200 vph	3,000 vph	4,200 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph	4,000 vph	5,600 vph
All Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(66)	66(65)	66(65)	66(65)	66(64)	66(65)	65(64)	66(65)	64(63)
		188 vph	66(65)	66(65)	66(66)	66(65)	66(65)	65(65)	66(65)	65(64)	66(65)	65(64)	66(65)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(63)	66(65)	63(62)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	64(64)	66(64)	64(62)	66(64)	63(62)	65(63)	61(59)
90% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	65(65)	66(65)	66(65)	66(65)	65(64)	66(65)	64(62)
		188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(63)	66(64)	64(62)
	750 vph	188 vph	66(66)	66(65)	66(65)	66(65)	66(65)	65(64)	66(65)	65(63)	66(65)	65(63)	66(64)	63(61)
		375 vph	66(65)	65(65)	66(65)	65(64)	65(65)	64(63)	65(64)	64(62)	65(63)	63(61)	65(64)	60(58)
85% Auto	375 vph	94 vph	66(66)	66(66)	66(66)	66(65)	66(66)	65(64)	66(65)	66(64)	66(65)	65(64)	65(64)	65(63)
		188 vph	66(65)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(65)	65(64)	65(63)	63(62)
	750 vph	188 vph	66(66)	66(65)	66(66)	66(65)	66(65)	65(64)	66(65)	65(64)	66(64)	64(63)	66(64)	63(61)
		375 vph	66(65)	66(65)	66(65)	65(64)	66(65)	64(63)	65(64)	64(62)	65(63)	64(62)	65(63)	61(59)
No Auto	375 vph	94 vph	66(65)	65(63)	66(64)	66(64)	66(64)	64(61)	66(63)	65(60)	66(63)	65(60)	66(62)	62(57)
		188 vph	66(64)	65(63)	66(63)	65(63)	66(63)	63(61)	65(62)	63(58)	65(61)	63(57)	65(60)	60(54)
	750 vph	188 vph	66(64)	64(61)	66(63)	64(61)	65(63)	62(59)	65(61)	62(54)	65(60)	62(55)	64(59)	55(45)
		375 vph	64(61)	59(56)	63(61)	55(50)	62(58)	50(45)	62(57)	54(47)	62(56)	53(46)	60(54)	42(37)

Note: vph = vehicles per hour; values in parentheses are ramp weaving speeds