-Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-08/0-5284-P1		

4. Title and Subtitle	5. Report Date
GUIDELINES FOR APPLYING MANAGED LANE STRATEGIES TO RAMPS	September 2007 Published: December 2007
	6. Performing Organization Code
7. Author(s) Beverly Kuhn, Kevin Balke, Nadeem Chaudhary, Debbie Jasek, Ganesh Karkee, Kwaku Obeng-Boampong, Jeffrey Shelton, Steven Venglar	8. Performing Organization Report No. Product 0-5284-P1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5284
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Product 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Feasibility and Guidelines for Applying Managed Lane Strategies to Ramps
URL: http://tti.tamu.edu/documents/0-5284-P1.pdf

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 lane operational strategies to ramps could maximize existing capacity, manage demand, offer choices, improve safety, and generate revenue. This project will investigate 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 document provides guidance on identifying when to consider managed ramps based on relevant factors including target users in the corridor, congestion level, ramp spacing/density, ramp volumes, accident history, etc.

17. Key Words	18. Distribution Statement
Managed Lanes, Freeway, Operations, Ramps, Guidelines	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	96	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

GUIDELINES FOR APPLYING MANAGED LANE STRATEGIES TO RAMPS

by

Beverly Kuhn, Ph.D., P.E.
Senior Research Engineer

Kevin Balke, Ph.D., P.E.
Research Engineer

Nadeem Chaudhary, Ph.D., P.E.
Senior Research Engineer

Debbie Jasek
Associate Transportation Specialist

Ganesh Karkee
Assistant Research Scientist

Kwaku Obeng-Boampong
Associate Transportation Researcher

Jeffrey Shelton
Associate Transportation Researcher

and

Steven P. Venglar, P.E.
Associate Research Engineer

Product 0-5284-P1
Project 0-5284
Project Title: Feasibility and Guidelines for Applying Managed Lane Strategies to Ramps

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

September 2007
Published: December 2007

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge of the overall project was Beverly T. Kuhn (Texas P.E. #80308).

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.

ACKNOWLEDGMENTS

This project was conducted in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA); special thanks are extended to TxDOT and FHWA for support of this research project. Thanks are also extended to the University of Texas at El Paso and Dr. Ruey Long (Kelvin) Cheu as an integral partner in the research effort. The researchers also acknowledge the following members of the Project Monitoring Committee for their leadership, time, efforts, and contributions:

Program Coordinator

- Carol Rawson, P.E., Traffic Operations Division, TxDOT

Project Director

- Michael Chacon, P.E., Traffic Operations Division, TxDOT

Current Technical Panel

- James Bailey, P.E., Waco District, TxDOT
- Cynthia Flores, P.E., Traffic Operations Division, TxDOT
- Andrew Oberlander, P.E., Dallas District, TxDOT

Research and Technology Implementation (RTI) Engineer

- Wade Odell, P.E., Research and Technology Implementation Office, TxDOT

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

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 are interfering 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 in the number of lane miles across the country (*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 has placed enormous demands on the already burdened transportation infrastructure, particularly the freeway systems.

There is a certain realization that transportation agencies cannot construct 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

Managed lanes are one method transportation agencies use successfully across the country 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 that 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 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.

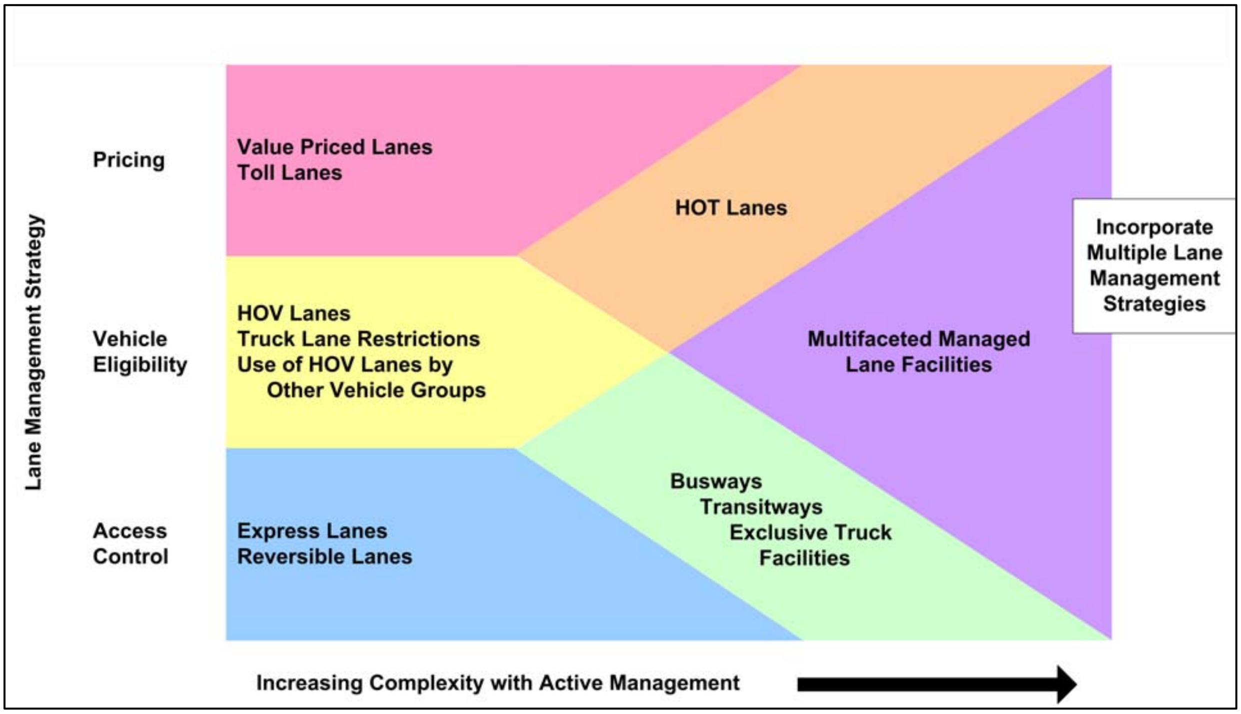


Figure 1. Lane Management Strategy Complexity (*5*).

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 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 (*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. To encourage car pooling and high-occupancy vehicles, many states currently provide separate bypass lanes on ramps (*7, 8, 9*). The California Department of Transportation manual also provides guidelines for proper signs to use with HOV and car pool bypass lanes on ramps (*7*). As another example, the Washington Department of Transportation *Design Manual* states: "[C]onsider 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). 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 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.

DOCUMENT OBJECTIVE

The objective of this document is to provide general guidance on identifying when to consider managed ramps based on relevant factors including target users in the corridor, congestion level, ramp spacing/density, ramp volumes, accident history, etc. Not all managed ramp operational strategies can provide benefits to freeway operations, but those discussed in the following sections have the potential to improve operations and safety such that transportation agencies should consider them for implementation.

CHAPTER 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 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 1. Possible Managed Lanes Goals (Adapted from *10*).

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 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 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 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 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 3 shows some of the measured benefits from variations of ramp meter deployment in the United States.

Table 3. Measured Benefits of Ramp Meter Deployments in the United States (*11*).

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 1160 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 as an alternative to installing a ramp meter, and/or 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 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 hypothetical freeway/ramp configuration shown in Figure 2 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 feet in length with a merge area of 1500 feet 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 link 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 feet. Also, the length of the acceleration lane for the ramp is varied by using five different acceleration lane lengths, as shown in Figure 3.

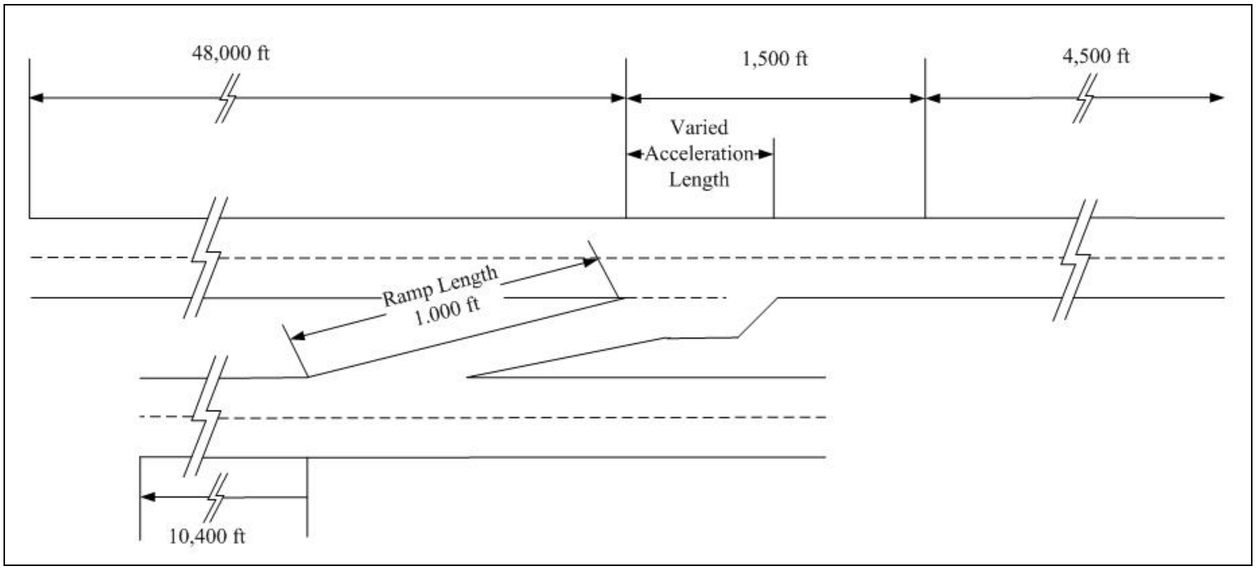


Figure 2. Basic Freeway/Ramp Configuration.

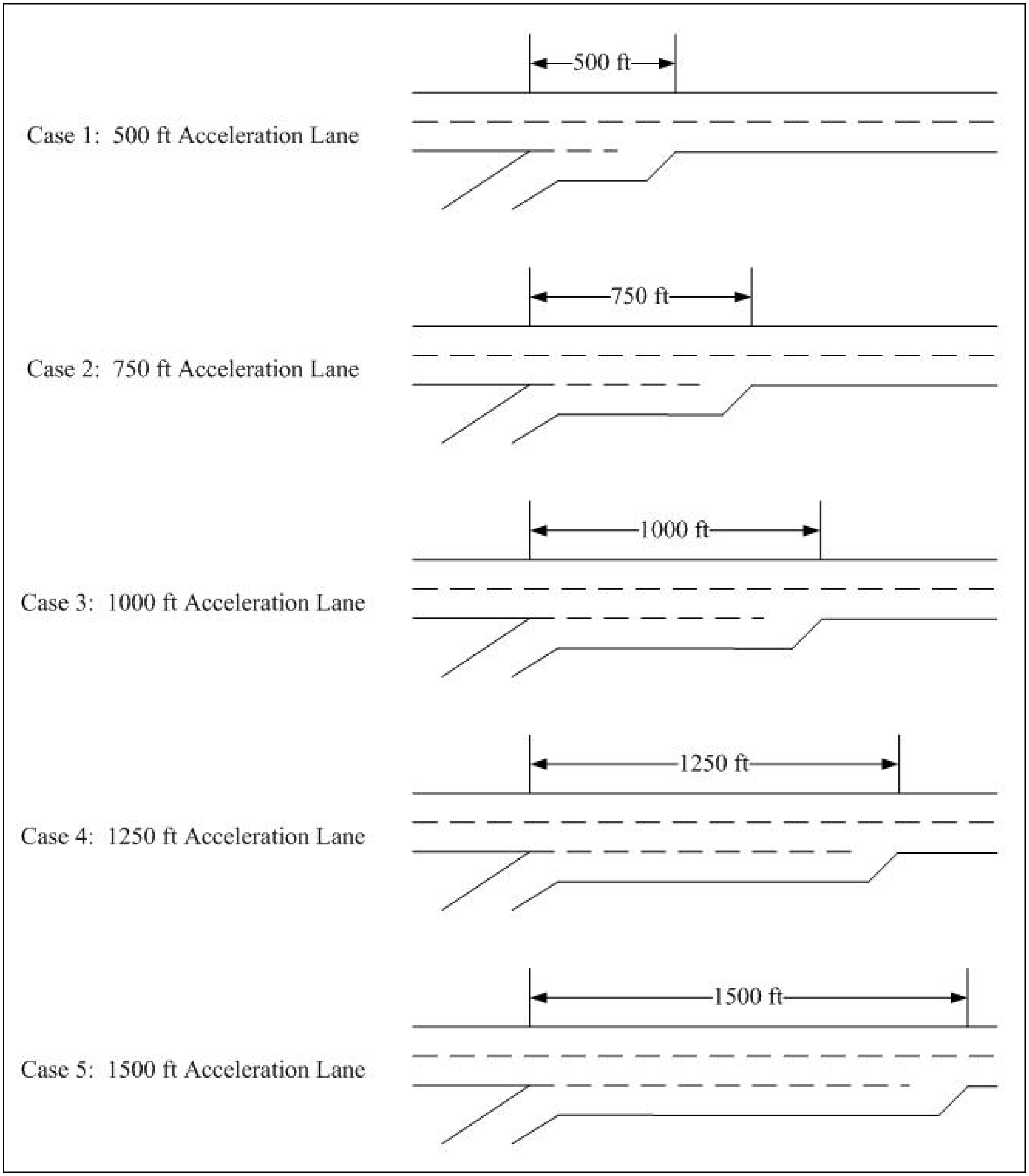


Figure 3. Different Acceleration Ramp Lengths.

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 for a gap that is big enough to merge into the freeway lane, or if the drivers are 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 single-lane, single-vehicle ramp metering strategies. Generally, ramp demands greater that 900 pcphpl require either dual-lane metering or bulk meter to accommodate the total demand without excessive queues building on the ramp. Table 4 shows the freeway demand levels researchers examined at each ramp configuration, while Table 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 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 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

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. 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). Researchers set a long length of the travel time segment because an initial investigation showed a queue extending approximately 9 miles upstream of the entrance ramp during some combination of ramp and freeway demand level. Researchers set VISSIM to record the average travel time every 60 seconds during the data collection period. Researchers 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 shows 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 occurs 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 in Figure 4. 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 4). Then working parallel to the X axis (see ② in Figure 4), 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 4). 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.

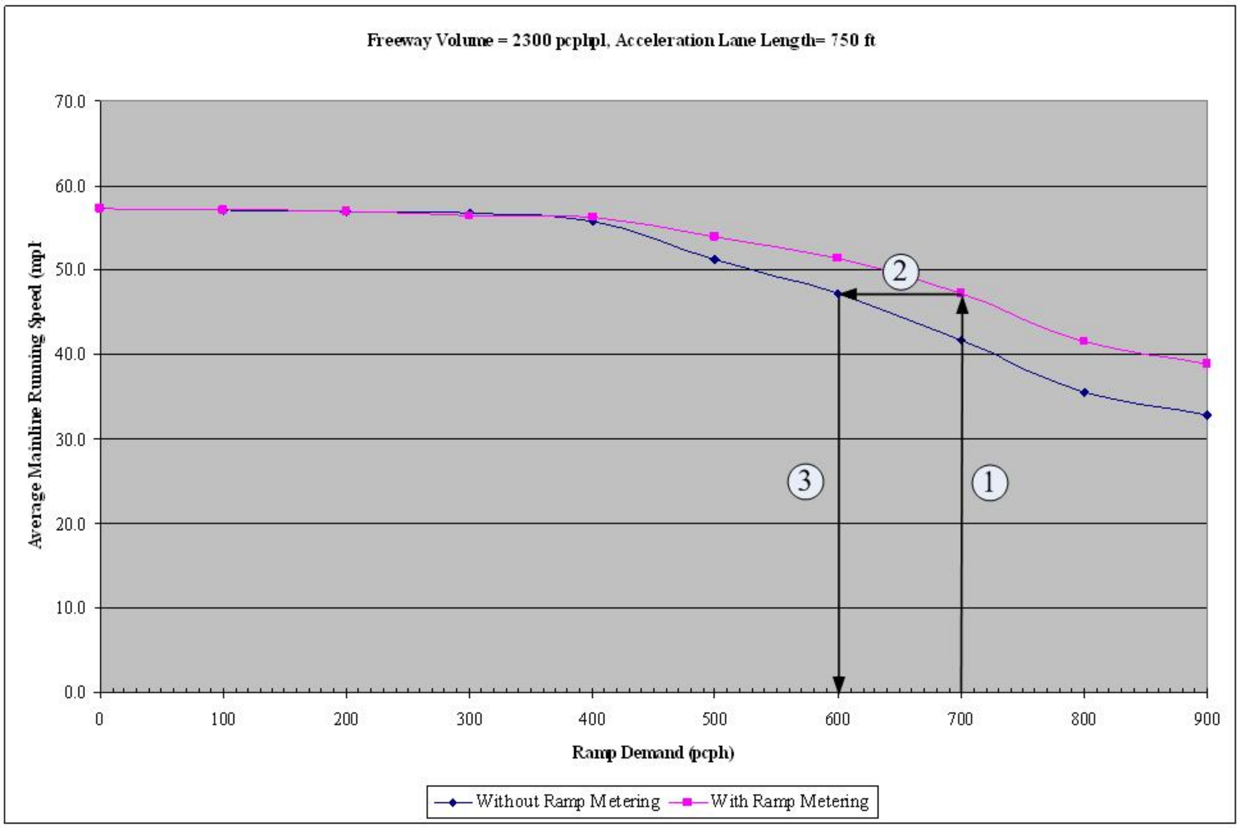


Figure 4. Illustration of Process Used to Determine Ramp Demand at a Non-Metered Ramp to Achieve an Equivalent Level of Operations on the Freeway where Ramp Metering was Utilized.

Figure 5 through Figure 11 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.

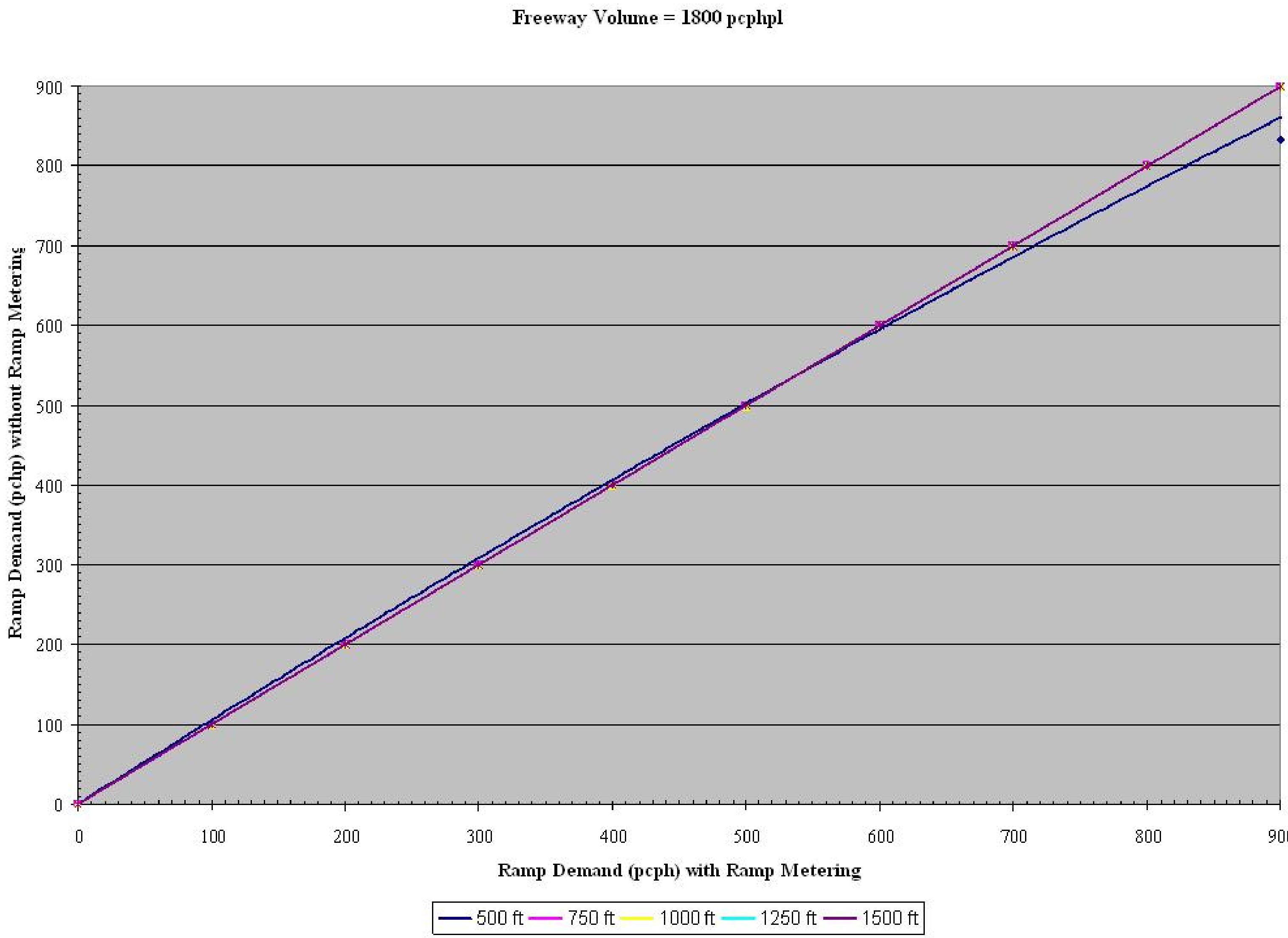


Figure 5. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1800 pcphpl

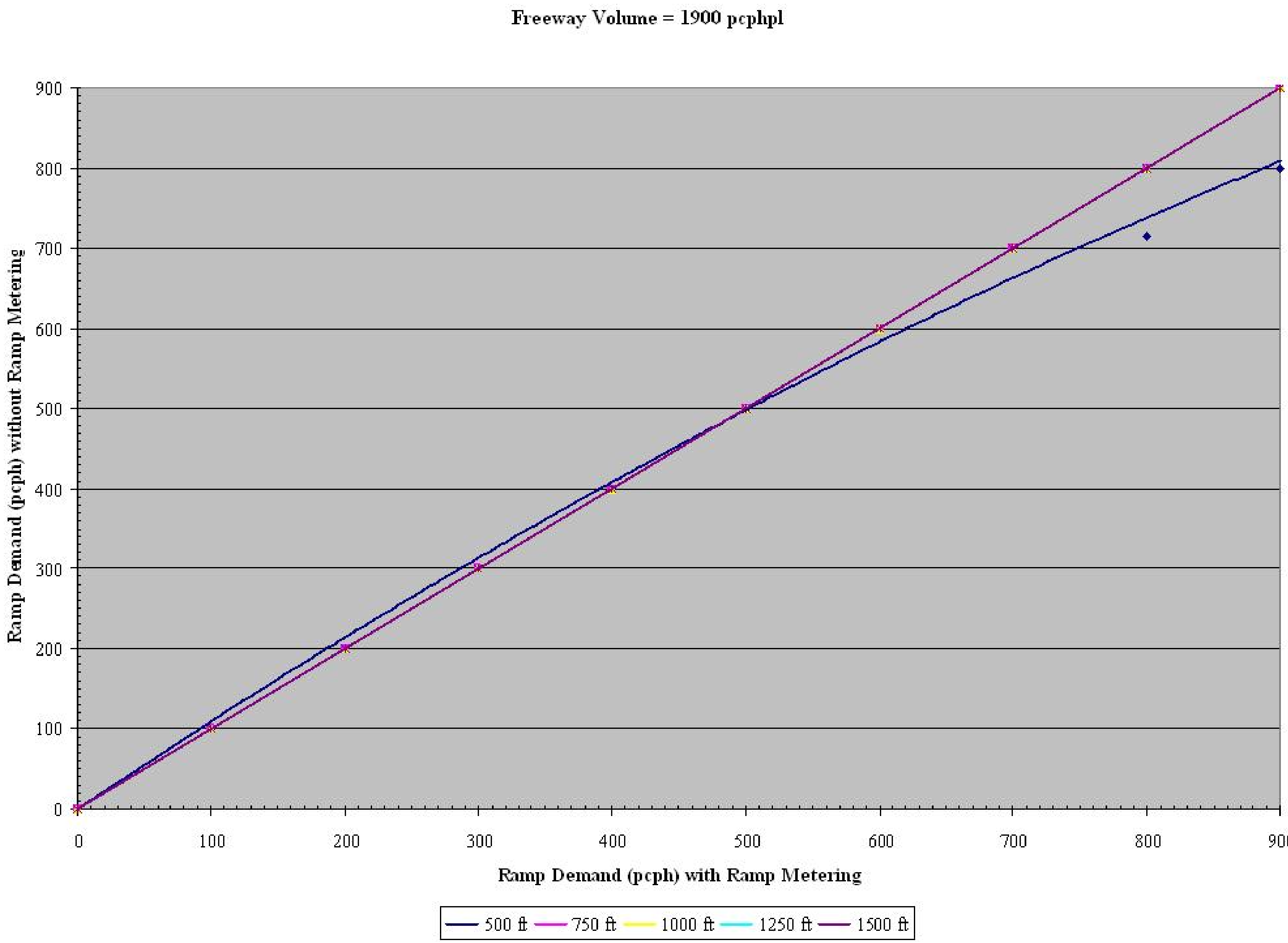


Figure 6. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 1900 pcphpl

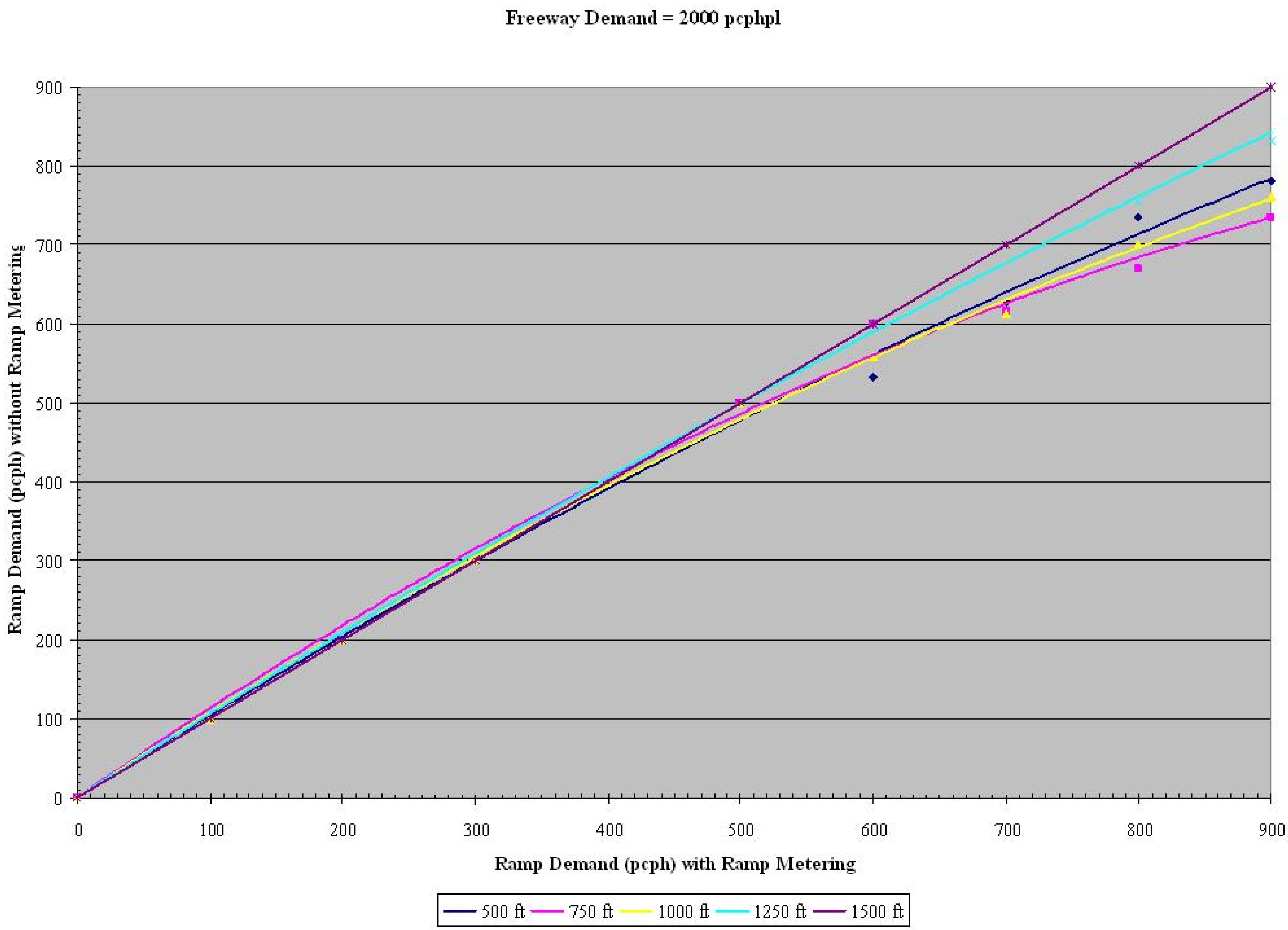


Figure 7. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2000 pcphpl

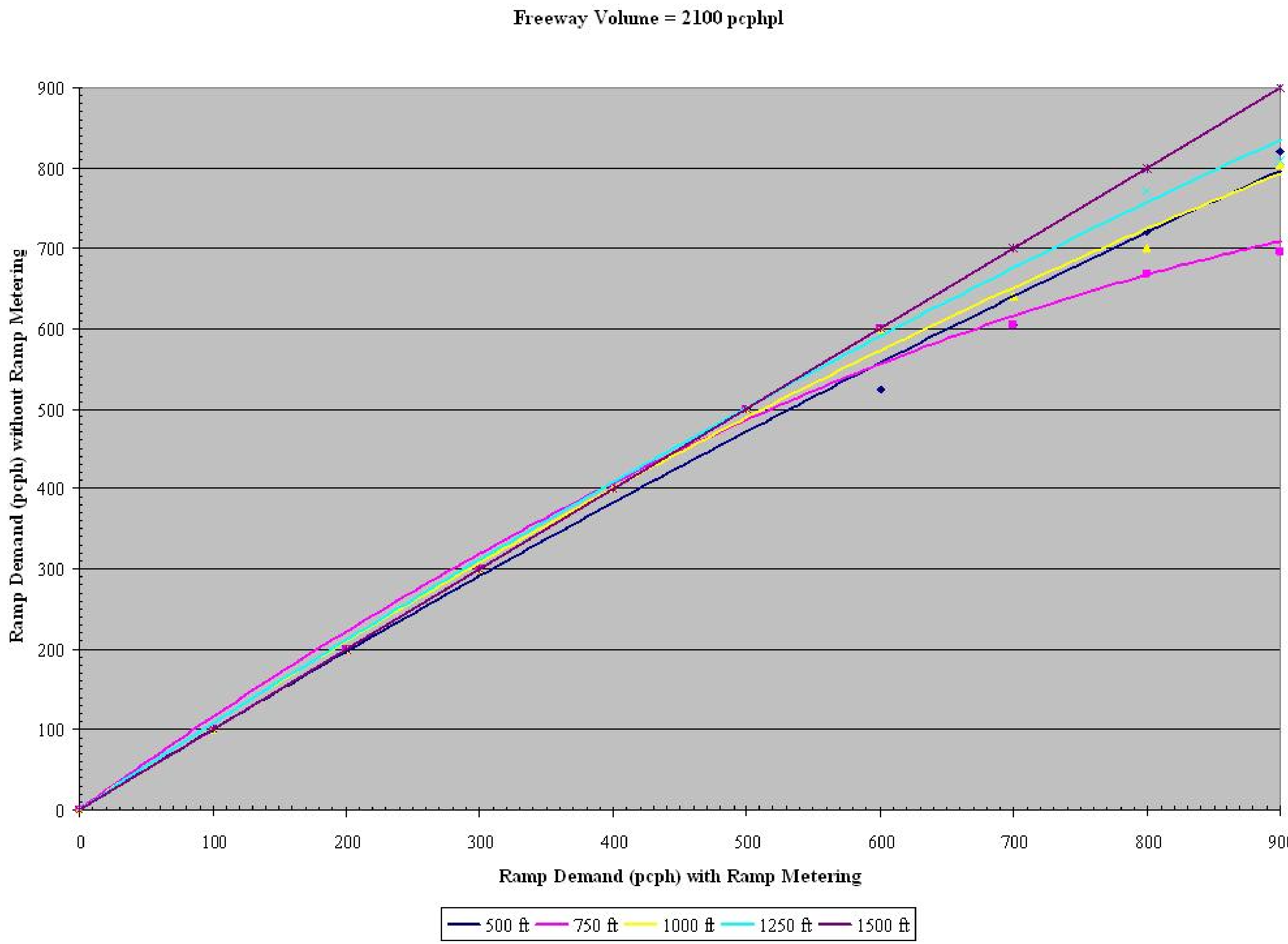


Figure 8. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2100 pcphpl

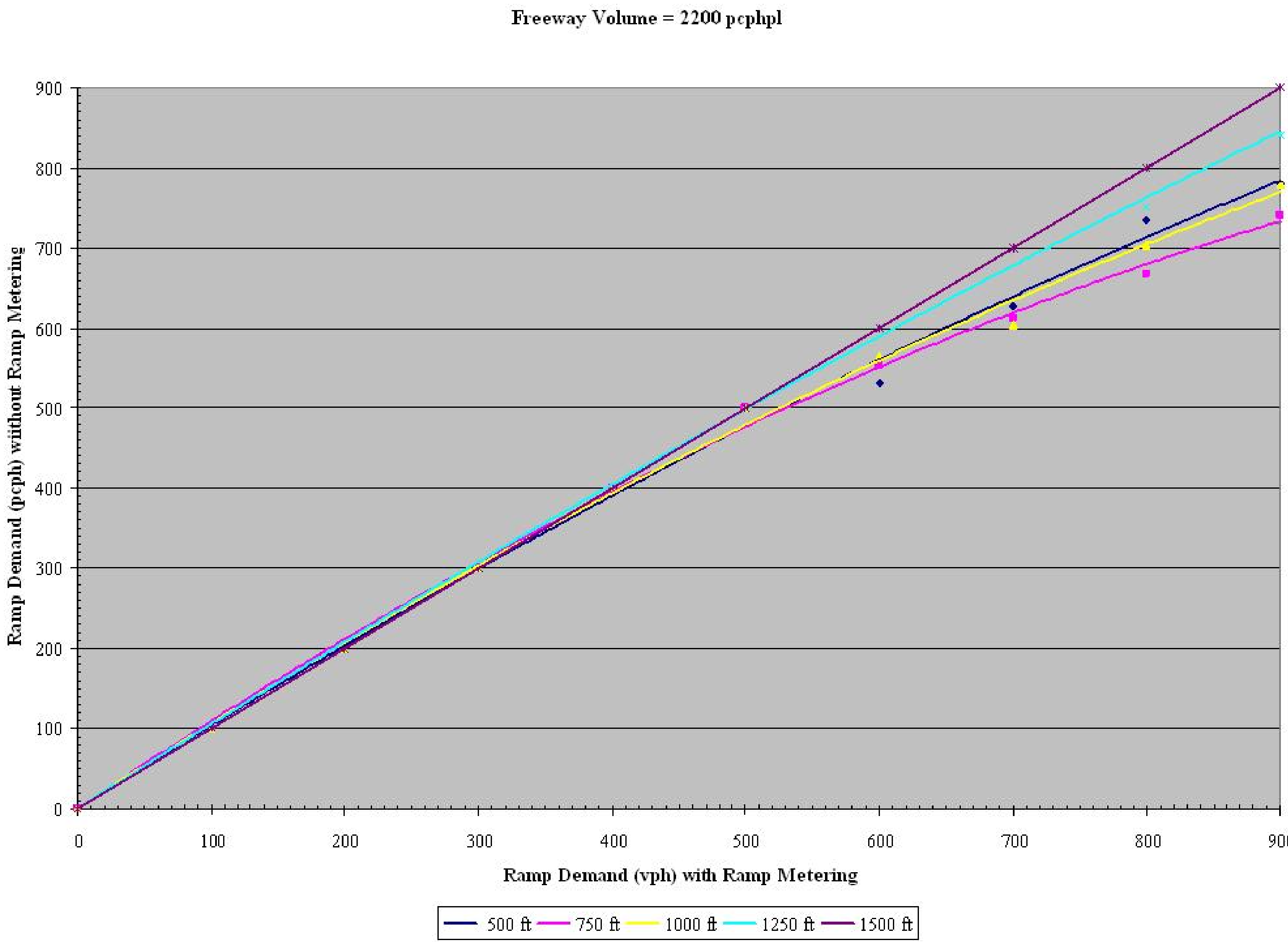


Figure 9. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2200 pcphpl

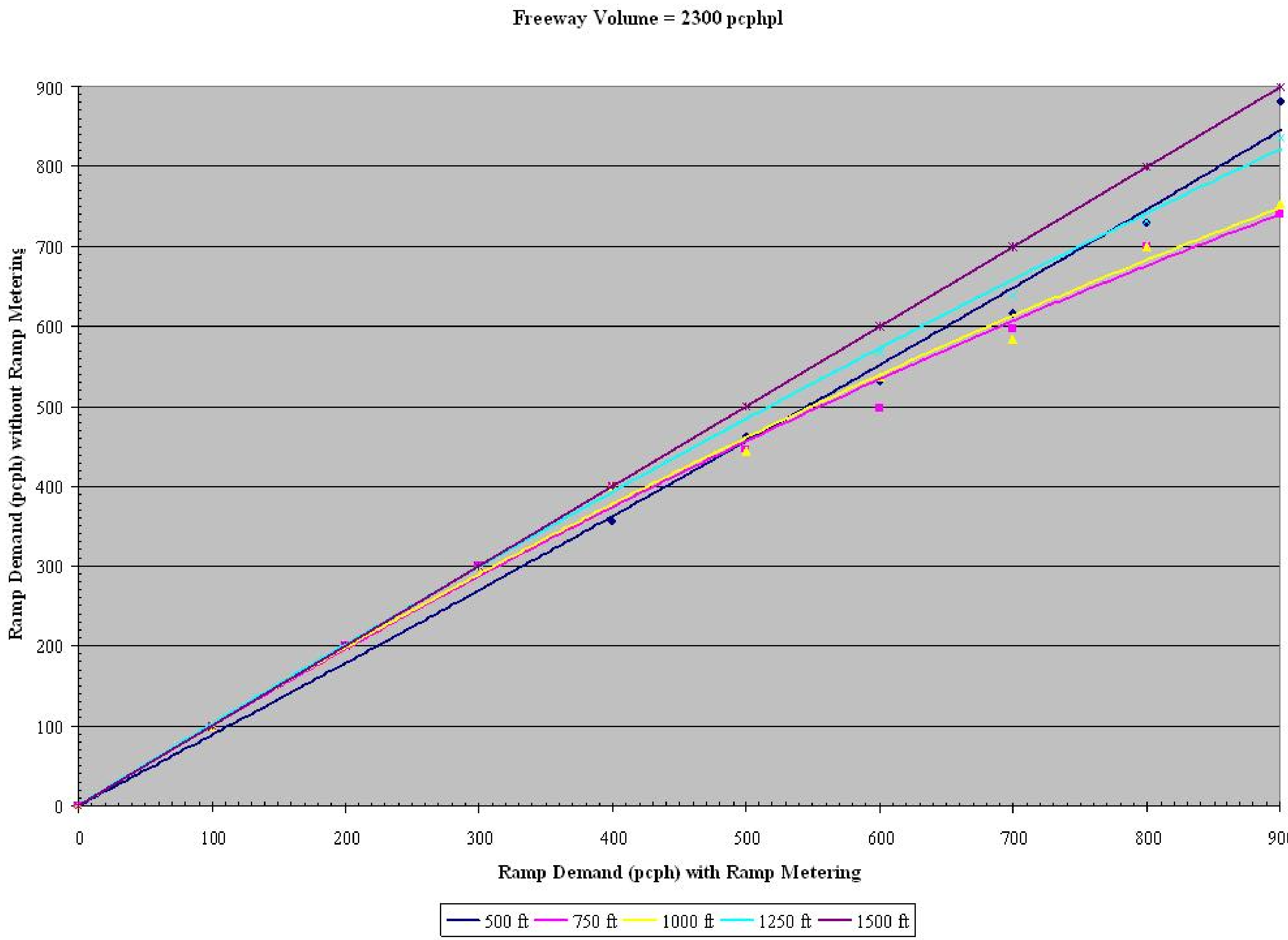


Figure 10. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2300 pcphpl

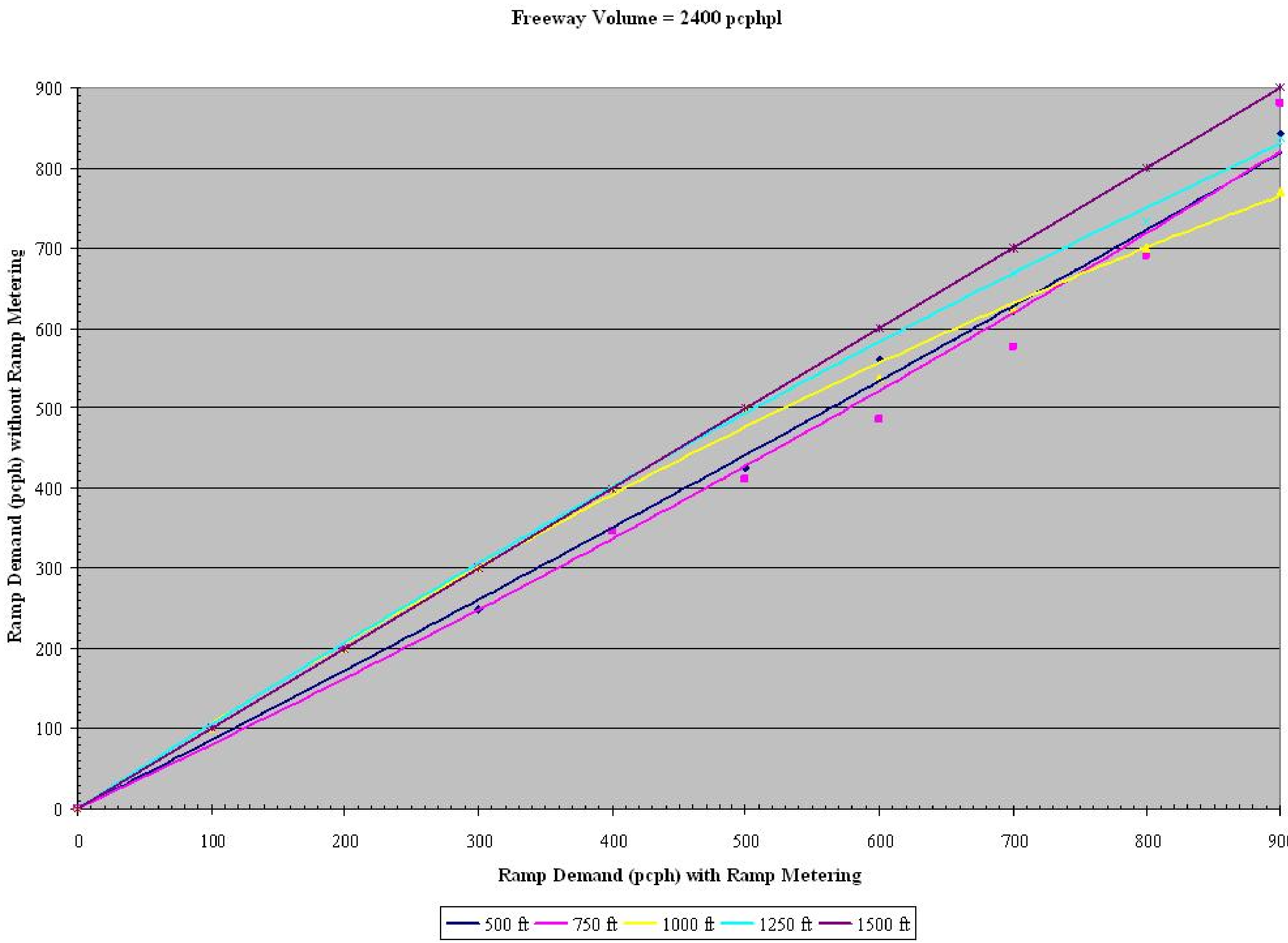


Figure 11. Managed Lane Ramp Demand Level Required to Achieve an Equivalent Level of Performance on a Freeway Segment Operated with a Ramp Meter – Freeway Volume = 2400 pcphpl

Figure 12 illustrates the use of the previous graphs. 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 9), the practitioner would then locate on the x-axis the amount of traffic that currently exist on the ramp (in the example, 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 the 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 the example, the amount of traffic that would need to be diverted away from the ramp by a managed lane strategy equals 65 pcph.

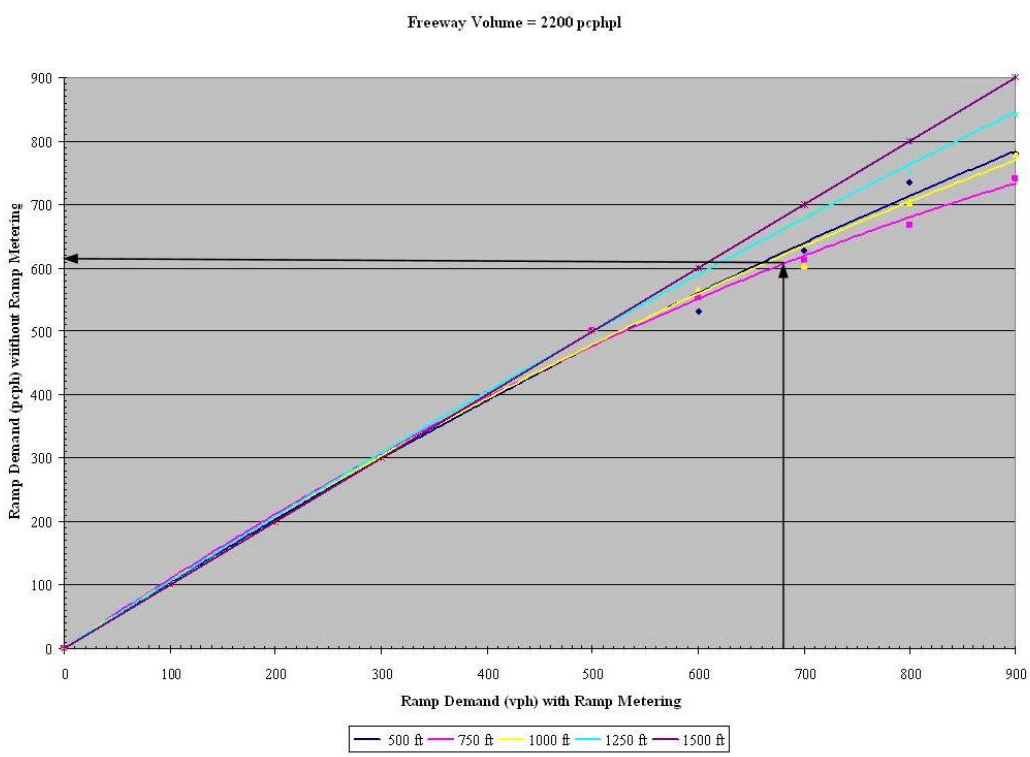


Figure 12. Illustration of Use of Ramp Demand Curves to Determine Amount of Traffic to be Diverted by Managed Ramp Strategy.

Table 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	$y = -000022482174688057 5x^2 + 1.02514527629234x$	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 6 shows the "best fit" regression equations and the regression correlation coefficient (R-squared value) for each line shown in Figure 5 through Figure 11. 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 7 and Table 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. These tables provide 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. They show that a managed lanes 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 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 8. Percentage of Demand that must be Diverted from Ramp by Managed Lanes Strategies (Continued).

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, researchers compared the performance of a freeway segment with and without ramp metering. Researchers used two measures to assess the performance of the freeway: average running speed and throughput. The 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. The research team 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. The researchers 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.

CHAPTER 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 amount of volume on a freeway facility in conjunction with the amount 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

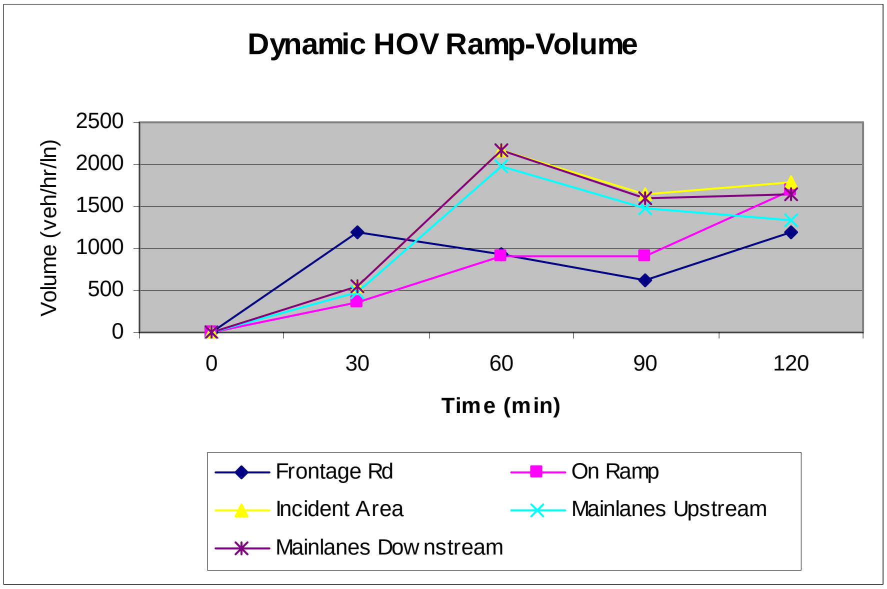
A comparative analysis can also be performed for ramp management strategies for incident management. Overall performance measures included average overall travel time and average stop time. It must be noted that the network performance of these scenarios includes all data collected within the entire 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 13 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.



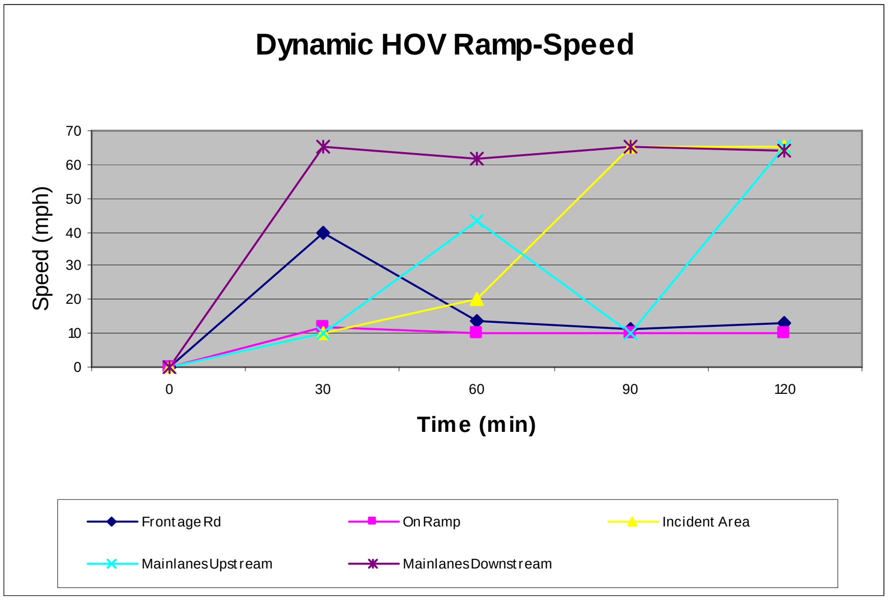
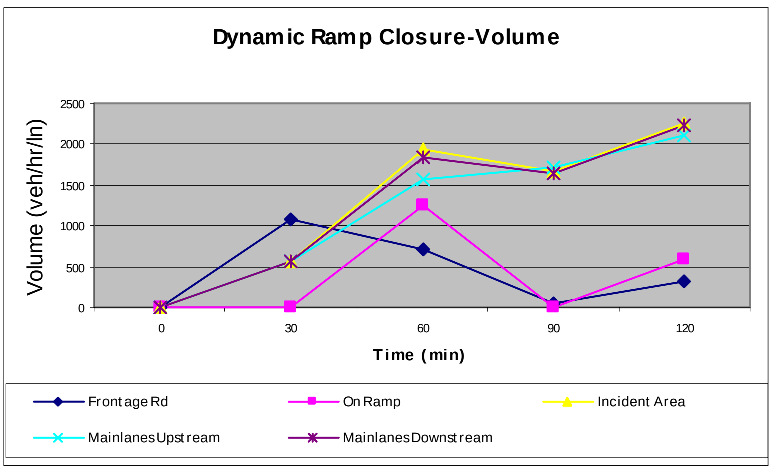


Figure 13. Dynamic HOV Ramp Performance Measures.

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 14 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.



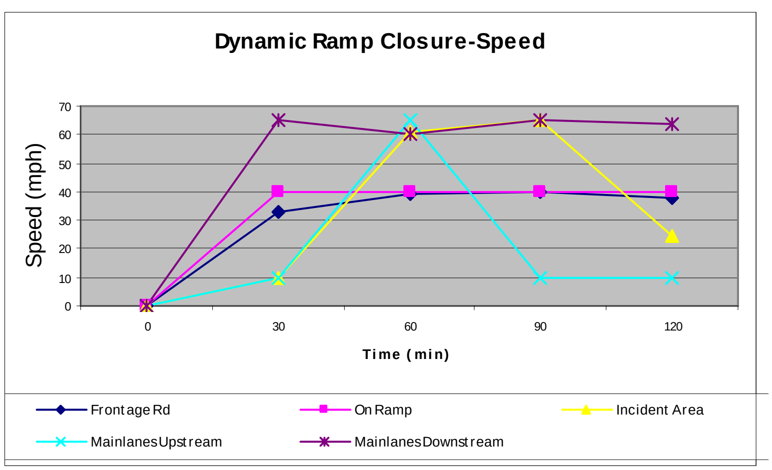


Figure 14. Dynamic Ramp Closure Performance Measures.

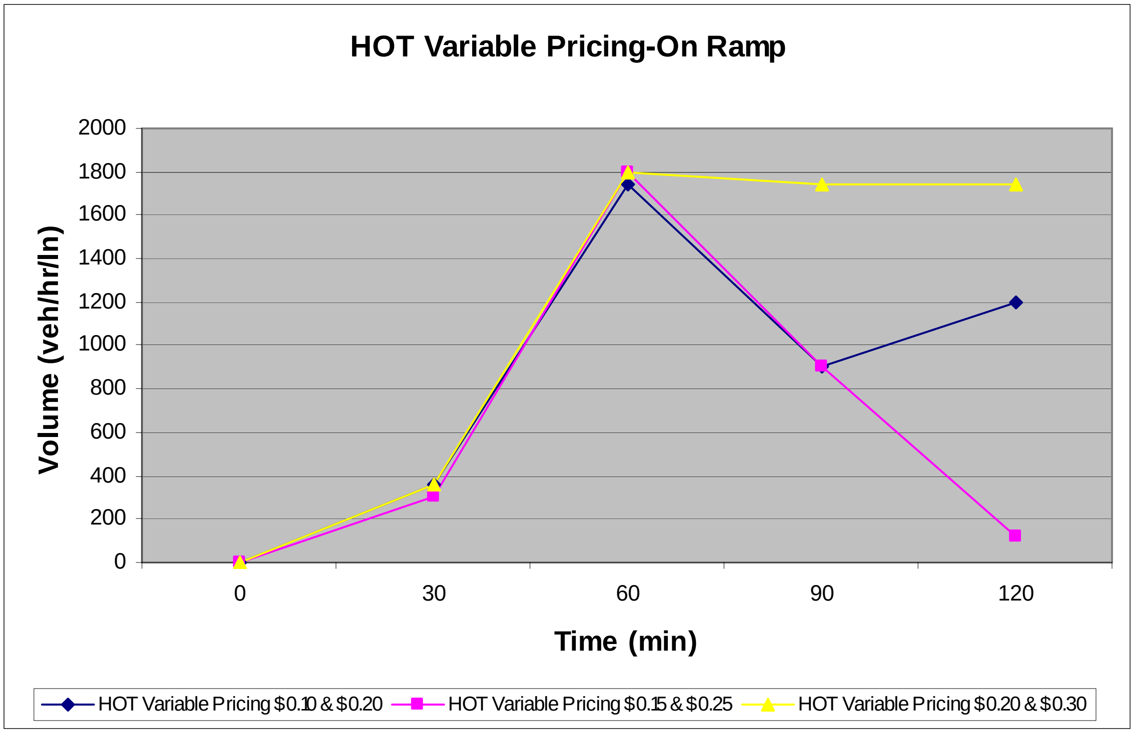
Dynamic Variable Pricing (HOT)

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 9 shows the tolling rates used for each of the three defined HOT scenarios.

Table 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. 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.



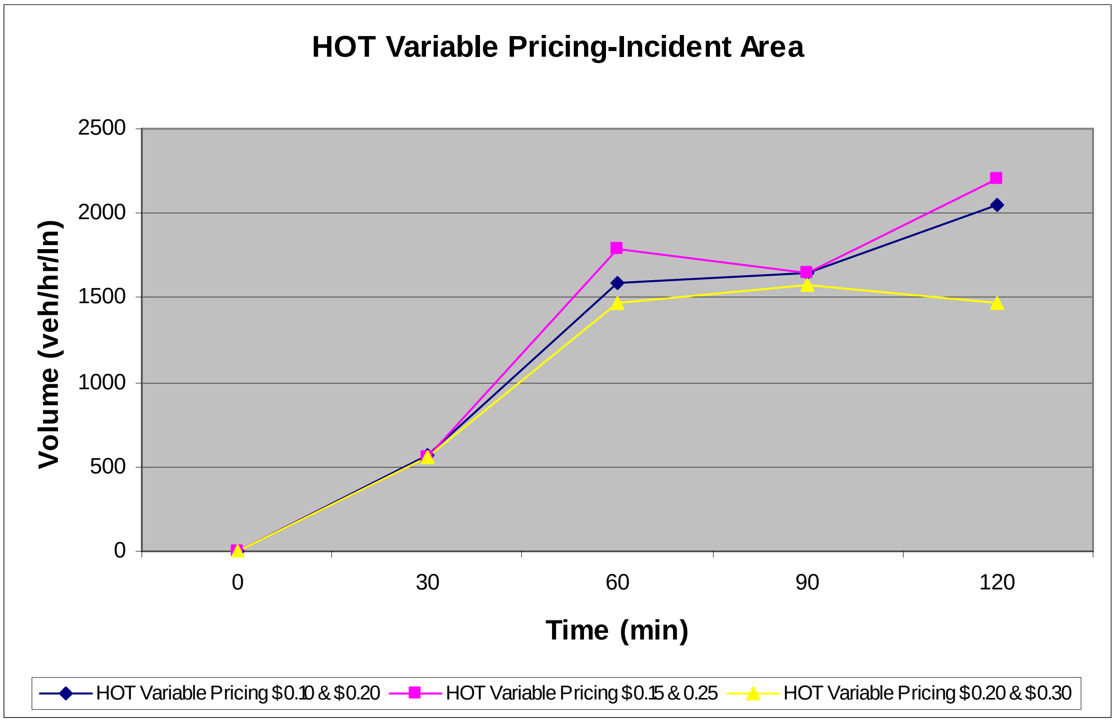
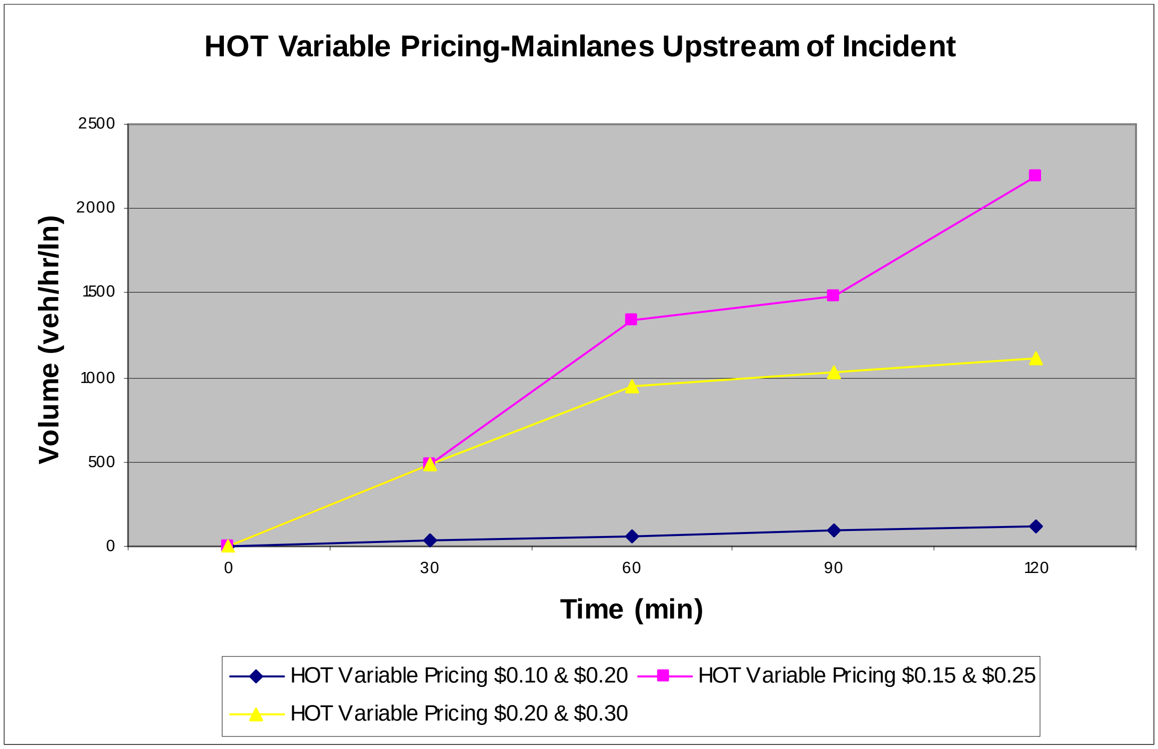


Figure 15. Tolling Scenarios – Volume.



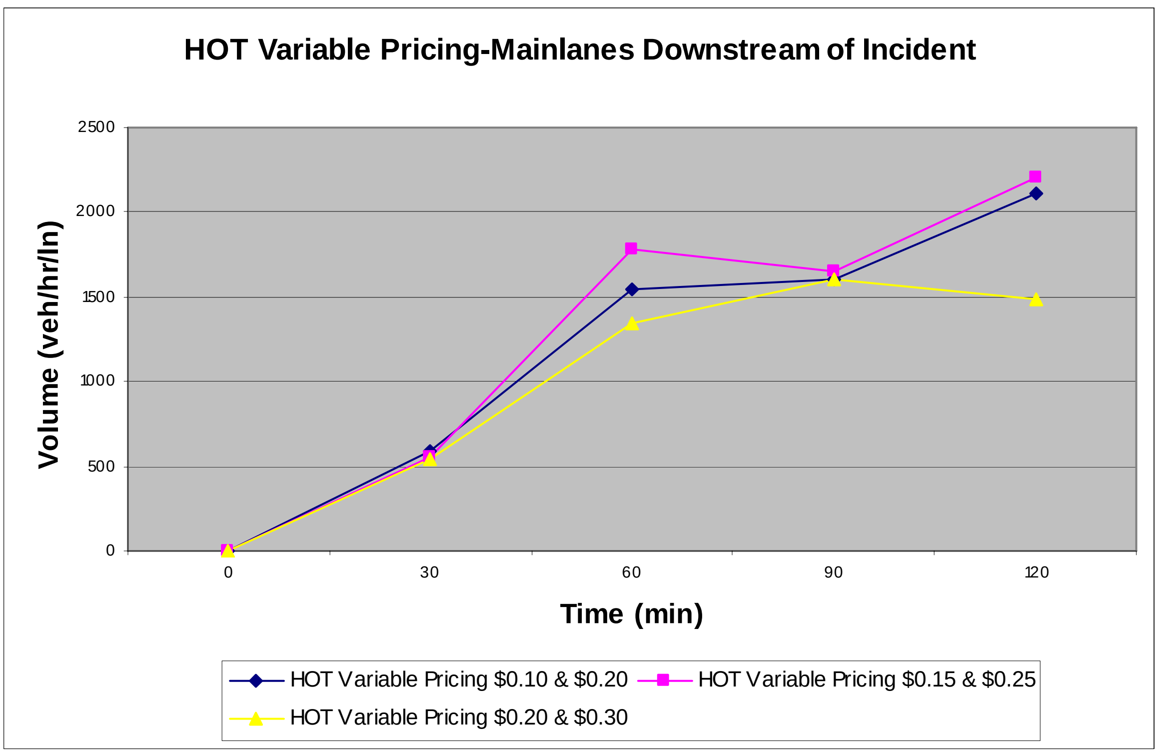


Figure 16. Tolling Scenarios – Volume (Continued).

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 17.

Total ramp closure creates a better balanced flow of traffic on the open freeway mainlane and therefore reduces the overall travel time. Figure 18 illustrates that the highest variable pricing rate has the highest average stop time. This outcome is proof of the fact that price elasticity dictates routing decisions for motorists (*12*).

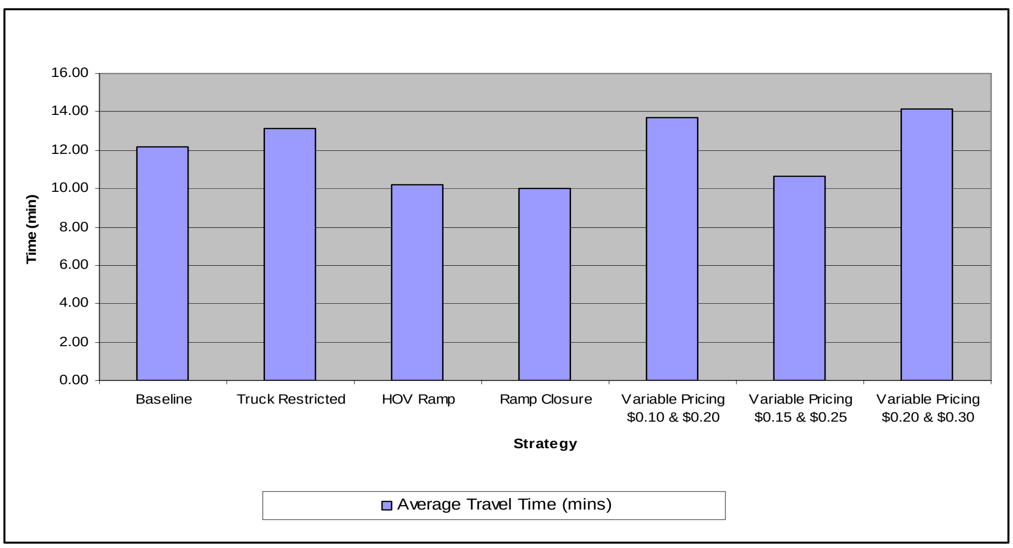


Figure 17. Comparative Analysis of Average Network Performance – Incident Management.

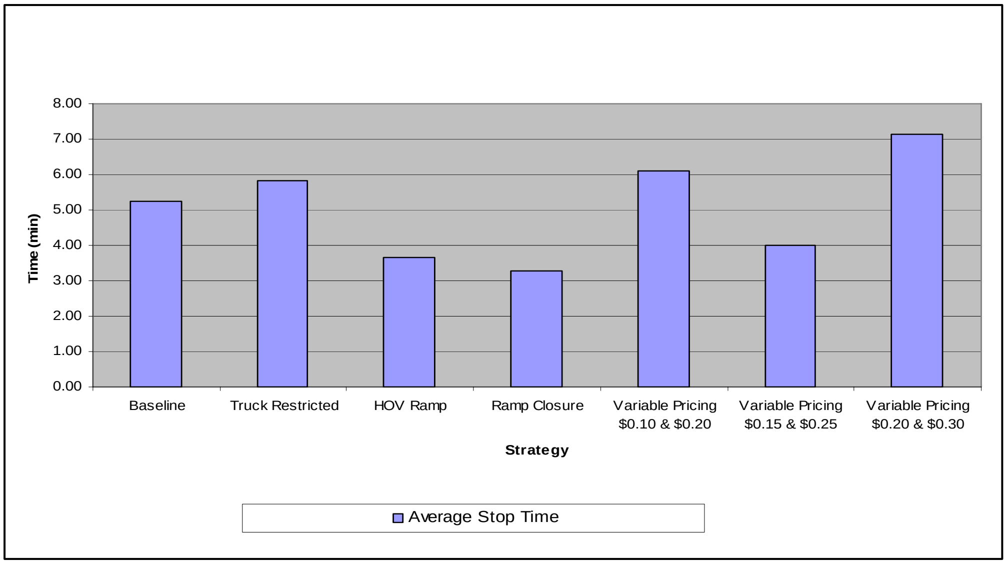


Figure 18. Comparative Analysis of Average Stop Time – Incident Management.

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 the 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. Speed on freeway mainlanes adjacent to exit ramps 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 19.

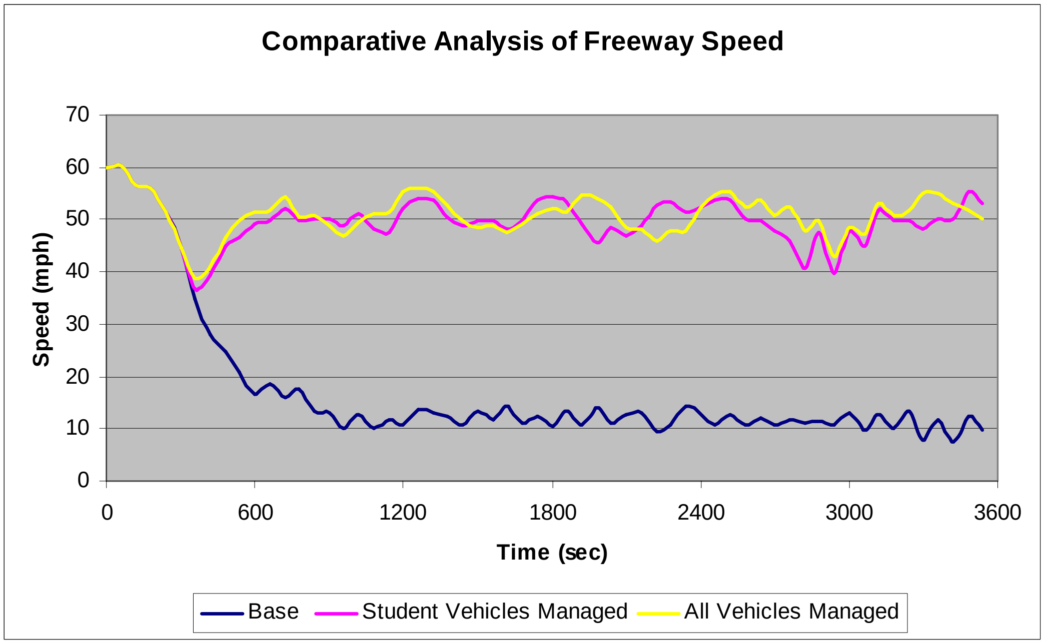


Figure 19. Comparative Analysis of Freeway Speed-Special Event Management.

If ramp storage from the stop bar at a terminal intersection is approximately 900 feet 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 20.

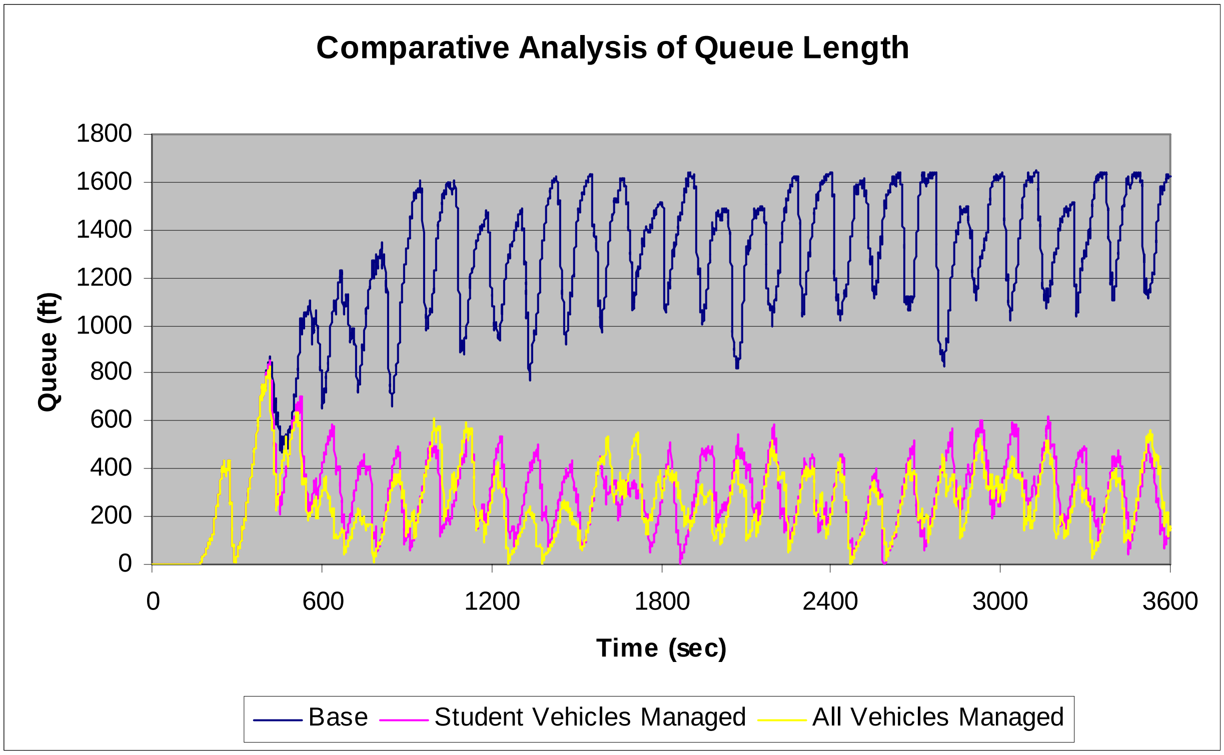


Figure 20. Comparative Analysis of Queue Length-Special Event Management.

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.

CHAPTER 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 (*13*).

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 (*14*). 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 (*15*). Figure 21 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 (*16*), from which Figure 22 is extracted. Figure 21 and Figure 22 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.

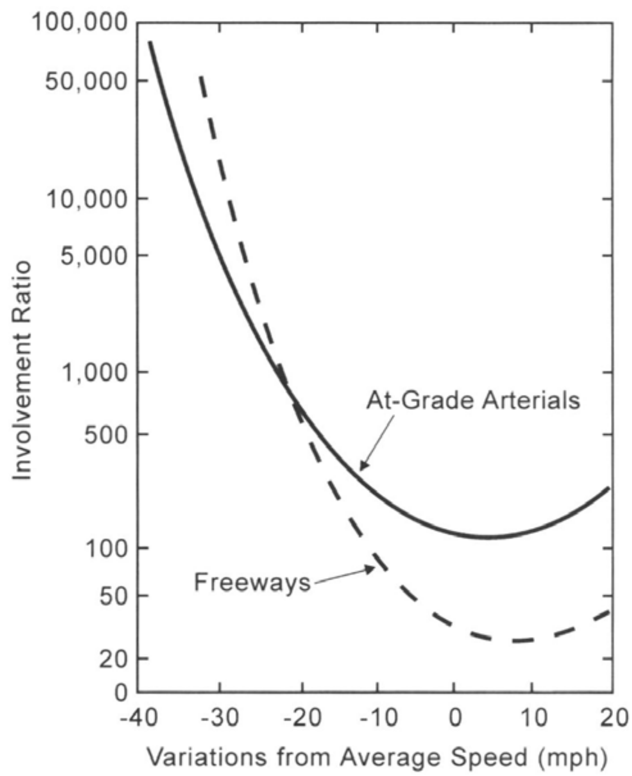


Figure 21. Crash Rate as a Function of Speed Differential (Adapted from *15*).

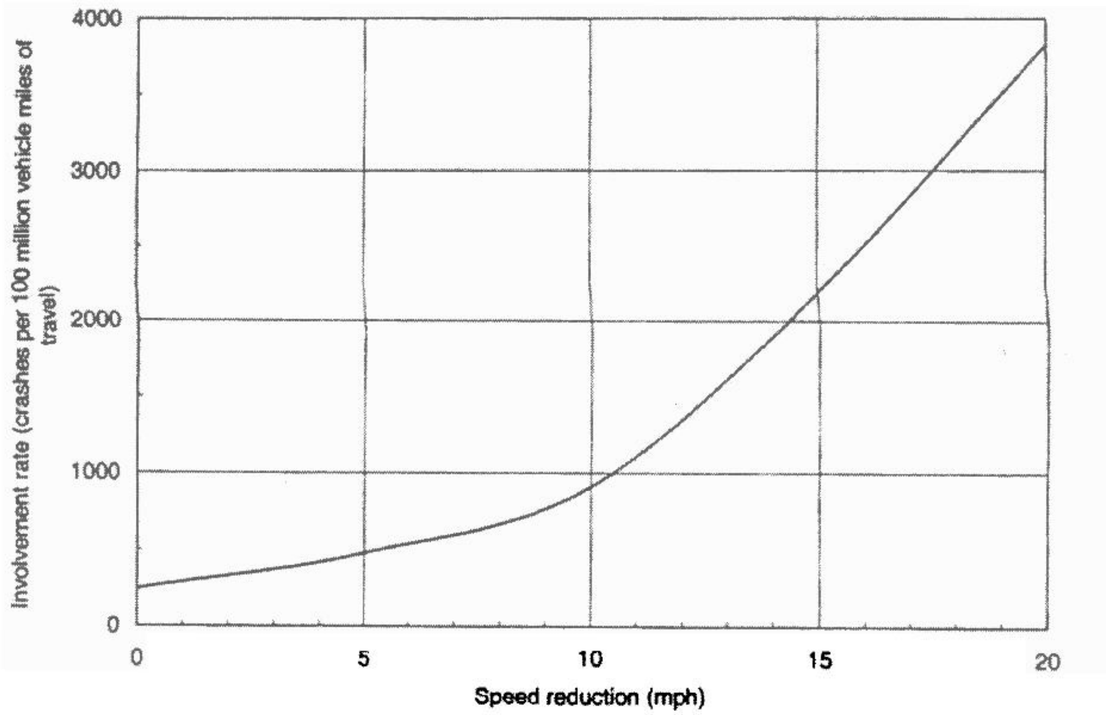


Figure 22. Crash Involvement Rate of Trucks for Which Running Speeds Are Reduced Below Average Running Speed of All Traffic (*16*).

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 23 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 24 illustrates the ramp merge condition where an acceleration lane is provided. Figure 25 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.

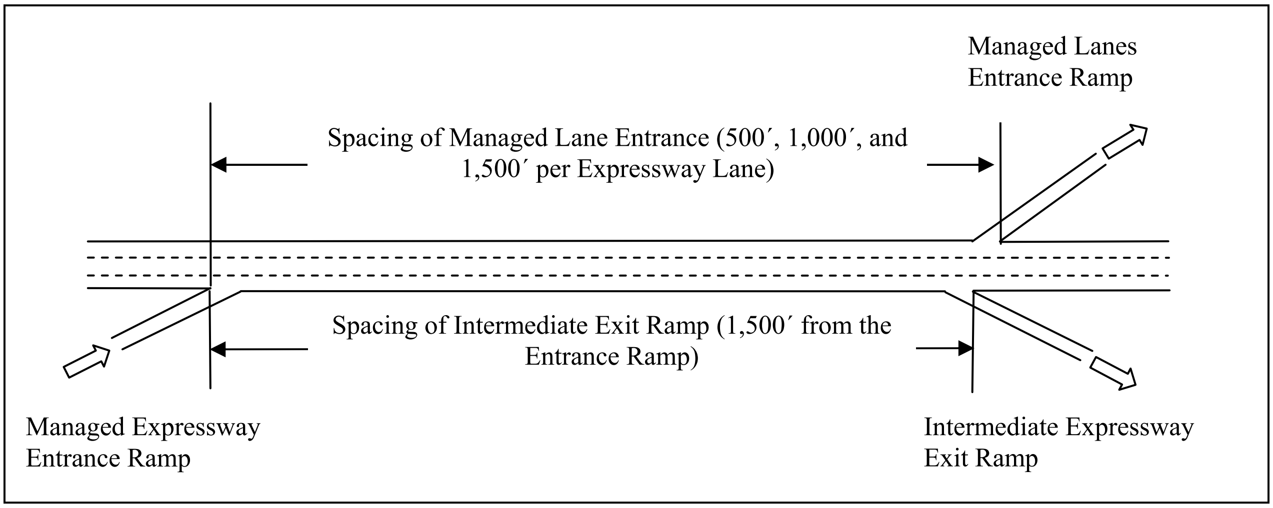


Figure 23. Expressway with Forced Merge Ramp (with Intermediate Ramp).

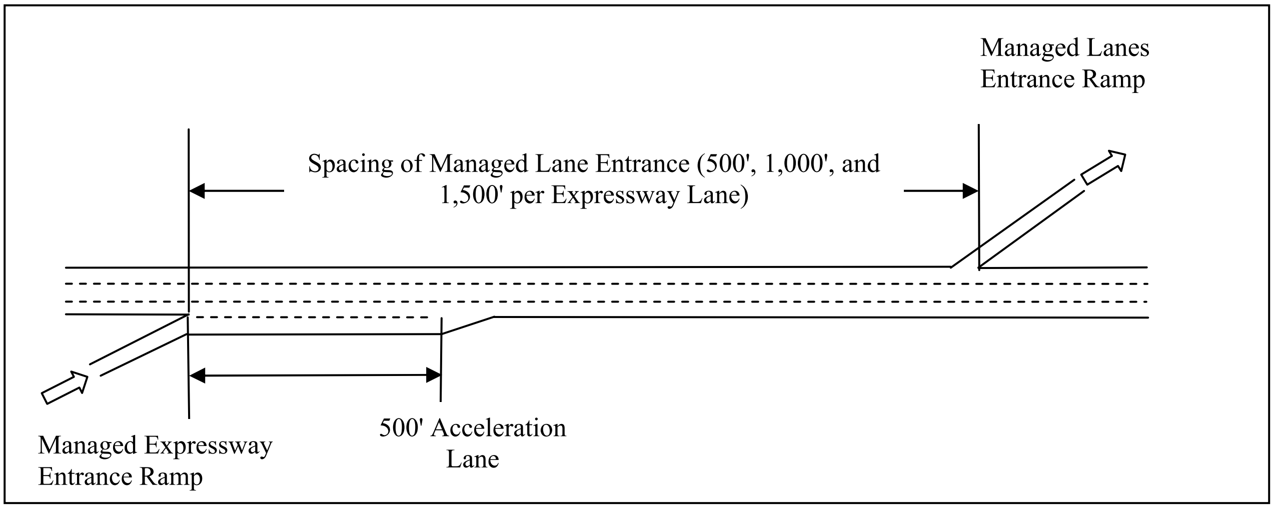


Figure 24. Expressway with Acceleration Lane Ramp Merge (without Intermediate Ramp).

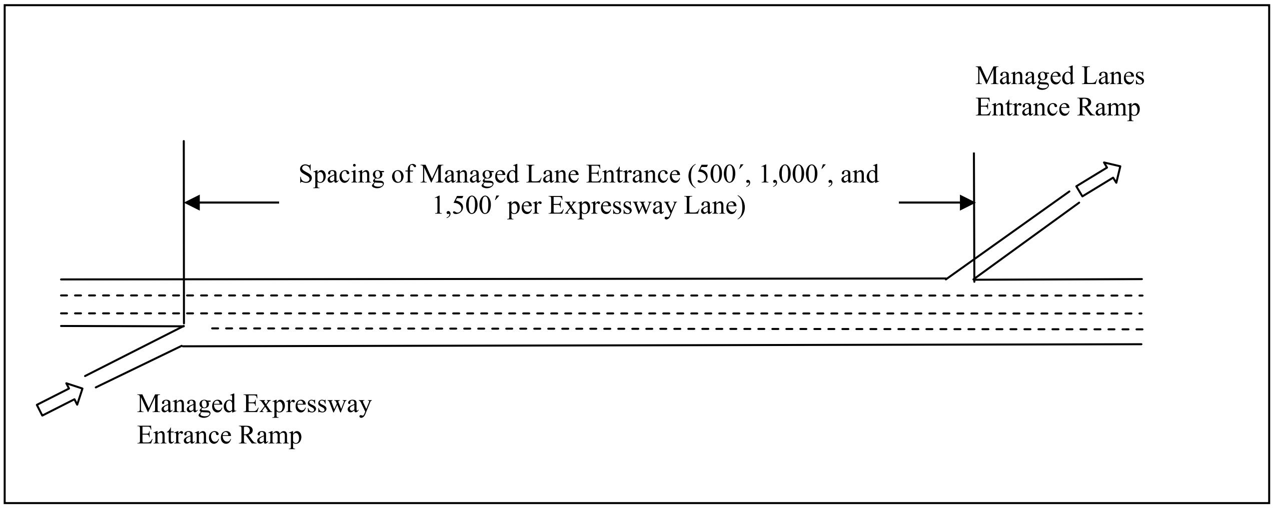


Figure 25. Expressway with Full Auxiliary Lane Ramp Merge (without Intermediate Ramp).

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 26 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.

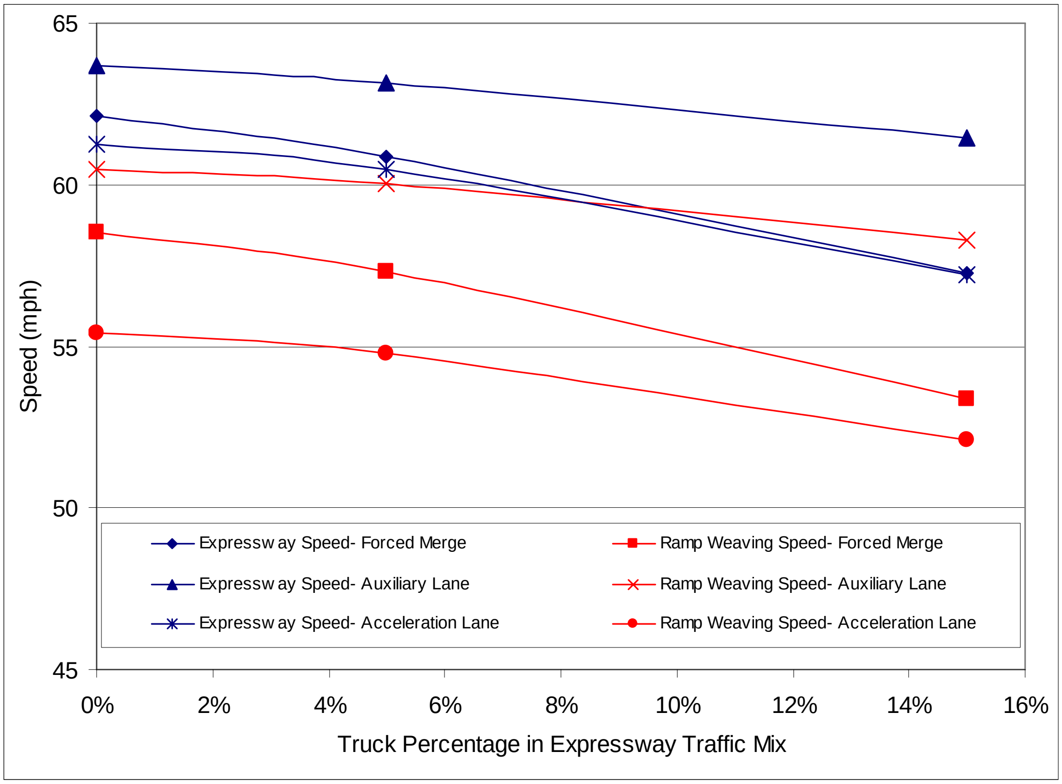


Figure 26. Expressway and Ramp Weaving Speeds with Different Expressway Truck Mixes.

Space between Managed Ramp to Managed Lanes Access Point

Different ramp spacings of 500 feet, 1000 feet and 1500 feet per expressway lane also impact the operations of the freeway when managing ramps for managed lanes facility preference. Figure 27 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 28. Ramp weaving speeds also increase with an increase in spacing entry ramp to expressway and entry ramp to the managed lane.

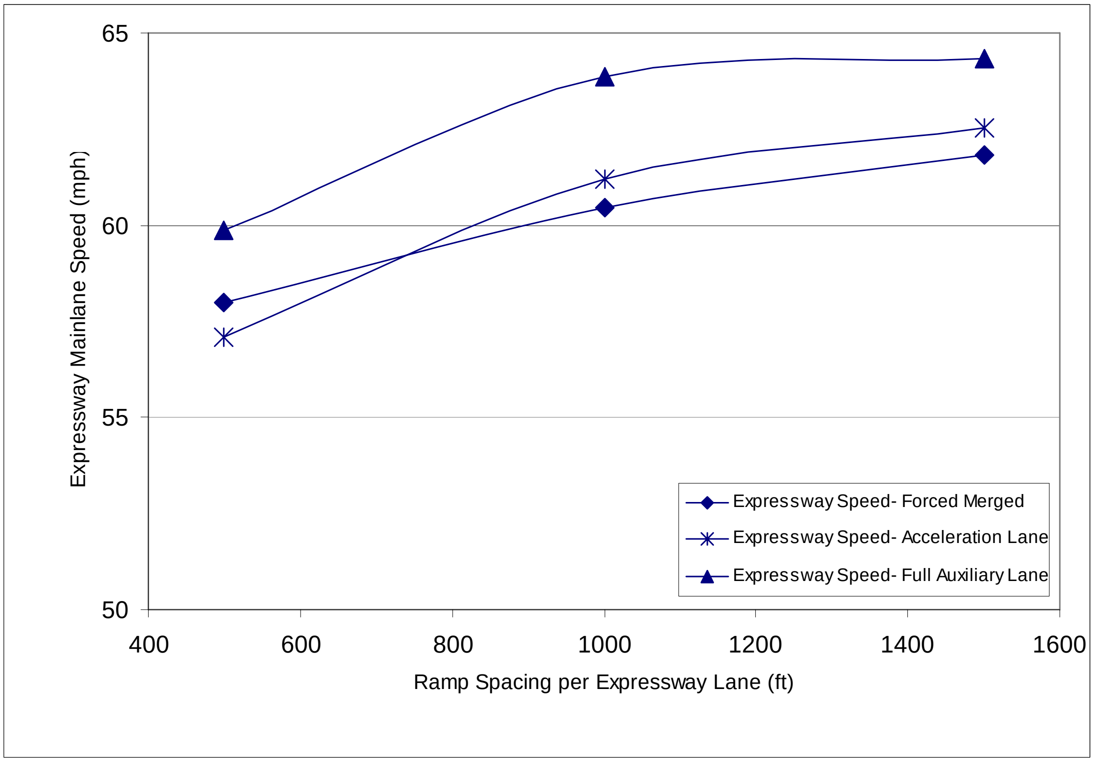


Figure 27. Expressway Mainlane Speeds with Different Ramp Conditions and Ramp Spacing.

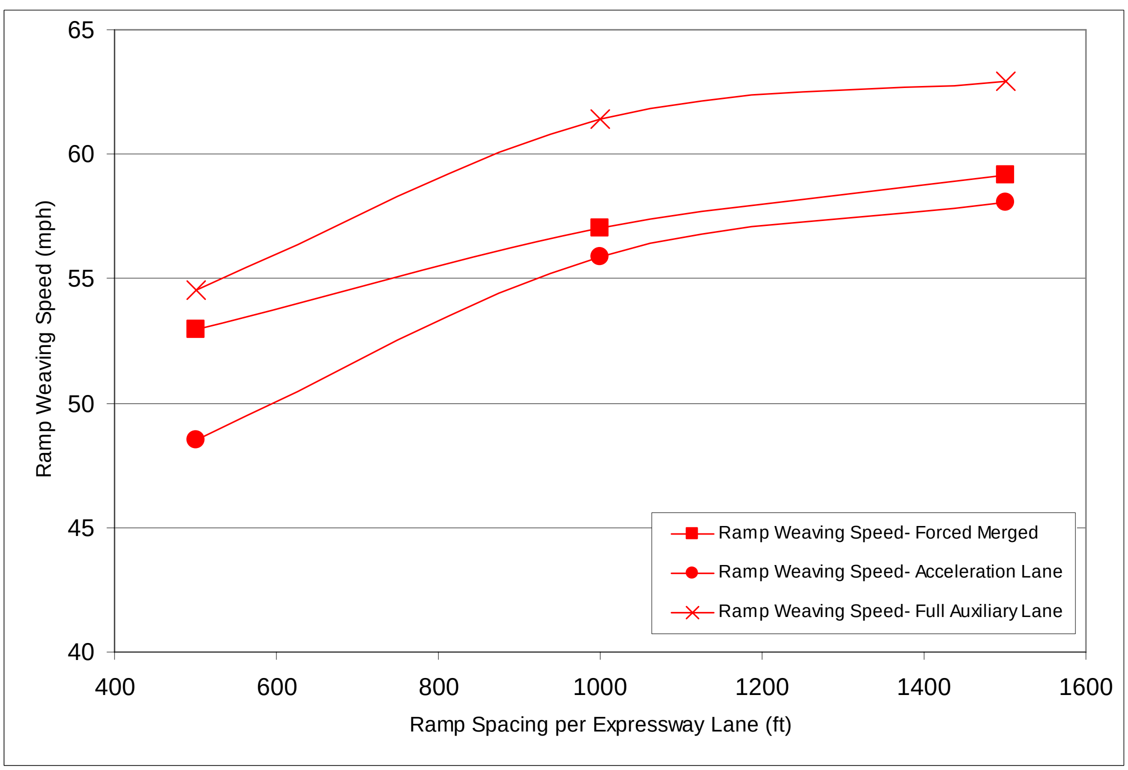


Figure 28. Ramp Weaving Speeds with Different Ramp Conditions and Ramp Spacing.

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; 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 29 and Figure 30, respectively.

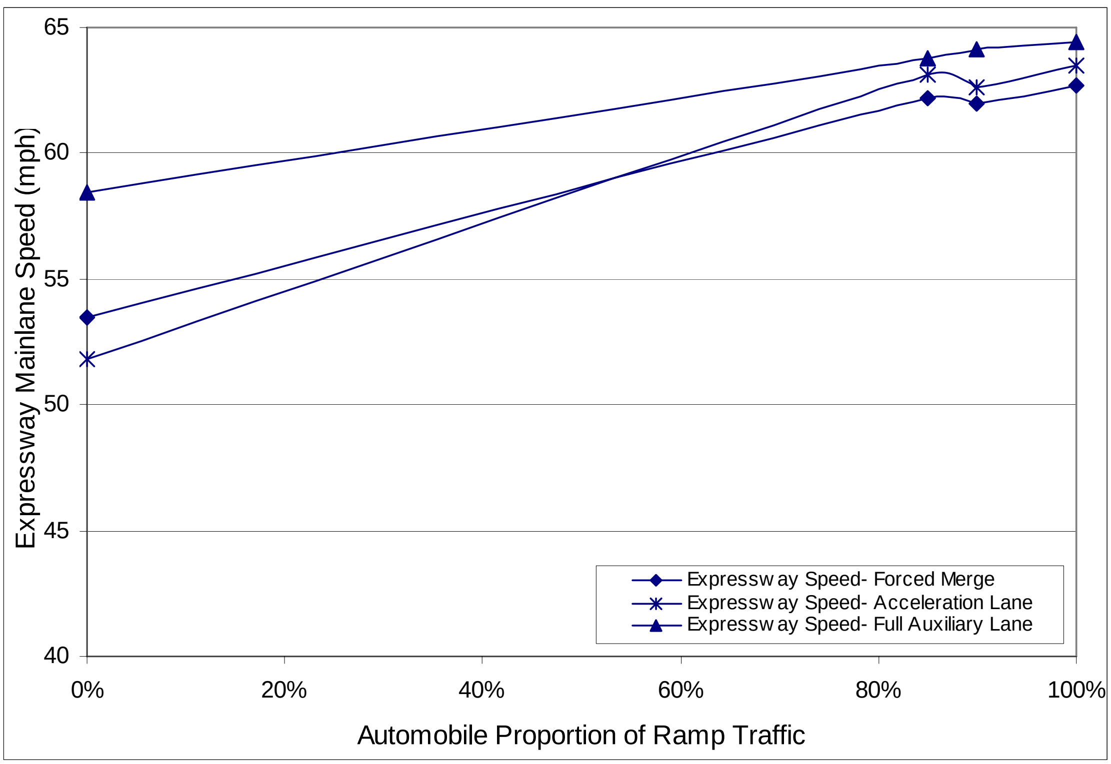


Figure 29. Expressway Mainlane Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

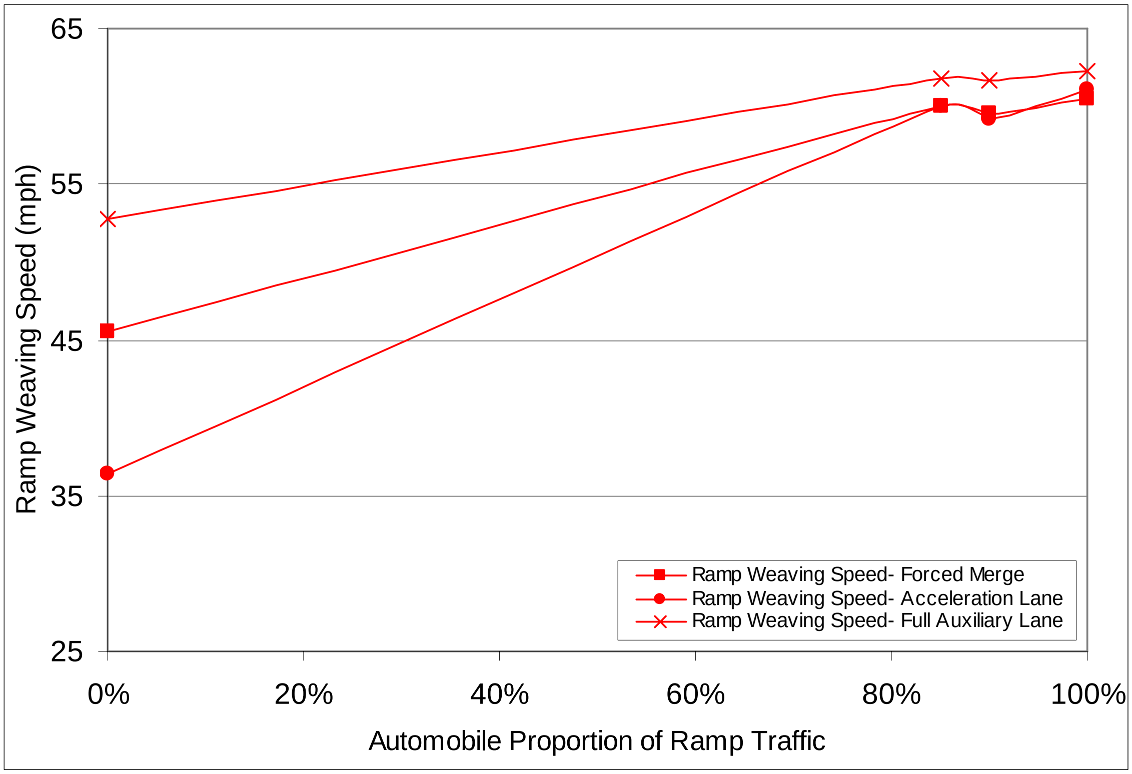


Figure 30. Ramp Weaving Speeds for Varying Ramp Automobile Proportions and Merge Conditions.

Figure 31 and Figure 32 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 the traffic mix reaches zero, e.g., 100 percent automobiles on the ramp.

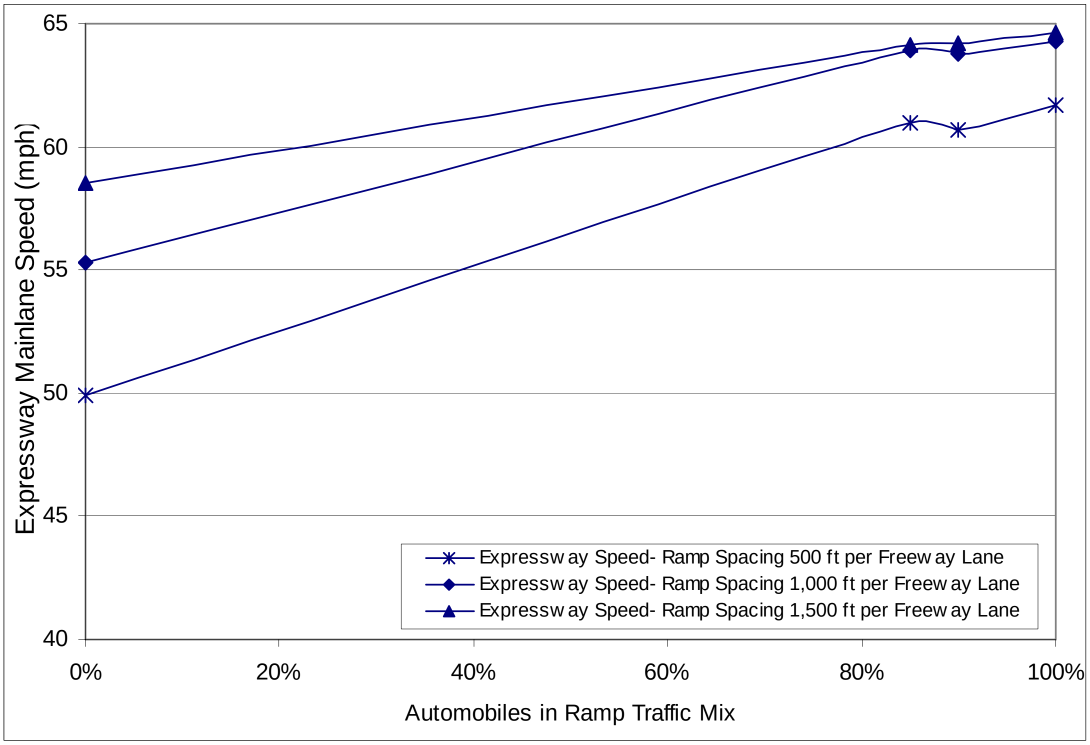


Figure 31. Expressway Mainlane Speeds with Varying Automobile Proportions and Ramp Spacing.

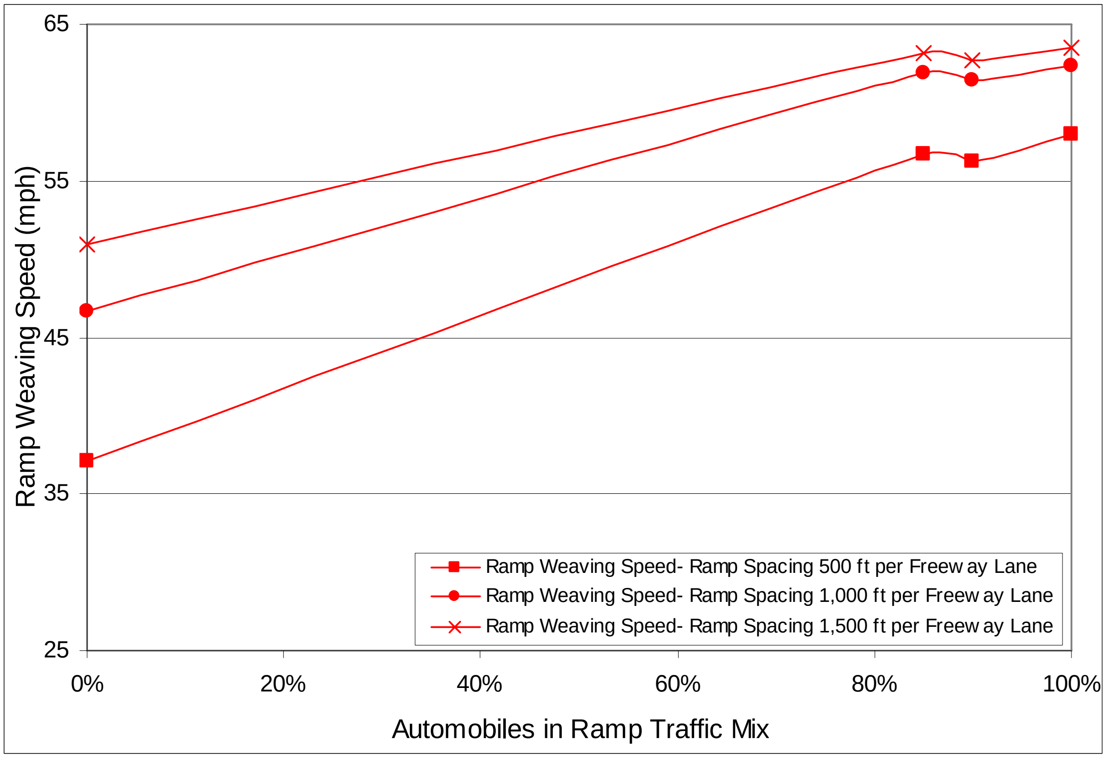


Figure 32. Ramp Weaving Speeds with Varying Automobile Proportions and Ramp Spacing.

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 33 shows both expressway mainlane and ramp weaving speeds with different ramp merge conditions and expressway flow levels.

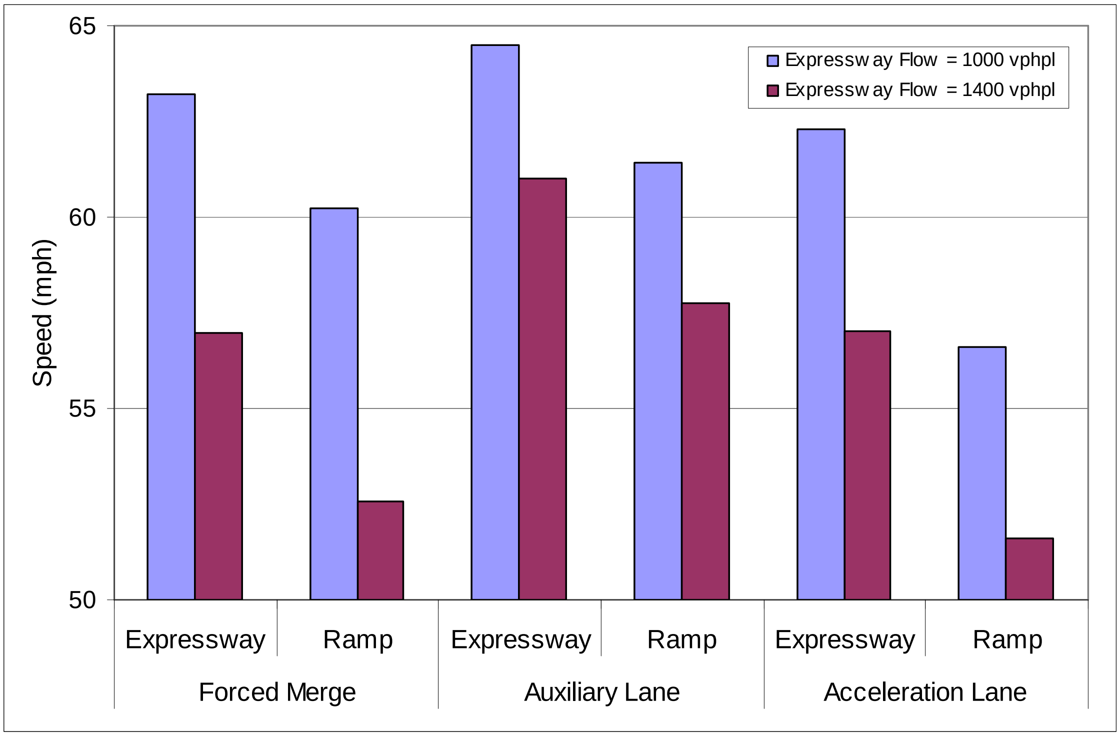


Figure 33. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Expressway Flow Levels.

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 34 illustrates expressway mainlane and ramp weaving speeds with and without the intermediate ramp and across different ramp merge conditions.

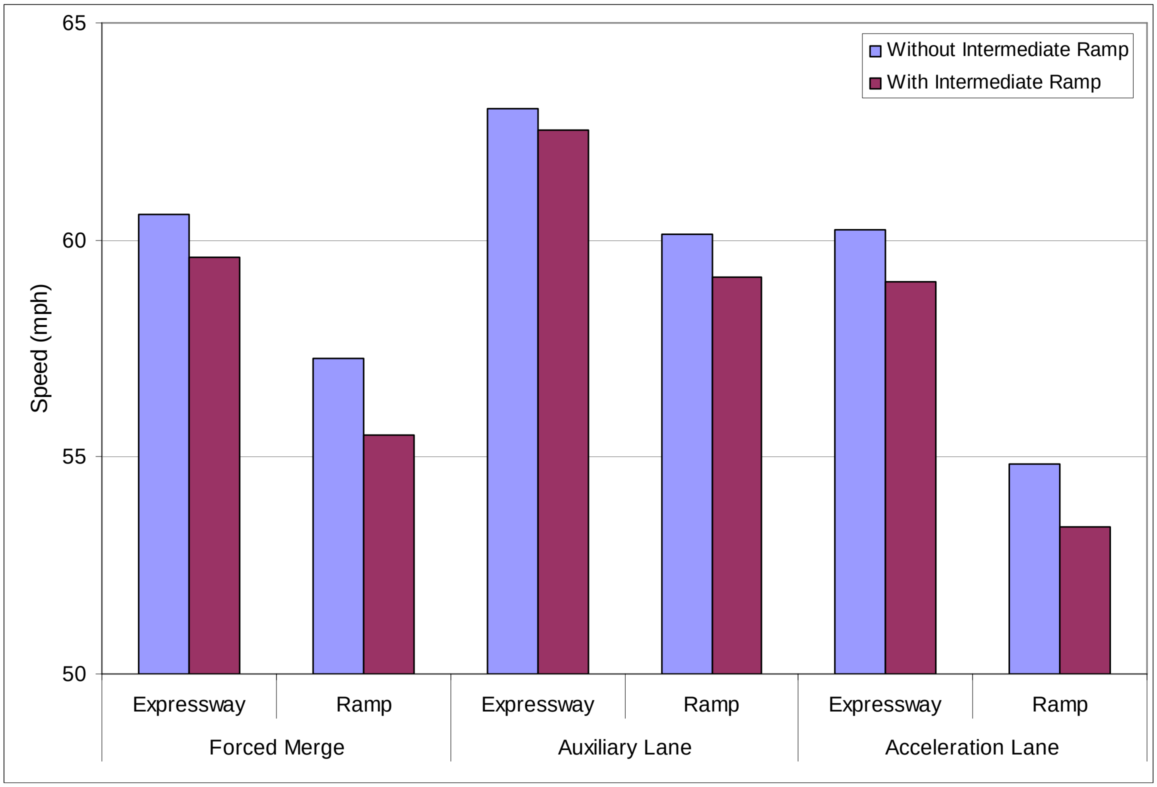


Figure 34. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Intermediate Ramp Scenarios.

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 35 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 36 illustrates the significance of the weaving traffic proportion on expressway mainlane and ramp weaving speeds and which organizes results by managed ramp merge condition.

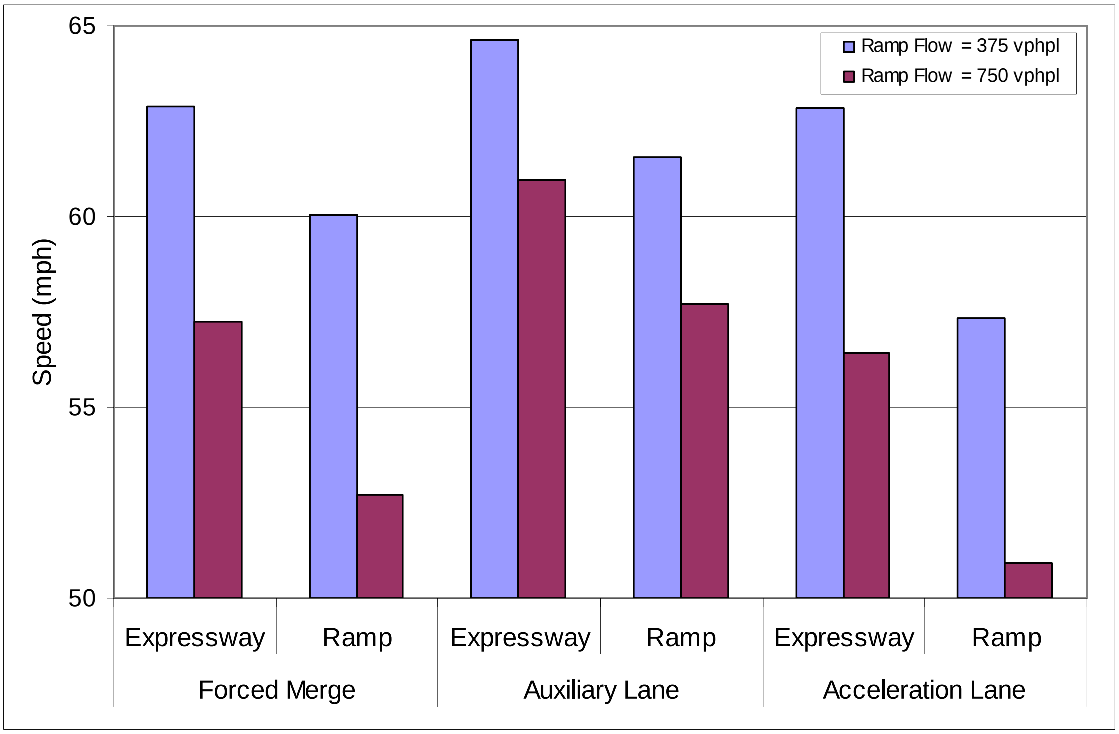


Figure 35. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Ramp Flow Levels.

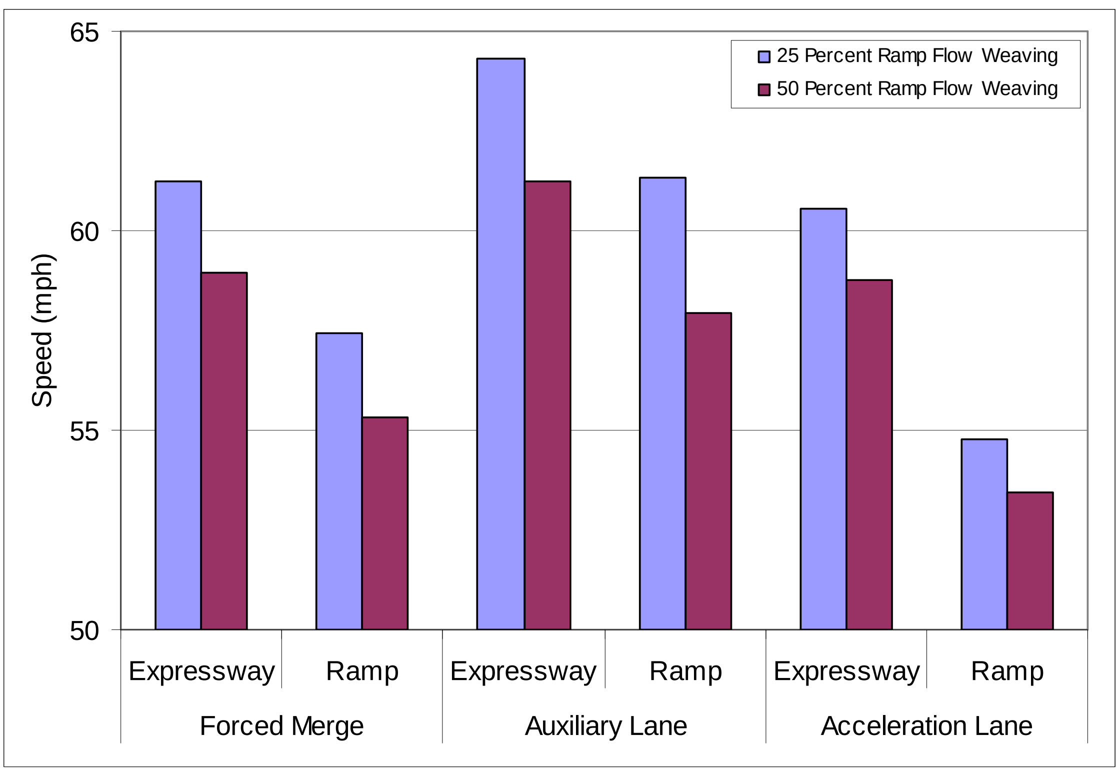


Figure 36. Expressway Mainlane and Ramp Weaving Speeds with Different Ramp Merge Conditions and Proportions of Ramp Traffic Weaving to the Managed Lane.

CHAPTER 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 feet 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 (*14*). Previous research has shown that large fluctuations in speed greatly increase the potential for crashes (*15*). 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 60-62 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 1ft/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 amount of 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 53-60 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 37. This lane also has the highest increase in speed of 21 percent when compared to all other scenarios, as shown in Figure 38.

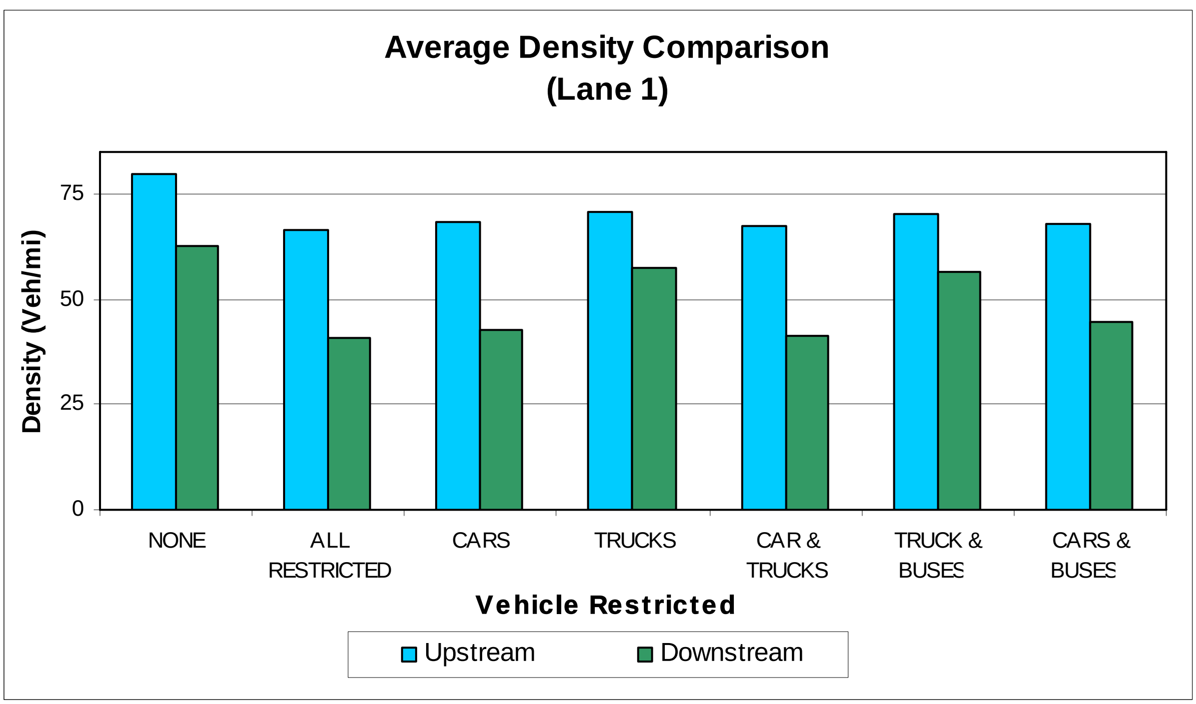


Figure 37. Average Density Comparison for Lane 1- Upstream and Downstream.

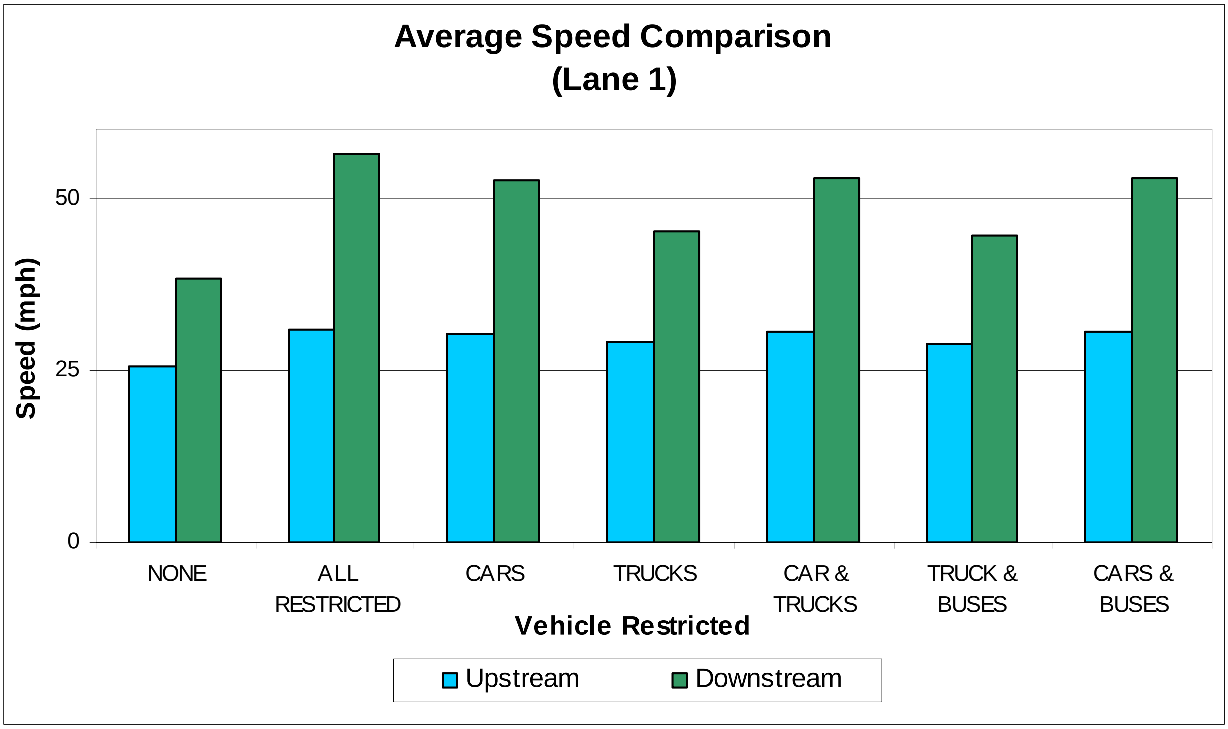


Figure 38. Average Speed Comparison for Lane 1- Upstream and Downstream.

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 in the far right lane by 35 percent when compared to "do nothing," as shown in Figure 37. Speed also increased significantly on the far right lane as Figure 38 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 39 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.

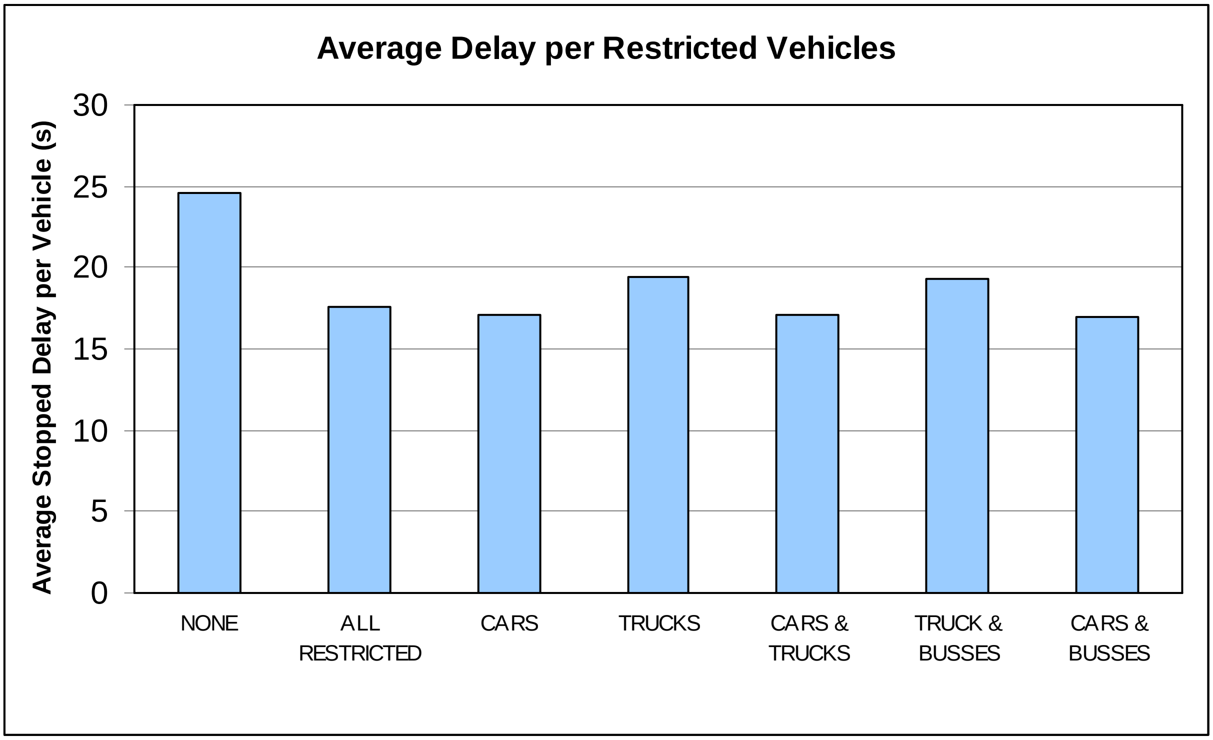


Figure 39. Average Stopped Delay per Vehicle in Seconds.

CHAPTER 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 (*17*). 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 (*17*).

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 40 illustrates the types of managed ramps-centered knowledge a driver needs and how it varies by familiarity with a facility.

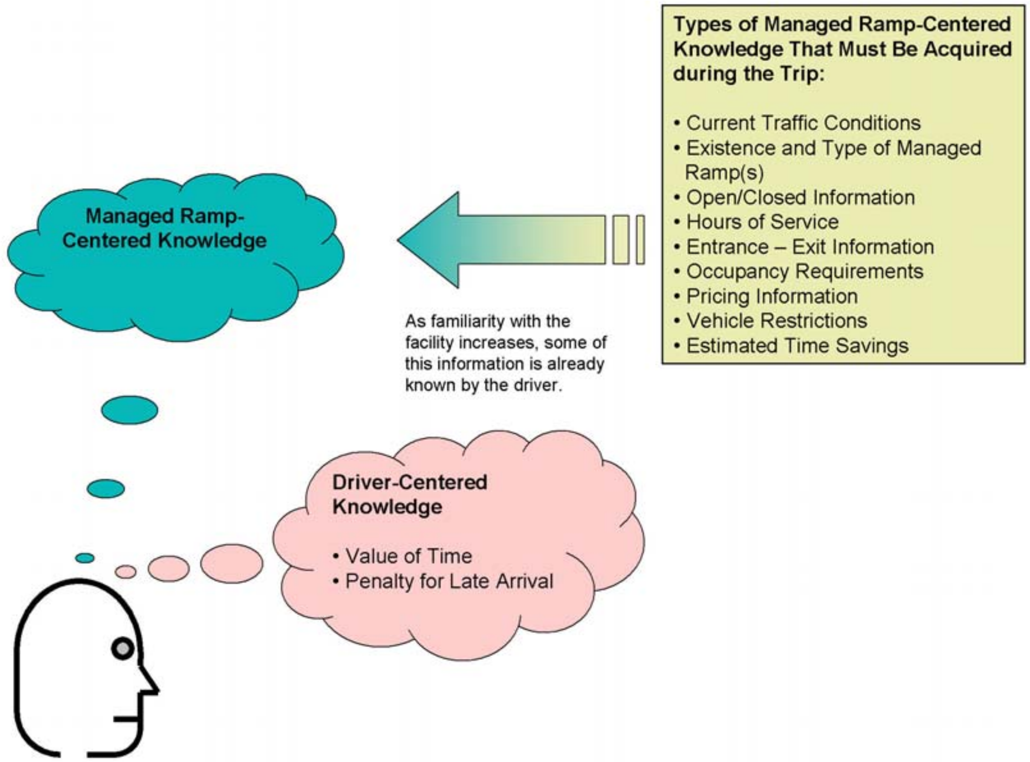


Figure 40. Driver Information Needs (Adapted from *18*).

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 (*19*). 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 (*19*). 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 (*20*). 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 (*21*).

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 (*22*). 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 (*22*). Development of enforcement policies and programs ensures that all appropriate agencies are involved in the process and have a common understanding of the project and the need for enforcement (*20*). 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 (*20*). 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 (*23*). 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 (*24*).

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 (*25*).

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 (*26*).

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 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, and revenue collection. 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 (*27*).

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 (*27*). 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.

REFERENCES

1. *2002 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance Report to Congress.* U.S. Department of Transportation, Washington, D.C., 2002.

2. *National Transportation Statistics 2002.* Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, D.C., 2002.

3. Schrank, D., and T. Lomax. *The 2004 Urban Mobility Report*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2004.

4. Kuhn, B., G. Goodin, A. Ballard, R. Brydia, S. Chrysler, T. Collier, S. Cothron, W. Eisele, D. Fenno, K. Fitzpatrick, S. Song, G. Ullman, and S. Venglar. *Year 4 Annual Report of Progress: Operating Freeways with Managed Lanes.* Report No. FHWA/TX-05/0-4160-19, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2004.

5. Collier, T., and G. Goodin. *Managed Lanes: A Cross-Cutting Study*. Report No. FHWA-OP-04-001, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2004.

6. Piotrowicz, G., and J.R. Robinson. *Ramp Metering Status in North America*. Report DOT-T-95-17, FHWA, U.S. Department of Transportation, Washington, D.C., 1995.

7. Centrico, *Ramp Metering Synthesis*, Centrico supported by The European Commission DG-TREN-TEN-T, December 2001.

8. *Design Manual,* Design Office, Washington DOT, November 1999.

9. *High Occupancy Vehicle Bypass Lanes, Location Analysis Report.* Arizona DOT. Prepared by Kimley Horn, July 1991.

10. Goodin, G., and G. Fisher. *Decision Framework for Selection of Managed Lanes Strategies*. FHWA/TX-05/0-4160-21, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2005.

11. Jacobson, L., J. Stribiak, L. Nelson, and D. Sallman. *Ramp Management and Control Handbook* Report No. FHWA-HOP-06-001. P.B. Farradyne, Rockville, MD, 2006.

12. Shelton, J. *A Dynamic Modeling Approach For Applying Managed Lane Strategies to Freeway Ramps,* in Civil Engineering, 2007. The University of Texas at El Paso, El Paso, TX, p. 74.

13. Middleton, M., S. Venglar, C. Quiroga, D. Lord, and D. Jasek. *Strategies for Separating Trucks for Passenger Vehicles: Final Report.* Research Report No. FHWA/TX-07/0-4663-2, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2006.

14. Kuhn, B.V., A. Goodin, M. Ballard, R. Brewer, J. Brydia, S. Carson, T. Chrysler, K. Collier, K. Fitzpatrick, D. Jasek, C. Dusza, and G. Ullman. *Managed Lanes Handbook*. Research Report No. FHWA/TX-06/0-4160-24, Texas Transportation Institute, The Texas A&M University System, College Station, TX, October 2005.

15. Stover, V., and K. Koepke. *Transportation and Land Development, 2nd Edition*. Institute of Transportation Engineers, Washington, D.C., 2002.

16. *A Policy on Geometric Design of Highways and Streets, 5th Edition*. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2004.

17. Task Force for Public Transportation Facilities Design of the AASHTO Subcommittee on Design. *Guide for High Occupancy Vehicle (HOV) Facilities.* American Association of State Highway and Transportation Officials, Washington, D.C., 2004.

18. Schrock, S., G. Ullman, A. Williams, and S. Chrysler. *Identification of Traveler Information and Decision-Making Needs for Managed Lanes Users*. Research Report No. FHWA/TX-04/0-4160-13, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 2004.

19. Chrysler, S., A. William, S. Schrock, and G. Ullman. *Traffic Control Devices for Managed Lanes*. Research Report No. FHWA/TX-04/4160-16, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2004.

20. Cothron, S., S. Skowronek, and B. Kuhn. *Enforcement Issues on Managed Lanes*. Research Report No. FHWA/TX-03/4160-11, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2003.

21. Goodin, G., C. Swenson, J. Wikander, and B. Palchik. *Managed Lanes Operations: Strategies for Enforcing Carpool Preference on Priced Facilities.* 84th Annual Meeting Compendium of Papers CD-ROM, Transportation Research Board, Washington, D.C., 2005.

22. Wikander, J., and G. Goodin. *High-Occupancy Vehicle (HOV) Lane Enforcement Considerations Handbook*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., to be published.

23. Cairns, S., J. Greig, and M. Wachs. "Environmental Justice & Transportation: A Citizen's Handbook" (January 1, 2003). Institute of Transportation Studies. Research Reports. Working Paper ejthandbook found at Institute of Transportation Studies web site: http://repositories.cdlib.org/its/reports/ejthandbook. Accessed February 2005.

24. Atlanta Regional Commission. Transportation Solutions for a New Century, Adopted October 23, 2002. Atlanta Regional Commission web site: http://www.atlantaregional.com. Accessed February 2005.

25. *Environmental Justice*, U.S. Environmental Protection Agency Website: http://www.epa.gov/compliance/environmentaljustice/. Accessed February 2005.

26. Neudorff, Louis G., Jeffrey E. Randall, Robert Reiss, and Robert Gordon. *Freeway Management and Operations Handbook*. FHWA-OP-04-0003. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2003.

27. Brydia, R., and S. Song. *Interoperability Issues on Managed Lanes Facilities.* Research Report No. FHWA/TX-05/0-4160-18, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2004.