NCHRP

REPORT 687

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Guidelines for Ramp and Interchange Spacing

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Guidelines for Ramp and Interchange Spacing

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher Hedges
Staff Officer
Transportation Research Board

This report provides guidelines for ramp and interchange spacing based on design, operations, safety, and signing considerations. The guidelines will be valuable to transportation agencies who need to balance system efficiency and safety with the need to provide access for local users. The guidelines are intended to aid the decision-making process when an agency is considering new ramps or interchanges on existing facilities, modifying ramps and interchanges of existing facilities, or when planning and designing new highway and interchange facilities. The guidelines also offer standardized definitions measuring ramp and interchange spacing, which have varied in previous design manuals guides.

Interchanges are essential components of freeways for providing reasonable access and mobility. However, interchanges can greatly diminish the traffic operations, safety, and capacity of the through lanes of the freeway. Transportation agencies are tasked with constructing new freeways with interchanges, reconstructing existing freeways and interchanges, and adding interchanges to existing freeways.

The AASHTO *Policy on Geometric Design of Highways and Streets* contains guidelines on the distance between successive ramp terminals. On urban freeways and other facilities that carry large traffic volumes, two or more ramp terminals are often located in close succession. To provide adequate space for signing, adequate gaps for entering motorists, and sufficient weaving lengths, the AASHTO policy provides minimum ramp terminal spacing dimensions for various ramp pair combinations. Spacing between successive ramp terminals depends on the classification of the interchanges involved, the function of the ramp pair (entrance vs. exit), and the potential for weaving. The guidelines provided in the AASHTO policy are acknowledged to be based on operational experience and recommend basing actual spacing on operations and safety procedures derived from applied research.

Although the location and spacing of interchanges and ramps on freeways has a major effect on the ability of a freeway to carry traffic effectively, this is a topic for which little research or literature has been published. Recent research indicates that a majority of freeway accidents occur at interchanges and in weaving sections between closely spaced entrance and exit ramps. The spacing of interchanges on an urban road network can also result in tradeoffs between providing adequate service and access with both safety and operations. As a result, making sound decisions requires a clear understanding of the impacts of ramp and interchange spacing on safety and operations.

Under NCHRP Project 03-88, "Guidelines for Ramp and Interchange Spacing," a research team led by Kittelson & Associates, Inc., evaluated and summarized design, operations, safety, and signing considerations that influence ramp and interchange spacing decisions. The team conducted simulation modeling, calibrated with field data, of closely-spaced pairs of ramps and developed safety performance models. The team then developed guidelines to assist practitioners in selecting ramp and interchange spacing values for their particular design context. The selection criteria include geometric design needs, operational performance, signing needs, and safety performance. The results will also provide information that can also be incorporated in future editions or updates of relevant AASHTO manuals, including the *Policy on Geometric Design,* the *Highway Capacity Manual*, the *Manual on Uniform Traffic Control Devices,* and the *Highway Safety Manual*. A final report documenting the full research effort will be posted on the TRB website as *NCHRP Web-Only Document 169* and can be found at http://www.trb.org/Main/Blurbs/164815.aspx.

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Preface

Freeway facilities are intended to provide a high level of mobility and allow drivers to travel safety and efficiently. Freeways are characterized by limited access, with all connections to adjacent roads and land provided with ramps and interchanges. These ramps and interchanges are known to impact freeway performance, especially if placed too close to one another. Planners, designers, and operators of freeways must strike a balance between preserving the mobility of facility and providing access for local users. These Guidelines provide users with aids and tools to consider and evaluate potential impacts of ramp spacing, as well as information on many factors that influence ramp and interchange spacing needs.

Under NCHRP Project 03-88, the research team conducted operational and safety assessments of two types of ramp pairs—an entry ramp followed by an exit ramp (EN-EX) and an entry ramp followed by another entry ramp (EN-EN). Future research results may allow similar assessments of other ramp combinations. Furthermore, NCHRP 03-88 research was focused on relatively simple, single lane, service ramps and interchanges. Additional research may be valuable to address larger, more complex designs such as multi-lane ramps and system interchanges. Until future research is completed the principles and fundamental approach suggested in these Guidelines should be applicable in considering those ramp and interchange spacing needs.

These Guidelines present substantial discussions on geometric design, traffic operations, safety, and signing, and the role each of these play in determining ramp and interchange spacing needs. The Guidelines define "ramp spacing" and "interchange spacing" and recommend ramp spacing values be the primary consideration in freeway and interchange planning and design. Geometric design principles, as well as site-specific features, dictate minimum lengths needed for ramps and other interchange components. Traffic volumes can necessitate increased spacing beyond the dimensions needed purely for geometrics. Safety tradeoffs, which have rarely been quantified until recently, can now be considered in project decision making. Finally, signing and other human factors considerations should be taken into account at the earliest in the evaluation process when making choices about ramp and interchange spacing.

The transportation profession is beginning to move away from rigid design criteria towards performance-based metrics that allow flexibility in design while still meeting the needs of system users. The prominence of safety effects of design choices is increasing within the profession as evidenced by the publication of the first addition of the Highway Safety Manual. Both of these trends are reflected in the Guidelines. The Guidelines present ranges of minimum recommended spacing dimensions for various conditions rather than single "one-size-fits-all" dimensions. Additionally, the Guidelines advocate for quantifiable safety analysis on par with operational analysis and evaluations.

Summary

NCHRP Report 687: Guidelines for Ramp and Interchange Spacing assists roadway planners and designers as they consider the feasibility of new or rebuilt interchanges and ramps. The Guidelines are not intended to set ramp and interchange spacing standards. Rather, they are informational and present a process for assessing spacing within the context of each design environment.

These Guidelines were produced as part of NCHRP Project 03-88, which studied the relationship between ramp and interchange spacing and geometric design, traffic operations, safety, and signing. These Guidelines define interchange spacing as the distance between the centerlines of successive crossroads with interchanges on a freeway. Ramp spacing is defined as the distance between the painted tips of successive ramps. The Guidelines were developed primarily for ramps and interchanges on fully controlled access freeways but could also be applied on ramp and interchanges on partially controlled access highways.

Prior to NCHRP Project 3-88, little research focused on ramp and interchange spacing had been conducted in recent decades. Rules of thumb such as one mile minimum interchange spacing in urban areas and two mile minimum interchange spacing in rural areas date from the early days of the Interstate Highway System. The minimum recommended ramp spacing values in the AASHTO's *Policy on Geometric Design of Highways and Streets* (Green Book) stem from publications that date from the 1970s.

Research conducted as part of NCHRP Project 3-88 was primarily focused on two areas. Operations research investigated the impact of ramp spacing on freeway speed. Safety research investigated the impact of ramp spacing on crash frequency and severity. Due to the wide variety of interchange forms and ramp designs, these Guidelines emphasize the importance of ramp spacing versus interchange spacing.

The Guidelines contain substantial background information related to freeway and interchange geometric design, traffic operations, safety, and signing. The information is drawn from major resource documents such as the AASHTO Green Book, *Highway Capacity Manual, Manual on Uniform Traffic Control Devices, Highway Safety Manual,* and *ITE Freeway and Interchange Geometric Design Handbook*; other past studies; and research conducted as part of NCHRP Project 03-88. The Guidelines present a framework for evaluating ramp and interchange spacing, and provide insights into the factors that influence minimum ramp and interchange spacing dimensions for various interchange forms and ramp combinations.

Chapter 1 introduces the purpose, scope, and applicability of the Guidelines. Chapter 2 presents policy considerations, Chapter 3 presents geometric

design and signing considerations, and Chapter 4 presents traffic operations and safety considerations. Chapter 5 provides users with a framework for evaluating the adequacy of ramp and interchange configurations with regard to spacing and includes insights into factors that influence minimum dimensions. Appendix A provides five case studies to illustrate and apply the framework and considerations from Chapter 5. Appendix B provides additional traffic operations data from NCHRP Project 03-88 that addresses scenarios not directly addressed by the *Highway Capacity Manual*. The data quantifies the impact of ramp spacing on freeway speed and the benefit (speed increase) associated with adding an auxiliary lane between a closely spaced entrance-exit ramp pair.

Chapter 1 Introduction

1.1 RAMP AND INTERCHANGE SPACING DEFINITIONS

The terms "ramp" spacing and "interchange" spacing are sometimes used interchangeably when, in fact, they differ considerably. Ramp and interchange spacing dimensions are the result of completely different measurements. When applied to ramp and interchange configuration design concepts and considering traffic operations, safety, and signing there is relatively little correlation between "ramp" and "interchange" spacing.

Interchanges and their historic rule-of-thumb "one-mile" spacing in urban areas are ultimately a byproduct of the traditional spacing of urban street networks. The networks and their grid vary, but it is relatively common to have major streets and roadways set upon a one-mile grid, with minor streets placed uniformly at values of 8 to 10 streets per mile. During the early days of freeway and interchange planning, the one-mile spacing in urban areas was a result of balancing total system travel demand. In major cities, early traffic models and studies showed that interchanges placed one mile apart balanced traffic flow on the arterials. Spacing values greater than one mile resulted in overly congested conditions on those arterials that interchanged with the freeway (*1, 2, 3*).

Ramp spacing values are primarily a byproduct of individual ramp operational and design requirements and elements. The ramp spacing dimensions between interchanges are fundamentally what remains after combining the individual ramp components from a cross street to the freeway mainline (in the case of an onramp) or the freeway mainline to the cross street (in the case of an offramp). Properly designed ramp elements account for: three-dimensional roadway design needs; appropriate horizontal alignment that facilitates appropriate speed change; appropriate vertical alignment that provides roadway profiles that facilitate grade changes and sight distance needs; and cross-section design considerations that reflect cut and fill slopes or retained earth construction costs within the ramp footprint.

Operational considerations of an onramp include providing appropriate speed-change characteristics between interchanging facilities or the need to meet operational demand. For example, a cross-street double left turn feeding a diamond interchange onramp requires two receiving lanes for some distance before a lane is dropped at an appropriate rate to create a single-lane entry. On exit ramps, the ramp length should adequately serve the anticipated queue storage at the ramp terminal intersection and provide adequate sight distance and deceleration lengths to the back of that queue. The exit ramp should have sufficient tangent length or transition curve beyond the physical gore to meet deceleration requirements for the controlling curve just as the entrance ramp should have sufficient tangent length (or transition curve) to facilitate acceleration after the controlling entry curve.

Design configurations based on capacity and operational needs are the largest single determinant of ramp length.

The appropriate consideration of design and operational details has a great influence on the driving characteristics and performance of the ramps. Ramp design, in turn, directly influences ramp spacing values. These spacing values influence mainline operations and safety and solidify the need for an integrated and dynamic approach for developing ramp and interchange configurations and resultant spacing values.

Attaining ramp characteristics appropriate for a given project context helps establish the ramp terminal locations on the highway and, therefore, the spacing values between ramps. Considering sign placement and attaining appropriate stopping and decision sight distances can influence exit ramp terminal locations. "Interchange" spacing merely provides the general framework of the dimension between freeway cross-street centerlines. Ramp spacing is derived after the sequential ramps are appropriately configured to meet geometric design, traffic operational, signing, and safety needs.

But from where are ramp spacing values measured? The American Association of State Highway and Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets* (Green Book) provides guidance on ramp spacing values (*4*). The Green Book dimensions had been historically noted to be from "like points." This means from gore to gore or from painted tip to painted tip. Yet each of these ramp design event points may yield considerable differences between the associated dimensions and, therefore, predicted operations. Further, each agency was able to choose to measure their respective "like points" differently than another. Therefore, it was possible that two adjacent states may have evaluated and considered ramp spacing values differently for the same interstate freeway that passes within their respective states.

These Guidelines define a new vernacular for the profession. In developing these Guidelines, the authors have reviewed and considered ramp and interchange spacing values and measurements from seminal documents such as the Green Book, the *Highway Capacity Manual* (HCM), and the *Manual on Uniform Traffic Control Devices* (MUTCD) (*4, 5, 6*). These Guidelines have created the following definitions for interchange and ramp spacing:

Interchange Spacing: "The distance measured between the respective centerlines of freeway cross streets that include ramps to or from that freeway" (see Exhibit 1-1).

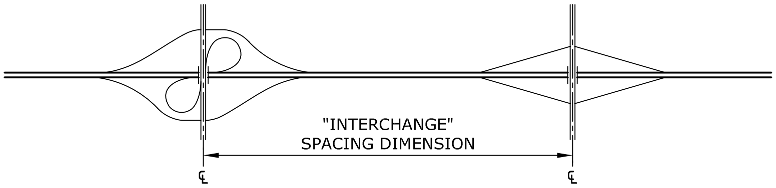


Exhibit 1-1 Definition of Interchange Spacing

Ramp Spacing: "The distance between the tips of the actual or theoretical convergence of the painted gore stripes (painted tips)" (Exhibit 1-2).

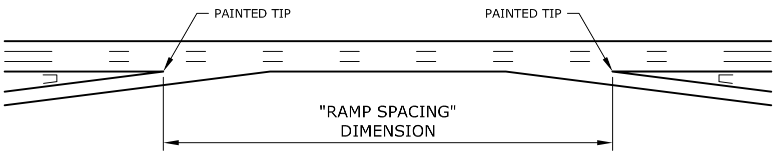


Exhibit 1-2 Definition of Ramp Spacing

1.2 INTENDED USERS

These Guidelines are intended to be a useful resource that can be applied to planning, operational, feasibility, and design studies of freeway, highway and interchange facilities. They are intended for individuals who are considering new ramps or interchanges on existing or new freeways and highways, or are considering modifications to existing ramps and interchanges. These Guidelines are meant to be used by engineers, planners, students, researchers, and policymakers.

1.3 SCOPE OF GUIDE

These Guidelines focus on fundamental ramp and interchange spacing principles for general-purpose, uninterrupted-flow facilities. The Guidelines were developed primarily with freeway (fully controlled access) facilities in mind. However, the same concepts and principles presented in this document could also be applied to partially controlled access highways and expressways that have a mixture of interchanges and at-grade intersections. For simplicity, "freeway" is used in this document when referring to a facility with interchanges.

These Guidelines present considerations about elements that influence ramp and interchange spacing decisions to help users understand planning, operational, signing, safety, and design tradeoffs in making informed ramp and interchange spacing decisions. These Guidelines are not rigid standards, and users are responsible for applying professional judgment in making appropriate planning and design decisions for their unique contextual environment.

These Guidelines do not explicitly or comprehensively address the following topics. However, many of the principles and fundamental considerations presented in these Guidelines may be applicable and useful to users who are considering the following topics:

- High-Occupancy Vehicle applications,
- Weigh stations,
- Rest areas,
- Collector-distributor roadways,
- Turning roadways,
- Loop ramp design, and
- Spacing between ramps/interchanges and at-grade intersections on non-freeway highways.

As projects move further into the preliminary and final design stages, the flexibility to make meaningful adjustments in ramp and interchange spacing values diminishes greatly.

These Guidelines will provide the most value in the planning and pre-design stages of a project when the most opportunity exists for investigating ramp and interchange configuration and spacing options. The greatest flexibility to evaluate design, operational, safety, and potential tradeoffs occurs in the early stages of project development. The guidance this document provides is based on design, operational, and safety principles that should be carried through planning, design, construction, and maintenance and can be reviewed at any project stage.

1.4 RELATIONSHIP TO RECOMMENDED RESOURCE DOCUMENTS

These Guidelines complement ramp and interchange spacing principles and objectives that are contained in well-known, established resource documents. The following resource documents should be used when evaluating ramp and interchange spacing in addition to and in conjunction with these Guidelines:

- *A Policy on Geometric Design of Highways and Streets* (AASHTO Green Book) (*4*);
- *Highway Capacity Manual* (HCM) (*5*);
- *Manual on Uniform Traffic Control Devices* (MUTCD) (*6*); and
- *Highway Safety Manual* (HSM) (*7*).

In addition, many of the freeway and interchange planning and design principles provided in these Guidelines are documented in the ITE *Freeway and Interchange Geometric Design Handbook* (*8*).

Chapter 2 Ramp and Interchange Spacing Overview

This chapter provides an overview of the project development process, policy considerations, and an overview of the relationship of major published resource documents associated with ramps and interchanges.

2.1 INTRODUCTION

2.1.1 Project Development Stage

There are numerous definitions of the project development stage and, regardless of the specific terms used, they generally represent an advancing sequence of activities that originate in solution concept planning and, if appropriate, culminate in a project's implementation.

Ramp and interchange spacing evaluations vary depending on the stage of the project development process. Each project stage can affect how each of the policy and technical considerations is assessed. During any project development stage, the operational, design, safety, human factors, and signing controls should be considered to make informed decisions about ramp and interchange spacing dimensions.

Evaluations should also consider the design, operations, and safety tradeoffs for a particular project need. The level of analysis should be commensurate with the respective project development stage. And while early project planning activities may not typically require the same level of analysis or detailed evaluation of a later preliminary design stage, each professional should be prepared to provide a level of analysis and level of detail that is needed to support project decision making.

For the sake of discussion, these Guidelines have simplified the project development process to focus on the following three stages:

- Planning—This represents the earliest stages of project development when project issues are being identified and solutions concepts are being considered and evaluated. Ramp and interchange spacing values are influenced by fundamental considerations of interchange type and configuration. In retrofit situations, solutions may be greatly influenced by the constraints of the unique context of that location. At this stage, ramp and interchange spacing values are influenced by the same factors and considerations of later design stages, albeit using planning-level evaluation information.

For new construction, this stage may provide the most flexibility to consider and apply solutions that optimize ramp and interchange spacing in relation to design, operations, signing, and safety considerations.

- Preliminary Design—This stage provides the balance of flexibility and design detail. Typically, a wide range of concepts and alternatives may be considered. As concepts are screened and refined, increasing detail is available for design, operations, safety, and signing evaluations within a project's contextual environment. Professionals assess the solution concepts from the planning stage and quantitatively evaluate each solution using design and operations tools and techniques. Traffic operations and three-dimensional roadway design input is available to conduct analyses, and yet there is flexibility to select and refine alternative solutions in balance with the project's contextual environment.

- Final Design—There is limited flexibility in modifying solutions in a meaningful way by this project stage. A single alternative has been selected and the primary emphasis is developing design and construction documents for the project's implementation. During this stage there may be minor design or operational adjustments; however, there is fundamentally little flexibility to positively affect ramp and interchange spacing values.

2.1.2 Common Scenarios

No project is "typical," and each has its own unique opportunities and challenges. Ramp and interchange spacing evaluations and recommendations should be predicated on that project's contextual design environment. However, there are likely a general range of scenarios that may be common to many conditions faced by the user. Considering the variety of possible common scenarios provides insights about the flexibility or constraints of that scenario that might be applied to other projects within a similar scenario.

For example, new interchange projects on new facilities may generally provide more flexibility in the types of solutions that optimize ramp and interchange spacing values. By contrast, in a complex urban environment, a retrofit project of an existing interchange may have less overall flexibility in the solutions under consideration. Evaluations in these scenarios may be focused on balancing project tradeoffs to optimize the design variables. For example, maximizing ramp spacing dimensions may be secondary to lengthening an exit ramp to minimize queue spillback on the mainline from the ramp terminal intersection.

Case Studies in Appendix A illustrate spacing assessments in different environments.

These Guidelines provide a sequential approach to considering the design aspects that influence ramp and interchange spacing and provide guidance in evaluating a range of considerations of the safety and operational performance of the possible solutions. Case Studies included in Appendix A present examples of how to consider the adequacy of ramp and interchange spacing values in different scenarios. Common ramp and interchange spacing scenarios include the following:

- New interchange on a new facility;

- New interchange on an existing facility (illustrated in Case Studies 2, 3, and 5);
- Extensive modifications to an existing interchange or interchange system on an existing corridor;
- Retrofits to a partial-access controlled facility to convert an at-grade intersection to an interchange (illustrated in Case Study 1); and,
- Retrofits to an existing corridor that may include partially or completely removing an existing interchange (illustrated in Case Study 4).

2.2 POLICY CONSIDERATIONS

Designing, operating, and managing a roadway (including interchanges and ramps) should align with the appropriate jurisdictional policies associated with that facility. The facility location and type (Interstate, freeway, highway, and other managed access facilities) can often dictate the appropriate spacing guidelines, design parameters, and technical considerations that should be applied.

2.2.1 Interstate Freeways

Interstate freeways are intended to provide the highest service levels in terms of mobility and safety. Interstate freeway access control is essential to preserving the integrity of the overall system. Therefore, the FHWA must grant approval for any new or revised access point on an Interstate freeway. The FHWA policy criteria for new or revised access is described in the August 27, 2009 edition of the Federal Register (Volume 74, No. 165) (*9*).

FHWA must approve new interchanges or changes of access from existing interchanges on the Interstate Highway System.

This FHWA policy document describes the following eight points FHWA considers in granting an Interstate access:

1. The existing system is incapable of accommodating desired access or traffic demands;
2. All reasonable alternatives to a new interchange have been considered, including transportation system management;
3. The proposal does not have an adverse safety or operational impact on the freeway;
4. A full interchange at a public road is provided;
5. The proposal is consistent with transportation and land use plans;
6. A comprehensive interstate network study is prepared;
7. There is coordination with transportation system improvements; and,

8. The request is considered as an alternative in environmental evaluations.

Some of these points consider evaluating non-interchange alternatives to achieve transportation objectives. Others necessitate concept development at a level sufficient to appropriately analyze design tradeoffs of potential new or modified interstate access. These Guidelines support efforts to consider ramp and interchange spacing when evaluating new or revised interstate accesses.

2.2.2 Non-Interstate Freeways

Non-interstate freeways are managed primarily by state and local highway agencies and toll authorities. Many state departments of transportation require some form of "interchange justification report" (IJR) or "interchange modification report" (IMR) for requests made for new or modified interchanges on their network. Highway agencies sometimes adopt the FHWA policy criteria or incorporate elements of the criteria in their own policy or procedural documents to adapt the guidelines for specific state regulations. The primary interest of transportation agencies remains consistent with the fundamental considerations of the FHWA access point policy: to objectively evaluate sound technical information about the design, operational, and safety tradeoffs of proposed changes to the controlled access highway. Policies from two transportation agencies are presented in the following sections.

The considerations by these agencies may provide helpful insights to other users who are conducting ramp and interchange evaluations. The outcomes of freeway and interchange planning considerations will influence or be influenced by ramp spacing values.

Florida

Florida is an example of one state that has a formal approval process for new interchanges.

The Florida Department of Transportation (FDOT) requires that IJRs or IMRs be prepared for most new or modified interchanges on existing limited access, non-interstate facilities. To assist with this process, FDOT has published the *Interchange Handbook* (*10*). The need for an IJR or IMR is made by considering the following criteria:

- The need was previously defined by the (Florida *Intrastate* Highway System) planning process, master plan, and/or traffic or safety report;
- The FHWA interchange modification criteria (contained in the FDOT *Interchange Handbook*);
- The complexity of the proposal and potential impact on adjacent interchanges (spacing, operational overlap, change in traffic patterns);

- The potential impact on the operation and safety of the mainline (change in level of service, merge, diverge, weaving impacts, need for auxiliary lanes);
- The facility jurisdiction (turnpike, FDOT, local expressway authority);
- Consistency with local government transportation and land-use plans; and,
- Known policy, public, or environmental issues that could affect approval of the Interchange Proposal.

Once an IJR or IMR is submitted, the following criteria are considered by FDOT:

- Is the analysis and documentation complete, accurate, sufficient, and consistent with the interchange process? If not, does FDOT concur with any deviations?
- Is the need for the interchange fully justified and in the best interest of the public?
- Does the proposal meet the eight FHWA policy criteria?
- Does the proposal impact the operation and safety of the mainline, adjacent interchanges or the surrounding street network and, if so, are the impacts properly mitigated?
- Has an Arterial Access Management Plan been developed and agreed to (where required)?
- Are the final funding commitments consistent with the proposed opening and interim and design years, and are they in place?
- Are all exceptions to policies and standards approved?
- Is the proposal consistent with local government and MPO land-use and transportation plans?
- Is the proposal consistent with the [Florida *Intrastate* Highway System] Plan?

FDOT provides guidance to maximize safety and reduce conflicts at entrances and exits by doing the following:

- Spreading and clarifying decision points;
- Creating uniformity in design and operations; and,
- Creating clear and simplified signing.

The handbook notes that new interchanges should be considered only after improvements to adjacent interchanges and the arterial system have been considered, as well as TSM and alternative travel modes. The handbook also notes that in "rare circumstances" travel demand will not be the primary justification for an interchange.

Minneapolis-St. Paul, Minnesota

In the Minneapolis-St. Paul metropolitan area, new interchanges and major modifications to existing interchanges must be approved by the Metropolitan Council, which is the local metropolitan planning organization. This approval process applies to all existing freeways in the metropolitan area regardless of which agency operates them. In some cases, interchanges on facilities that are not full freeways must also be approved. The following criteria must be met for a new or modified interchange to be approved (*11*):

1. Additional interchange capacity should support the Metropolitan Council's transportation plans.
2. The need for capacity or safety improvements must be documented.
3. Interchanges should only connect to metropolitan highways, minor arterials, or collectors.
4. New or expanded interchanges are not to be provided as a convenience for short trips, to compensate for the lack of an adequate minor arterial and collector system, or to compensate for deficient minor arterials and collectors.
5. The operational integrity of mainlines and weaving sections must be maintained, and
6. Interchanges should be spaced a minimum of one mile center-to-center. If a spacing less than this is determined to be appropriate, safe operation of the mainline must be preserved.

The Metropolitan Council also provides design criteria for ramps and interchanges.

1. Whenever possible, standard ramp and interchange configurations should be used in design.
2. Interchange ramp configuration and design should be based on traffic forecasts.
3. Traffic backups resulting from interchange ramp designs must occur on cross streets and frontage roads rather than on the mainline.
4. Selected collector and minor arterial roadways connecting with the proposed interchange must be adequate for the anticipated volumes on the interchange.
5. Ramp configurations must be capable of being signed for safe and expeditious movement prior to construction approval.

6. Interchange ramp configuration and design should provide for preferential treatment of transit and rideshare vehicles.
7. Cross-street improvements, if needed, should be coordinated with interchange construction.

2.3 MAJOR PUBLISHED RESOURCE DOCUMENTATION

A ramp and interchange spacing evaluation typically requires applying operational, design, signing, and safety guidance provided in the *Highway Capacity Manual* (HCM), *A Policy on Geometric Design of Highways and Streets* (Green Book), the *Manual on Uniform Traffic Control Devices* (MUTCD), and the *Highway Safety Manual* (HSM).

Since 1984, the AASHTO Green Book has provided a general rule of thumb for minimum interchange spacing and values for minimum ramp terminal spacing. These Guidelines provide additional information and considerations to accompany the Green Book's guidance, and underscore the relationship between traffic volumes and preferred minimum ramp spacing dimensions. In short, these Guidelines emphasize the importance of integrating traffic operations, design, safety, and signing when considering decisions that influence ramp and interchange spacing decisions (*4*).

The Green Book provides guidance on minimum interchange and ramp spacing values that is discussed in Chapter 3.

Among the vast array of traffic control guidance, the HCM provides analysis procedures for weaving sections and ramp-freeway junctions. These Guidelines include planning-level advice on minimum ramp spacing dimensions based on HCM procedures (*5*).

The HCM provides operational analysis procedures for various interchange elements that is discussed in Chapter 4.

The MUTCD specifies how many advance guide signs should be placed prior to an exit and how far in advance of an exit they should be placed. The MUTCD and the *Texas Freeway Signing Handbook* provide guidance on how many signs should be placed at the same point (*6, 12*).

The MUTCD provides signing recommendations that are relevant to exit ramp spacing discussed in Chapter 3.

The HSM does not yet provide quantitative information for many of the elements associated with interchanges and there is no quantitative information regarding the effect of interchange spacing. Future editions of the HSM will likely provide additional information on topic areas such as freeways and interchanges. The research conducted to develop these Guidelines has resulted in safety prediction aids that can support ramp and interchange spacing evaluations consistent with the intent and principles of the HSM (*7*).

The HSM has limited interchange-related information; safety guidance in these Guidelines is discussed in Chapter 4.

Chapter 3 Design and Signing Considerations

This chapter provides an overview of the various design elements and signing considerations that affect choices and decisions about ramp and interchange spacing.

3.1 OVERARCHING DESIGN AND OPERATIONAL RELATIONSHIPS

Freeway design, interchange configurations, and ramp sequencing are integrated elements. The fundamental configuration of the freeway in terms of lane numbers and arrangements directly influences ramp design. And, in turn, appropriate entrance and exit ramp designs must adequately consider highway configurations and include design elements that integrate and balance ramp and highway operations. Design and operations decisions should be integrated as the relationships between them influence planning and design considerations.

Operations may be considered in two categories. The first considers the traffic operations quality in terms of volumes served, speeds, delay, and other common traffic engineering performance measures. The second relates to the "operational effects of the geometrics" provided. This includes speed consistency and uniformity resulting from vertical and horizontal design elements, and also the operational characteristics affiliated with the way geometric elements are configured. These configuration considerations encompass how the number and arrangement of freeway and ramp lanes are presented to drivers, including designated routes, the continuity of mainline lanes, and entrance and exit ramp locations and configurations.

The following are fundamental design and operational considerations of highway and interchange design. These mainline and ramp considerations influence traffic operations and directly impact design decisions that determine ramp and interchange spacing. The operational effects of having or not having these design elements may create traffic operation and flow conditions that supersede the influence of ramp spacing decisions. This could mean that ramp and interchange spacing decisions will not be fruitful unless broader freeway needs are first considered and addressed.

3.1.1 Lanes

- Number—The number of lanes provided for the freeway and ramps should be sufficient to serve forecast needs in balance with the surrounding roadway network. The capacity of freeways and ramps influences ramp spacing decisions. Heavy traffic volumes or congested conditions may require detailed operations analyses to understand the influence of ramp spacing. Similarly, in low volume conditions, ramp spacing may have relatively little influence on traffic operations.

- Basic—The basic lanes are the constant or minimum number of lanes provided throughout a significant length of a mainline roadway. Basic lanes should not be added or dropped indiscriminately. Interchange and ramp design must consider how to best blend the ramp exit and entrance designs. Should the mainline freeway segment contain conditions that add or drop basic lanes, the ramp design and spacing may require special consideration to optimize traffic operations.
- Auxiliary—Auxiliary lanes are supplemental lanes that provide additional capacity between interchange ramps or along a series of interchanges. An auxiliary lane may be provided along a series of interchanges and an additional auxiliary lane may be provided between an entrance and exit between a particular interchange. Auxiliary lanes may be required between entrance and exit ramp designs to provide lane balance (described below). Similarly, the presence of auxiliary lanes may create a "weaving" section and, therefore, professionals may consider multilane exits to reduce lane changes in the upstream segment even if the downstream ramp does not necessarily require two lanes based on ramp volumes.
- Balance—Lane balance involves providing an appropriate number and arrangement of lanes at freeway entrances and exits to reduce the number of required lane changes along the mainline. At entrance ramps, the number of lanes beyond the merging of two traffic streams should not be less than the sum of all traffic lanes on the two merging roadways, minus one. At exit ramps, the number of approach lanes on the mainline should be equal to or greater than the number of lanes on the mainline freeway beyond the exit plus the number of lanes on the exit ramp, minus one. Achieving lane balance through a series of ramps may require applying auxiliary lanes which, in turn, could influence ramp-freeway junction design locations and, therefore, ramp spacing dimensions.
- Continuity—The number of through lanes should be continuous along long stretches of a freeway. Additional lanes may be added and dropped (auxiliary lanes), but the continuity of the through lanes should be maintained to eliminate unnecessary lane changing. A lack of lane continuity can induce lane changes that could be compounded by interchange entrance and exit ramps. Ramp spacing, sequencing, and terminal locations could be influenced by lack of mainline lane continuity and the effort to attain it.

3.1.2 Uniformity

Single or multiple entrance and exit ramp design configurations can influence ramp spacing values.

- All right-hand exits—Left-hand exits should not be used because they do not meet driver expectations, create signing issues, and can create confusion for drivers attempting to exit the highway. Combining left- and right-hand exits violates operational uniformity and design consistency. Configurations to achieve right-hand entrances and exits could influence ramp-freeway junction locations and, therefore, the ramp spacing between interchanges.
- Single-exit design—Single-exit designs are generally preferred over two-exit designs, based on their improved operational efficiency, reduced weaving, simplified signing, and driver expectations. A single-exit design separates driver decisions by first allowing the driver to chose to exit the mainline and then later choosing the specific destination along the cross street.

  In some cases, a single exit may serve a high forecast volume that creates upstream or spot capacity issues for that high demand location. In some cases, from a traffic volume and distribution standpoint, two exit ramps might reduce impacts of "point loading" the single ramp and could be considered if the signing needs do not create other issues. Multiple-exit design could influence ramp spacing considerations.
- Single- and multiple-entrance design—Single-entrance designs can be used to "collect" traffic from two or more ramps and place that traffic on the freeway at a single location. The benefit of this orientation is to separate multiple locations of merging turbulence to a single location on the freeway. The location of that single entrance is somewhat flexible and provides flexibility to planners and designers. However, a single entrance concentrates traffic volumes and, depending on their magnitude, could represent a capacity issue.

  Multiple-entrance configurations require more concerted design efforts for their placement, but allow the freeway to absorb ramp traffic in multiple, smaller volume increments. Multiple entrances allow motorists to distribute themselves across lanes on each freeway section downstream of each entrance. This could reduce the right-hand freeway lane loading for subsequent downstream entrance ramps. The ramp spacing values will be influenced significantly by the configurations selected and the design and location of the freeway entrance ramp terminals.

  Exhibit 3-1 depicts a hypothetical example of single- and multiple-entrance configurations. The first example depicts a turning roadway configuration that creates a single-entrance design. If the downstream exit ramp terminal is fixed, the turning roadway configuration and single entrance yields a unique ramp spacing value.

If a multiple-entrance configuration is provided, as in the second example, the successive entrance ramp configurations could reduce spacing to the same existing downstream exit ramp terminal. Therefore, the upstream interchange ramp configurations influence ramp spacing values, and attaining specific ramp spacing values might dictate the configuration of the upstream interchange and ramp forms.

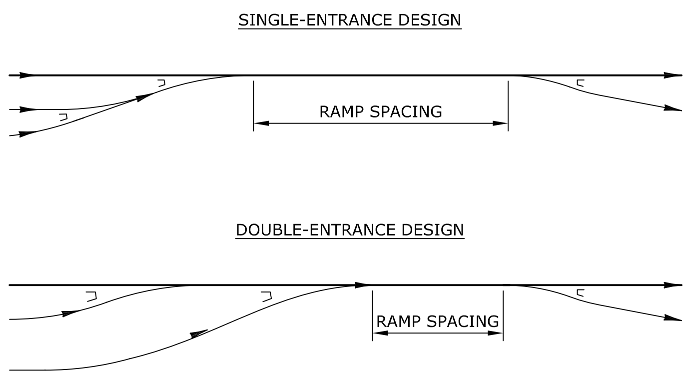


Exhibit 3-1 Single and Multiple Entrance Ramps

- Exit in advance of the cross street—Drivers anticipate selecting and exiting their exit prior to reaching it. It is not intuitive to pass one's cross street and then exit to reach it. Achieving an exit in advance of the cross street also requires considering exit sign placement and sign sequencing. Sign placement and sequencing can influence the specific location of the exit terminal, influencing ramp spacing values between adjacent ramps.

3.2 INTERCHANGE CATEGORIES

There are two primary categories for interchanges, which are dependent on the types of facilities that are being intersected. This section provides an overview of the various interchange forms, including system and service, as well as the various configurations.

Most states have established minimums for interchange spacing depending on the location type. In urban areas, a typical minimum spacing is one mile and in rural areas two to six miles. Research has shown there are a variety of contributing factors that have led to the typical one-mile minimum urban interchange spacing value. Factors range from guide sign sequencing needs for driver navigation to establishing an arterial and highway network that provides a balance between preserving freeway operations through managed access versus overloading a surrounding arterial network. Interchanges are often considered at crossing roadways. However, there is a variety of "T" and "Y" interchange variations for three-legged interchange applications. These interchanges can take high type (directional) forms that serve freeway-to-highway movements or lower type configurations (such as "trumpet" forms) that serve freeway-to-arterial connection needs. Within these forms, there are two ramp configurations related to loop ramp placement. The "A" form has its loop ramp in advance of the cross street while the "B" form has its loop ramp beyond the cross street.

3.2.1 Service Interchanges

Freeway ramp terminal locations should be established based on ramp operations and design needs.

A service interchange refers to an interchange between a freeway and a non-freeway (such as an arterial, collector, or local street). There are a variety of service interchange forms to serve a broad range of traffic volume conditions. However, diamond and interchanges with loops (partial cloverleafs and cloverleafs) are the most common forms. Entrance and exit ramps are commonly one lane wide, but two-lane ramps are not uncommon. Each of these forms can accommodate a wide range of traffic demands and have flexibility to adapt to the surrounding natural and built environment.

A variety of diamond forms exist. Low-volume rural configurations often have ramp terminal intersections set far apart to operate as isolated, stop controlled intersections. High-capacity forms can have relatively narrow footprints and serve traffic demand with coordinated traffic signals at the ramp terminals. Single-point diamond forms accommodate traffic demand via a single signalized intersection serving all four ramps. Freeway ramp terminal locations should be established by reviewing the ramp terminal traffic operations to establish queue lengths, and to be sure there is sufficient stopping sight distance and deceleration length from the comparatively high exiting speeds.

3.2.2 System Interchanges

A system interchange refers to an interchange between two freeways. These forms generally provide free-flow movements via ramps with design speeds that vary from 25 to 70 mph. A system interchange is typically a higher type form that will likely have flatter and longer merge and diverge areas. This may require a greater space between interchanges. Additionally, ramps may be grade separated and go over or under each other, which could also impact spacing. These interchanges can have four or more levels of roadways, with some of them being below the surrounding ground surface. There are many system interchange forms and contexts in which they are located. The unique context of these forms leads to a wide range of geometric solutions for the system interchanges and adjacent (if present) interchanges within the general influence area.

"Major fork" or "branch connections" are a subset of system interchanges generally found where a single freeway diverges into two freeways or where a single freeway terminates at another freeway and traffic volume is not heavily distributed in one direction. The bifurcating ramp connections at these interchanges often are two lanes wide, but three-lane connections are not uncommon. These ramp connections serve high volumes and typically merge and diverge at flatter angles than service interchange forms to facilitate high-speed movements between the freeway facilities. To attain appropriate lane balance and facilitate the distribution of interchanging traffic, the distance from the advance taper to the physical ramp nose can approach one-half mile. The special needs of these connections can influence the spacing dimensions to adjacent ramp terminals. Guide signing and sequencing must complement the freeway and ramp geometric design.

The ramp-freeway junction locations of system interchanges can be influenced by a variety of design, operational, and signing considerations, and the location of these termini should be evaluated carefully as they will have a significant influence on ramp spacing dimensions. Further, the typically increased traffic volume and complex geometry and lane configuration at system interchanges may warrant more detailed operations analysis at the earliest stages of a project compared to other relatively simple configurations.

System interchanges may have special geometric design, signing, or operational needs that require special consideration when determining ramp spacing dimensions

Finally, the complexity of system interchanges results in signing and marking needs that may exceed the typical signing considerations of simpler interchange configurations. Signing considerations should be evaluated at the earliest stage of concept development.

For both service and system interchanges, freeway entrance and exit ramp terminals should be located based on the unique design and operational needs of each ramp. Therefore, ramp spacing values (and the associated forecast traffic operations) should dictate planning and design decisions, not arbitrarily established interchange spacing dimensions. In all cases, planners and designers should understand the range of interchange applications for the variety of design environments. The interchange type and form will directly influence ramp placement and interchange and ramp spacing decisions.

3.3 RAMPS

A ramp is a length of roadway connecting two freeway facilities or a freeway and an arterial street. On freeways, entering and exiting maneuvers take place via ramps that are designed to facilitate smooth merging of onramp vehicles into the freeway traffic stream and smooth diverging of offramp vehicles from the freeway traffic stream to the ramp. Ramps consist of three geometric elements: ramp-freeway junction (merge or diverge); ramp proper; and ramp-street junction (ramp terminal intersection). A ramp-freeway junction is typically designed to permit high-speed and high-capacity merging and diverging with minimum disruption to the adjacent traffic (*5*).

3.3.1 Ramp Types and Design Considerations

The AASHTO Green Book describes the range of ramp types (*4*). These range from the diagonal ramp commonly used with diamond forms to loop ramps. Ramp design must account for speed changes and transitions to and from the interchanging facilities. Service interchanges typically require transitioning to a stop condition and providing adequate storage for queued vehicles. Semi-direct and directional ramps are mostly used in high-volume conditions. Exhibit 3-2 provides examples of ramp design components for exit and entrance ramps for a service interchange. The ramp-freeway junction and ramp terminal intersection locations are directly affected by providing ramp configurations that serve traffic capacity and operational needs for a given contextual design and operations environment.

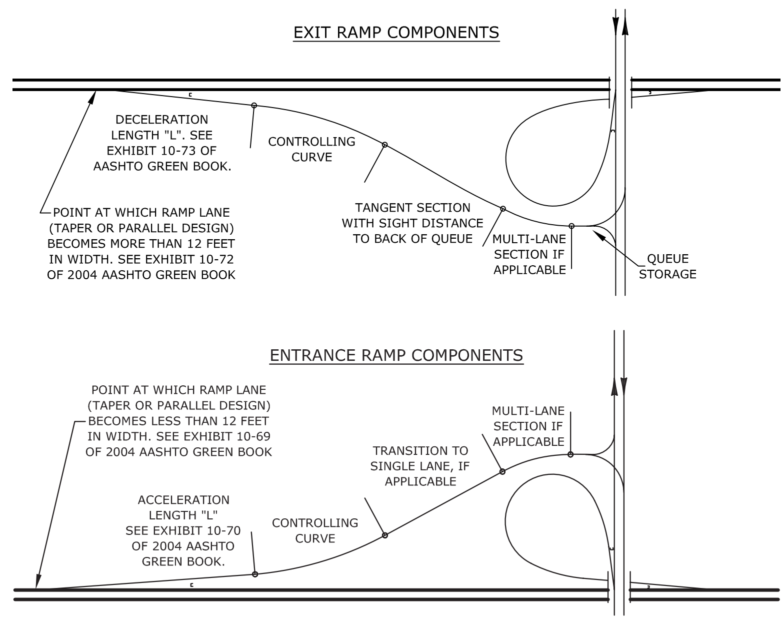


Exhibit 3-2 Ramp Design Components

Interchanges with loops can take a variety of configurations to adapt to traffic volumes and physical constraints. Adaptations include varying the number and location of loop ramps to different quadrants or configurations, based on project need. Much literature exists about the various forms and appropriately applying different configurations. Loop ramp design requires applying speed transition principles for decelerating and accelerating traffic.

System interchange ramp configurations often require special attention to grade separations as well as ramp and freeway levels. These three-dimensional considerations can affect horizontal ramp placement to attain desired grades. Single-exit and entrance designs require developing the longitudinal placement of diverge and merge areas on turning roadways.

Considering three-dimensional roadway design needs will influence interchange geometrics and will directly influence ramp and interchange spacing values.

Ramp and interchange spacing values are directly influenced by three-dimensional roadway design needs of interchange ramps.

Each of these ramp designs requires different considerations for their terminal treatments and geometric layout. The configurations of the ramps affect the geometric design and placement and clearly influence and are influenced by ramp and interchange spacing needs and decisions.

3.3.2 Turning Roadways

This section discusses turning roadways and example characteristics that may influence ramp and interchange spacing.

A turning roadway is a configuration where the entrance and exit ramps from or to multiple origins or destinations merge or diverge prior to or after exiting a mainline segment. This is a common attribute of "single exit" designs that provide a single exit or entrance that serves multiple destinations or origins. Exhibit 3-3 depicts turning roadways.

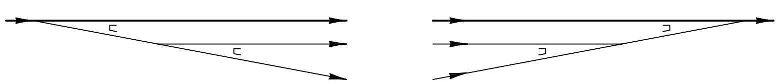


Exhibit 3-3 Turning Roadway Examples

A single exit design simplifies and separates driver decisions. A driver first makes a decision to exit the freeway and then makes a second choice about what direction they will travel on the crossroad. In some cases, additional ramp stem length may be beneficial to account for complex signing and generally helps drivers navigate and make appropriate decisions. Depending on how this length is developed, it could influence the freeway exit ramp terminal and influence ramp spacing values.

On a single entrance, the dimension between successive merges might be influenced by providing adequate merge lengths or choosing an optimal location to merge ramps on curvilinear ramp configurations. This added length could influence the location of the mainline merging end location and, therefore, influence the decision of locating a downstream ramp or interchange.

The geometry of a turning roadway can influence ramp spacing. Exhibit 3-4 depicts the effects of convergence angles on turning roadway configurations and how that influences ramp spacing. In this example, the location of the ramp merge to the freeway is influenced by the convergence angle of the turning roadway. A flatter convergence angle on the ramp shifts the entrance ramp terminal downstream compared to the configuration with the greater convergence angle. The flatter convergence angle may improve traffic flow and support superelevation transitions on the ramp elements.

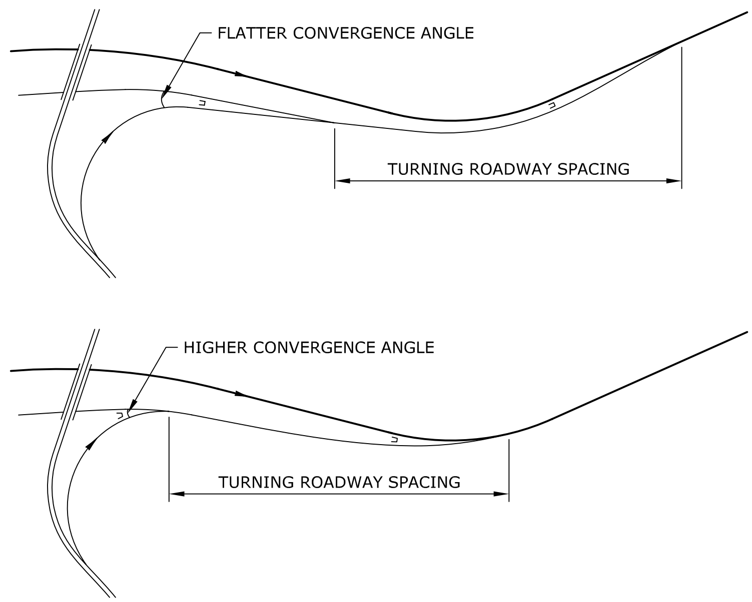


Exhibit 3-4 Effect of Turning Roadway Convergence Angle

Other turning roadway design and operational considerations can influence ramp spacing. For example, lane numbers and arrangements of the turning roadways could influence their length and, therefore, the location of the entrance or exit ramp terminal on the freeway. Exhibit 3-5 depicts an example of a ramp configuration that features lane drops along the turning roadway. In this example, the location of the ramp merge to the freeway is influenced by the need to drop lanes on the ramp after the convergence of the ramps prior to the ramp-freeway junction.

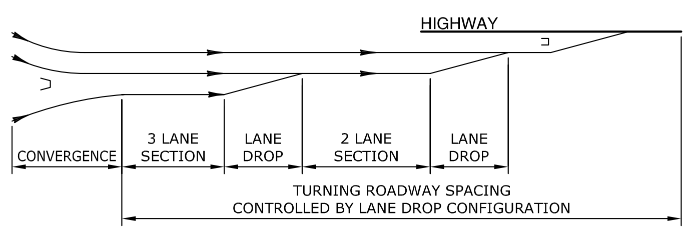


Exhibit 3-5 Effect of Lane Drops on a Turning Roadway

3.3.3 Collector-Distributor Roadways and Grade Separated Ramps

This section discusses considerations of collector-distributor roadways and grade separated ramps (ramp braids), including some of the operational, design, and signing considerations that may influence planning and design decisions that affect ramp and interchange spacing.

Three-dimensional geometric design, traffic operations, and signing needs may result in ramp spacing values that are unacceptable and, therefore, require considering other means of providing access to the highway. Collector-distributor (C-D) roadways and grade separated ramps (ramp braids) are two possible alternatives to providing freeway access ramps when adequate ramp spacing dimensions cannot be attained.

3.3.3.1 COLLECTOR-DISTRIBUTOR ROADWAYS

The AASHTO Green Book defines a C-D roadway as "an auxiliary one-way roadway separated laterally from but generally parallel to and connecting with the highway through roadway" (*4*). The purpose of this type of facility is to reduce the weaving and number of entrance and exit points on the mainline freeway while still providing adequate access to and from the freeway. C-D roadways are expected to operate at a lower quality of service and protect mainline operations by moving the turbulence of the entering and exiting traffic to the separate facility. C-D roadways allow merging and diverging movements to occur on lower speed roadways and typically under lower volumes when compared to the mainline freeway.

C-D roadways require special attention to determine their freeway ramp terminal locations. These locations influence ramp spacing dimensions.

For example, a C-D roadway system may be necessary to serve merging and diverging traffic for a series of closely spaced ramps or interchanges. The traffic volumes on the C-D roadway may influence how many connecting ramps are provided to and from the mainline. The need to address multiple merge and diverge locations may dictate the location along the freeway mainline of the exit to or the entrance from the C-D roadway. This could influence the design decisions of ramps or interchanges up or downstream of the C-D roadway system. Likewise, the adjacent locations of existing ramps or interchanges may influence the exit and entrance terminals of the proposed C-D roadway system and therefore influence ramp spacing values.

3.3.3.2 GRADE SEPARATED RAMPS (RAMP BRAIDS)

A ramp braid (or "basket weave") is a means using grade separated ramps to eliminate the overlapping merging and diverging friction or weaving of two or more closely spaced ramps by vertically separating ramps. For example, a traditional entrance ramp followed by a closely spaced exit ramp would be replaced with a configuration that has the exit ramp pass over or under the entrance ramp, and therefore, eliminate the overlap in the operational influence area on the freeway segment between what would otherwise be present between those two ramps.

Ramp braids eliminate lane changing or weaving between the junctions and effectively treat the entrance and exit ramps as isolated ramp merge and diverge areas. Ramp braids may also be used in complex interchange areas. For example, this could include locations where service interchange ramps may need to be located within or in close proximity to a system interchange.

Ramp braid configurations require considering the three-dimensional roadway design needs to facilitate ramp grade separations. These considerations can affect the general interchange "footprint" based on the angle at which the two ramps cross (flatter crossing angles generally result in a narrower footprint than greater angled crossings). Ramp braid configurations also influence ramp spacing dimensions since freeway entrance and exit gore locations are influenced by the need to make ramp grade changes at appropriate rates.

Exhibit 3-6 provides a schematic drawing that depicts the vertical and horizontal relationships of a conceptual ramp braid configuration. The shorter horizontal dimensions reflect configurations where each ramp profile is established to facilitate grade changes. The longer horizontal dimension reflects a configuration where only one ramp is configured to facilitate the required grade change. These considerations will influence the locations of freeway exit and entrance ramp terminals and, therefore, ramp spacing dimensions to adjacent interchanges

Freeway entrance and exit ramp terminals of braided ramps may influence ramp spacing dimensions.

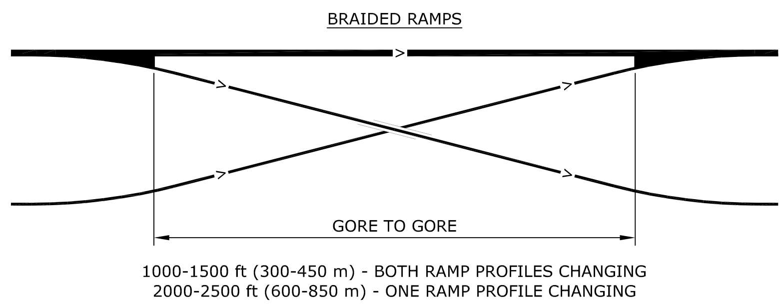


Exhibit 3-6 Ramp Braid Vertical and Horizontal Relationships.

3.3.4 Freeway Ramp Terminal Design

Entrance and exit ramp terminal designs vary from state to state and directly influence recommendations for ramp spacing dimensions. The type of ramp selected (parallel or taper) and the detailed geometrics of the ramp proper and the terminals influence the physical location of event points that influence traffic operations. Planners and designers should be familiar with the variability of entrance and exit ramp terminal designs. This includes being familiar with gore design elements including neutral area dimensions, and with how varying converge and divergence angles affect the overall length from the painted tip to the physical gore. Given the variability of ramp terminal design from state to state, applying ramp spacing dimensions from the AASHTO Green Book could lead to significantly different spacing dimensions between painted tips.

Exit ramp diverge angles commonly range from 2 degrees to 5 degrees. Gore area elements dimensions (mainline shoulder, neutral area, ramp shoulder) also vary from state to state. Therefore, the point on a ramp terminal in a state that uses a small diverge angle could result in a gore design and physical nose location that is longer compared to a state that uses a large diverge angle. Therefore, ramp spacing values can be influenced by the design details of a given freeway entrance and exit ramp terminal.

For example, assuming a 26-foot physical nose width, the dimension from the gore to the painted tip of a 2-degree exit diverge angle is over 475 ft longer than that of a 5-degree exit diverge angle. This is illustrated below in Exhibit 3-7. Therefore, applying a consistent point from which to measure ramp spacing values allows a uniformly defined event point that is independent of a particular entrance or exit ramp terminal design.

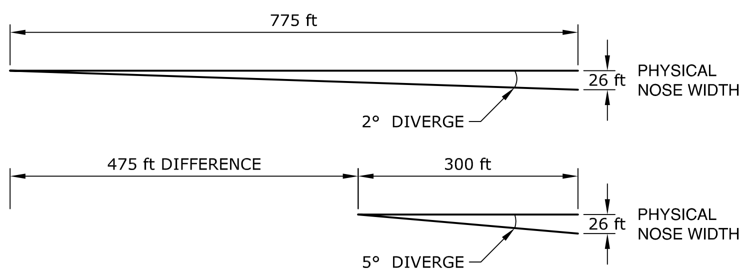


Exhibit 3-7 Effects of Exit Ramp Diverge Angle

Ramp-to-ramp spacing may also be affected by the application of "parallel" versus "tapered" ramp terminal designs. Parallel designs rely upon barrier striping to define the location of the actual merge or diverge on the freeway. These locations correspond to the "short" length in the HCM and represent the event points for ramp spacing values. Planners and designers should be familiar with the applications and considerations of parallel and taper ramp terminal forms, as their use can influence ramp-freeway junction locations.

3.3.5 Ramp Elements

Two or more successive (typical) diamond interchanges physically require cross street-to-cross street spacing of 4,300 to 5,300 ft, depending on the geometric design characteristics of the ramps and interchange (*8*). These basic geometric design considerations generally lend themselves to being able to implement one-mile interchange spacing. Interchange spacing can be separated into five distinct entrance and exit ramp segments that address three-dimensional geometric design and traffic operations between one crossroad to the next.

Each geometric segment is described in the following sections and shown in Exhibit 3-8. The design and operational needs for each segment are directly applicable to considering the influence of the entrance and exit ramp design for any interchange form. The following five segments reflect typical considerations between an upstream onramp and a downstream offramp.

- Segment 1: Crossroad to entrance gore—This minimum distance is typically in the range of 1,000 ft and is based on the need to achieve the grade change between the crossroad and freeway.
- Segment 2: Entrance gore to merging tip—The merging tip is the point at which the left edge of the ramp meets the right edge of the freeway. This distance commonly varies between 400 to 800 ft and is dependent on the form of the entrance design, such as parallel or taper.
- Segment 3: Entrance merging painted tip to exit diverging painted tip—The exit diverging tip is the point at which the left edge of the ramp meets the right edge of the freeway. This distance commonly varies between 1,600 to 2,000 ft. This distance is the dimension called out for ramp spacing in the Guidelines.
- Segment 4: Exit diverging tip to exit gore—This distance varies from 300 to 500 ft and is dependent on the diverge angle or the form of the exit design (taper or parallel).
- Segment 5: Exit gore to crossroad—This minimum distance is typically in the range of 1,000 ft but can vary significantly depending on the ramp design and ramp terminal intersection operation needs. The actual lengths should be based on the need to provide deceleration from the freeway queue storage for the ramp terminal intersection, and achieve the grade change between the crossroad and freeway.

These Guidelines recommend that ramp spacing be defined as the distance between the painted tips. Entrance and exit ramp terminal designs influence the location of the painted tips.

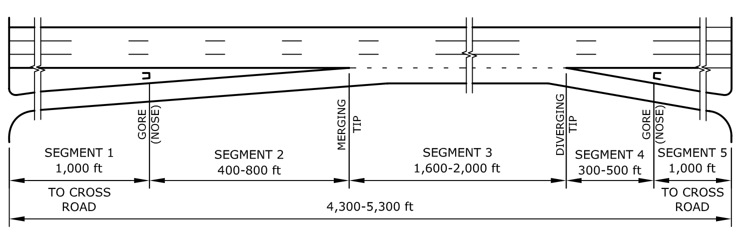


Exhibit 3-8 Dimensions of Ramp Components Between Crossroads (*8*)

The lengths of segments 1 and 5 are usually dependent on the site-specific traffic operations needs, and localize the topography and freeway and cross-street profile. Ramp lengths are affected by acceleration and deceleration needs, vehicle composition and other contributing factors, such as ramp metering storage needs on entrance ramps or ramp terminal intersection approach needs. Queue storage at the ramp terminal intersection can greatly influence ramp geometry and, ultimately, the location of the freeway exit ramp terminal.

Exhibit 3-9 provides a conceptual plan and profile example depicting horizontal and vertical relationships for a crossroad passing over a freeway. This corresponds to segments 1 and 5. Ramp lengths may also be influenced by the freeway profile grade; crossroad profile (over or under the freeway); decision sight distance on the freeway to the exit; or the sight distance along the ramp.

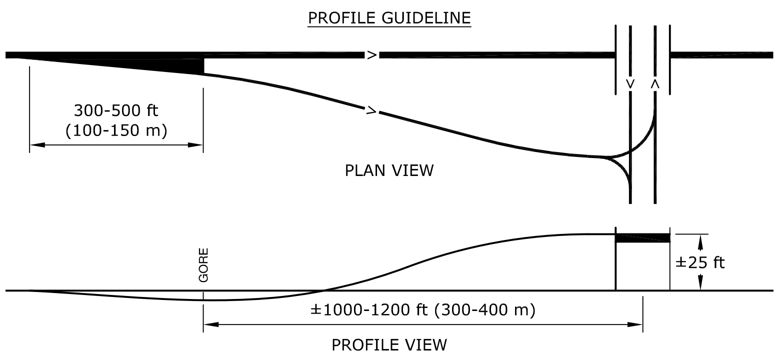


Exhibit 3-9 Conceptual Plan and Profile Example

Vertical alignment, sight distance needs, and queue storage can influence freeway exit ramp terminal locations and, therefore, ramp spacing dimensions.

Exhibit 3-10 depicts how the need to provide queue storage from a ramp terminal intersection could influence ramp length and the location of the ramp-freeway junction. This corresponds to segment 5.

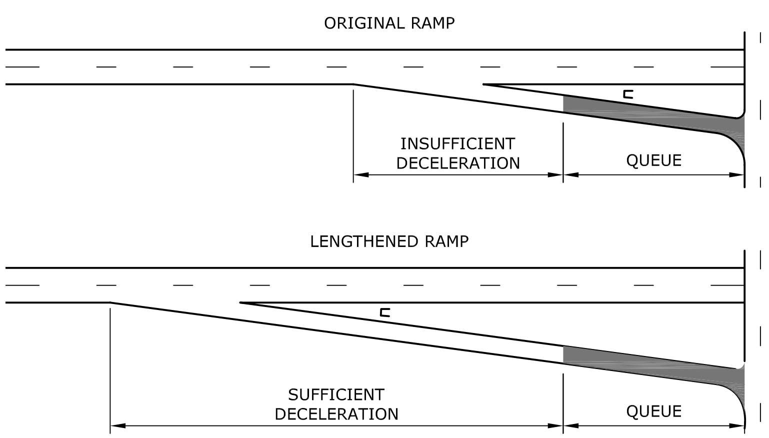


Exhibit 3-10 Effect of Queue Storage

Ramp lengths may also be influenced by the freeway profile grade; crossroad profile (over or under the freeway); decision sight distance on the freeway to the exit; or the sight distance along the ramp. Exhibit 3-11 depicts a vertical alignment that provides inadequate exit ramp decision sight and ramp stopping sight distance for a given ramp length.

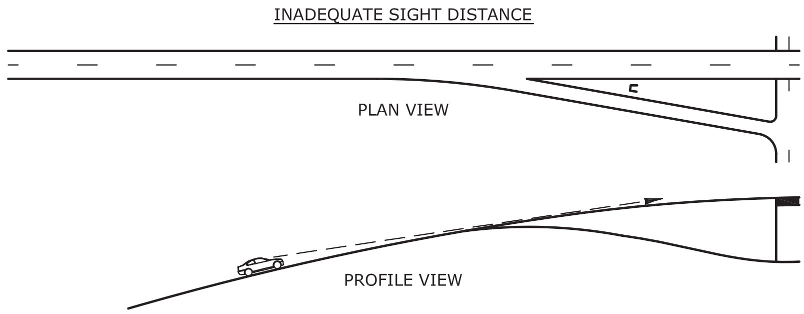


Exhibit 3-11 Effect of Grade (Inadequate Sight Distance)

Exhibit 3-12 depicts a vertical alignment that provides adequate decision sight distance and ramp stopping sight distance for the same conceptual freeway profile. This is achieved by lengthening the ramp and locating the exit diverge upstream to increase the crest vertical curve length. This fundamental concept also applies in providing entrance and exit ramp lengths that provide acceptable entrance or exit ramp profile grades.

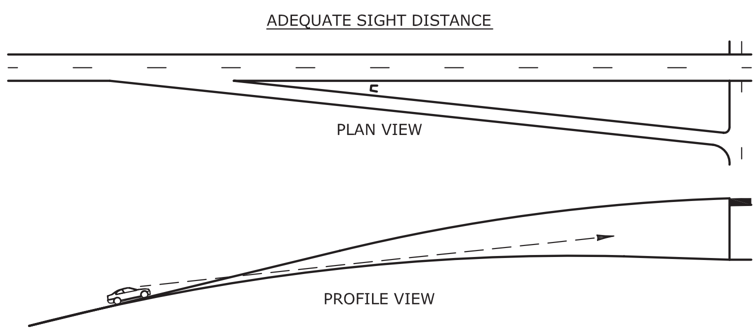


Exhibit 3-12 Effect of Grade (Adequate Sight Distance)

The AASHTO Green Book and some state design documents provide guidance on when to use an auxiliary lane.

Dimensions for segments 2 and 4 are influenced by the specific ramp terminal design values of the sponsoring highway agency. These values are affected by the type of entrance ramp (parallel or taper); the convergence angle on the merge; and gore element dimensions. Exit ramp design is affected similarly and considerations include the type of exit, the divergence angle, and the gore element dimensions. For entrance and exit designs, the gore elements, specifically the neutral area dimension, affect the overall gore width and, therefore, the length from the tip to the gore.

Ramp-to-ramp spacing dimensions can be influenced by applying “parallel” versus “tapered” ramp terminal designs. Designers and planners should understand the benefits and tradeoffs of various ramp terminal designs and how those ramp designs may affect ramp spacing dimensions.

3.4 AUXILIARY LANES

An auxiliary lane is often considered an additional freeway lane that connects adjacent on- and off-ramps. However, auxiliary lanes can include additional lanes that span the length of a freeway for several interchanges and can also include supplemental speed-change lanes (i.e., a second auxiliary lane) between adjacent interchanges.

The AASHTO Green Book notes the purpose of an auxiliary lane is to facilitate speed change, turning, storage for turning, weaving, truck climbing, and other purposes supplementary to the through traffic movement. AASHTO notes that auxiliary lanes are typically provided to improve operational efficiency in the following scenarios:

- Closely spaced interchanges;
- No local frontage roads exist; and,
- Distance between the entrance and exit terminal tapers is short (*4*).

When the distance between the successive ramps is less than 1,500 ft, the AASHTO Green Book states the speed-change lanes should be connected to provide an auxiliary lane (*4*).

Some state highway agencies provide additional guidance in determining the application of auxiliary lanes. For example, the *Caltrans Highway Design Manual* (Section 504.5, 2007) states that auxiliary lanes should be provided in cases when the weaving distance (as defined by Caltrans) is less than 2,000 ft (*13*). In addition, Caltrans notes auxiliary lanes should be considered at entrance ramp locations with significant truck volumes.

> Ramp spacing values may need to be increased if an auxiliary lane can not be included on the mainline.

Research conducted to develop these Guidelines and further discussed in Chapter 4 examined safety and operational impacts of auxiliary lanes. The research findings indicate the following:

- Auxiliary lanes have positive safety effects.
- At some ranges of traffic volumes and ramp spacings, auxiliary lanes provide major operational benefits

Continuous speed-change (auxiliary) lanes between interchange entrances and exits may also have unintended consequences. Auxiliary lanes create "weaving" sections, and weaving evaluations should be performed at the earliest stages of project development. And, depending on the configuration of the auxiliary lane and the downstream exit (i.e., a lane drop with a single-lane exit), "lane balance" may not be attained. Lane balance is described further in Section 3.1.1, but, in summary, providing lane balance reduces lane changes on the highway mainline.

Ramp spacing values may need to be increased if an auxiliary lane can not be added to the mainline for any reason (i.e., cross-section constraints such as a bridge or other right-of-way element). Increasing these values may only be possible by adjusting the location of new interchanges or by maximizing the spacing between highway ramp terminals at the expense of desirable ramp configuration qualities.

3.5 TERRAIN AND GRADES

Grades can influence the traffic capacity and operational characteristics of the freeway and the geometric design of ramps. Grade can positively or negatively impact vehicle acceleration and deceleration characteristics. The ability to adapt to ramp acceleration and deceleration needs provides flexibility and guidance on where a freeway ramp terminal entrance or exit might be located. This can directly influence ramp spacing values to adjacent ramps and interchanges.

The AASHTO Green Book provides ramp length and speed adjustments to account for ramp grade influences. For example, a ramp with a significant uphill grade may require less deceleration distance and, therefore, provide flexibility in locating a highway exit ramp terminal closer to the intended cross street. Similarly, an exit ramp with a significant downhill grade may require additional deceleration length because of the increase in speed associated with the gravitational forces acting on the vehicle. This may push the required location of a freeway exit ramp terminal farther away from the desired cross street.

Ramp spacing values can be influenced by freeway and ramp profile grades.

The HCM states the maximum extended grade on a freeway is usually 6%. The HCM notes default values of 2% grade on interstate freeways, 4% for an extended grade in rolling terrain, and 6% for an extended grade in mountainous terrain may be used in the absence of local data. Additional ramp length to adapt to prevailing profile grades can influence the location of an entrance or exit gore, and therefore, influence ramp and interchange spacing values.

3.6 VEHICLE FLEET

Interchanges and ramps should be planned and designed for an appropriate design vehicle composition. There have been changes to the typical vehicle fleet since the time in which the AASHTO interchange ramp spacing guidance was first developed. For example, while trucks have become more powerful, allowable loads have increased. Increased gross vehicle weights have countered increased truck power and limited changes in weight-to-horsepower ratios. The maximum gross vehicle weights may vary from state to state and, therefore, vehicle fleet composition may influence ramp and interchange spacing considerations to account for special acceleration or deceleration requirements.

3.7 RELATIONSHIP TO THE AASHTO POLICY

The intent of these Guidelines is to provide supplemental information in areas that may not be fully addressed within the AASHTO Green Book (*4*). For example, the Green Book has no discussion of how different interchange forms may affect the recommended minimum interchange spacing values. Similarly, the recommended minimum ramp terminal spacing values shown in the Green Book are "one-size-fits-all" values that are independent of traffic volumes. In some situations, geometric and traffic conditions may dictate greater spacing than minimums in the Green Book. In other situations, the guidance in the Green Book may be unclear. For example, the AASHTO Green Book has historically noted that ramp spacing should be measured between "like points." It is conceivable that various interpretations of the "like points" can yield a differing or inconsistent range of ramp spacing recommendations.

Chapter 10 of the Green Book titled Grade Separations and Interchanges provides general considerations for ramp and interchange spacing, as well as specific spacing information for the various ramp combinations. These Guidelines augment the information in the AASHTO policy by providing a clear distinction between the terms "interchange" and "ramp" spacing. In addition, these Guidelines suggest specific locations from which ramp spacing dimensions are measured. Finally, these Guidelines offer information about various design, operational, signing, and safety considerations when evaluating ramp spacing needs.

These Guidelines augment the information in the Green Book and provide complementary information that expands discussions on ramp and interchange spacing and the factors that should be considered when making design choices.

3.7.1 Interchange Spacing

As a rule of thumb, AASHTO suggests a minimum of one-mile interchange spacing in urban areas and a two-mile minimum in rural areas. The minimum spacing is measured between the centerlines of streets with ramps, and is determined by weaving volumes, ability to sign, signal progression, and length of speed-change lanes. In urban areas, spacing of less than one mile may be developed by grade separating ramps or adding C-D roads.

In addition to the Green Book, AASHTO also publishes *A Policy on Design Standards Interstate System* (*14*). The policy (January 2005) states that "as a rule, minimum spacing should be [1 mile] in urban areas and [3 miles] in rural areas, based on crossroad to crossroad spacing." Table 3-1 compares the interchange spacing guidance in these two AASHTO documents.

These Guidelines de-emphasize interchange spacing values between cross street centerlines and emphasize ramp design needs and associated ramp spacing values.

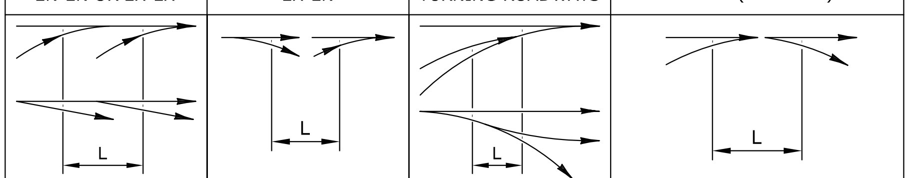
Table 3-1 AASHTO's Minimum Recommended Interchange Spacing

	All Roadways	Interstate Highways
Relevant AASHTO Policy	*A Policy on Geometric Design of Highways and Streets* (*4*)	*A Policy on Design Standards Interstate System* (*14*)
Minimum Recommended Urban Interchange Spacing	1 mile	1 mile
Minimum Recommended Rural Interchange Spacing	2 miles	3 miles

These Guidelines de-emphasize the measurement between adjacent cross-street centerlines and focus on the design, operational, safety, and signing considerations of individual ramps.

3.7.2 Ramp Spacing

Exhibit 10-68 (AASHTO 2004), shown in Exhibit 3-13, provides minimum lengths measured between successive ramps for each of the five possible ramp-pair combinations (*4*). The distance is measured between "like points," not necessarily the physical gores. A minimum distance of 270 ft is recommended between the end of the taper for the first onramp and the theoretical gore for the succeeding onramp for the entry-entry and exit-entry combinations.



EN-EN OR EX-EX		EX-EN		TURNING ROADWAYS		EN-EX (WEAVING)			
FULL FWY	C-D ROAD OR FWY.DIST.	FULL FWY	C-D ROAD OR FWY.DIST.	SYSTEM INTERCHANGE	SERVICE INTERCHANGE	SYSTEM TO SERVICE INTERCHANGE		SERVICE TO SERVICE INTERCHANGE	
						FULL FWY	C-D ROAD OR FWY.DIST.	FULL FWY	C-D ROAD OR FWY.DIST.
300 m [1000 ft]	240 m [800 ft]	150 m [500 ft]	120 m [400 ft]	240 m [800 ft]	180 m [600 ft]	600 m [2000 ft]	480 m [1600 ft]	480 m [1600 ft]	300 m [1000 ft]

Exhibit 3-13 2004 AASHTO Green Book Recommended Minimum Ramp Terminal Spacing (*4*)

These Guidelines (Chapter 5) provide minimum values that differ from the 2004 AASHTO policy.

The AASHTO Green Book provides a summary of loop ramp issues associated with cloverleaf and partial cloverleaf designs. For interchanges with loop ramps, these Guidelines will assume that ramps have been designed with proper exits and entries with appropriate acceleration and deceleration lengths provided for the respective controlling curves. Therefore, the ramp spacing values will always consider that appropriate acceleration and deceleration lengths have been provided.

AASHTO notes that loop-to-loop ramp volumes exceeding 1,000 vehicles per hour create the need for a C-D road configuration. If a loop-to-loop ramp configuration has not been designed with appropriate acceleration and deceleration lengths or the weaving volumes approach or exceed 1,000 vehicles per hour AASHTO states a C-D roadway should be considered. A C-D roadway will influence the up- and downstream ramp-freeway junction locations, which could affect ramp spacing values to adjacent existing or planned interchanges.

These Guidelines suggest the published values are a reasonable starting point in ramp spacing decisions, but they emphasize that site-specific traffic operations, safety, and signing needs should be integrated into evaluations in the earliest stages of ramp and interchange layout evaluations. Actual ramp spacing values should be determined based on considering the complete range of geometric, operational, safety, and signing needs for a particular location.

Chapter 5 of these Guidelines provides additional insights about how geometric design considerations may influence minimum ramp spacing values. Given the reference points at which ramp spacing dimensions are measured, some values differ from those in the AASHTO policy.

3.8 RELATIONSHIP TO STATE-LEVEL GUIDANCE

Many states maintain highway design and/or traffic engineering manuals that supplement national-level documents such as the AASHTO Green Book. Many of these documents provide recommended minimum dimensions for ramp and interchange spacing. The state-level dimensions are generally at or above the values in the AASHTO Green Book. A sample of state-level recommended minimum interchange spacing values are shown in Table 3-2.

Table 3-2 Sample of State DOT Guidelines for Minimum Interchange Spacing (*13, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24*)

	Urban Service Interchanges	Urban System Interchanges	Suburban or Transforming	Rural
California	1 mi	2 mi	-	2 mi
Florida*	1-3 mi	-	-	3-25 mi
Florida**	1 or 2 mi	-	3 mi	6 mi
Illinois	1 mi	-	2 mi	3 mi
New Jersey	1 mi	-	-	2 mi
Oregon	3 mi	-	-	6 mi
Pennsylvania	1 mi	-	-	2 mi

* Florida Manual of Uniform Minimum Standards for Design, Construction, and Maintenance for Streets and Highways

** Florida Technical Resource Document 1 and Plans Preparation Manual

Like the interchange spacing recommendations in the AASHTO Policy, the values in Table 3-2 are reasonable starting points when considering the feasibility of a new interchange. However, the design and placement of ramps will ultimately play a greater role in determining the adequacy of spacing. Ramp spacing values should ultimately dictate ramp and interchange spacing design decisions.

3.9 HUMAN FACTORS CONSIDERATIONS

This section summarizes some fundamental driver performance factors including age, expectations and tendencies, guidance, information distribution and handling, and driver error. Understanding and incorporating driver performance and expectations are essential to proper highway planning, design, and operation. Freeways and interchanges should consider driver capabilities and limitations, and should complement driver expectation and performance.

Human factors considerations can influence freeway and interchange design and directly influence ramp and interchange spacing dimensions.

Freeway ramp and interchange modifications or additions should consider and, to the extent possible, accommodate user needs. This means providing design elements that are consistent with driver expectations. Proposed ramp or interchange geometrics should be evaluated in conjunction with the surrounding road network. If the adjacent freeway system or subject ramp and interchange are within a context that violates design consistency and driver expectations, ramp and interchange spacing values might need to vary from "published" values to "customized" values to compensate for the specific site conditions.

For example, vintage freeway segments that lack basic lane continuity or have an inconsistent number and arrangement of ramps may require special care to ensure proposed ramps do not further degrade the overall driver experience. Further, the project's specific and anticipated users should be considered to help planners and designers understand how driver performance factors (including age, user type, expectations and tendencies, guidance, information distribution and handling, and driver error) may influence ramp and interchange spacing decisions. The ultimate design configuration selected should be consistent with and complement anticipated driver performance. Attempting to attain the intended driver performance can influence ramp and interchange configurations and affect ramp geometry and interchange spacing values.

3.9.1 Expectations and Tendencies

Each freeway and interchange project is unique, and each contextual design environment has its own range of project issues and considerations. Driver expectations and tendencies are common to any environment. Considering driver expectations within a specific contextual design environment could influence decisions on ramp and interchange spacing.

For example, an older freeway facility that includes design characteristics that are not consistent with contemporary design practice (i.e., lane drops, left exits, ambiguous route continuity) may require additional care and evaluation when considering new interchanges or ramps when compared to a similar highway incorporating desirable attributes that meet driver expectations. Similarly, at isolated interchanges drivers have the expectation that their exit will be in advance of their destination, or that the designated cross-road destination will be reached directly by the freeway ramp versus passing through a secondary roadway at which the ramp terminates.

Drivers have certain expectations when they are traveling along a freeway or navigating through an interchange; they include the following:

- A continuous through lane will not be dropped at an interchange;
- The straight alignment of a roadway will generally be the dominant route;
- Navigating a turn will require a speed reduction;
- An exit will be on the right side of the freeway; and,
- Signs will provide adequate information to make navigation decisions.

While traveling on a specific freeway, drivers may form expectations based upon unique aspects of the facility. For example, on a freeway with series of diamond interchanges spaced one-mile apart, a partial cloverleaf interchange one-half mile downstream for the previous interchange may be unexpected to drivers.

Decision sight distance should be provided at lane drops and exit ramps. Providing decision sight distance can influence ramp spacing values.

Drivers also have tendencies specific to freeways that can affect the operations, design, and safety of a facility. Drivers tend to:

- Travel at relatively high speeds (50 mph or greater) where deterrents are few and free-flow characteristics are present.
- Enter and exit curved roadways in a transitional path.
- Enter and exit high-speed freeways by a direct and gradually merging or diverging maneuver.

Considering and meeting driver expectations will influence freeway interchange, and ramp configurations. Providing configurations that meet driver expectations can directly influence ramp and interchange spacing values.

3.9.2 Decision Sight Distance

Decision sight distance is the sight distance required to detect an unexpected or otherwise difficult-to-perceive condition and then react safely with the appropriate maneuver. Decision sight distance accounts for the possibility of driver error and the ability to make corrective actions.

Decision sight distance should be provided whenever there is the likelihood for error in information reception, decision making, or control actions. Interchanges are locations where unusual or unexpected maneuvers can be required because of roadway changes, traffic control devices, and activity related to merging and diverging. Decision sight distance should be considered at interchanges and areas where drivers may be exposed to multiple information sources, and be provided at lane drops.

Ramp and interchange spacing decisions influence the complexity of the roadway environment and, therefore, providing decision sight distance should influence the design decisions. Attaining decision sight distance may require locating a highway exit terminal so that drivers can interpret and navigate appropriately. This may involve shifting an exit ramp terminal "upstream" of a mainline crest vertical curve that otherwise would block the view of an intended ramp, or locating an exit gore in advance of a cross-street overpass to meet drivers' expectations before they reach a destination or simply to ensure adequate visibility of exit and mainline signs.

3.9.3 Driver Workload

Interchanges and ramps have been integral parts of the roadway network since the 1920s. And though ramps and interchanges are common, they remain surprisingly complex roadway elements as they shift traffic from one facility to the other, often with high volumes and at high speeds. The complexity of freeways, interchanges, and ramps can increase based on a facility's contextual environment. Driver workload increases in complex environments and should be accounted for in ramp design decisions.

Professionals contemplating adding new interchanges or ramps or modifying existing ramps should consider overall driver workload to aid in ramp spacing decisions. Interchange and ramp design decisions should favor solutions that clarify roadway driving needs, separate driver decision making, and reduce conflicts. Providing configurations that minimize or reduce driver workload could influence ramp and interchange spacing values.

> Signing is a key human factors consideration that can influence ramp and interchange design, and therefore, ramp spacing dimensions.

Whether natural or man-made, there are other physical constraints that affect roadway geometric design configurations that should be considered in ramp and interchange spacing evaluations. Some of these factors include curvilinear alignments that may affect driver control and workload; constrained cross sections that may affect on- and offramp designs; and longitudinal grades that affect freeway mainlines, cross-street profiles, and ramp layout. Individually or combined, these factors influence planning and design decisions for ramp and interchange spacing.

3.9.4 Signing Controls

This section discusses signing considerations and how they influence ramp and interchange spacing. For example, depending on a project's context, a complex isolated interchange with multiple destinations may increase the needed number of sign panels and message units. The number of message units and the minimum sign spacing requirements could conceivably be a primary control in determining an interchange location or ramp configuration. Similarly, a complex urban freeway network's guide signing requirements could influence a decision about allowing a new interchange or set of ramps within a given roadway segment.

Guide signs are used by drivers as a navigational aid while they travel. On freeways, guide signs identify upcoming exits in advance of and at the ramp itself. Ideally, signing should provide enough information for drivers to identify and locate exits, but not so much information that drivers are overwhelmed with more information than they can comprehend. Other attributes of good freeway signing include the following:

With simple interchanges, signing needs typically have little influence on ramp spacing decisions.

- Clear and predictable,
- Uniform,
- Prioritizes most important information,
- Provides adequate advance notice of exits, and
- Does not overwhelm drivers.

The MUTCD includes guidance on signing and marking for interchange elements. The MUTCD and other documents discussed in the sections below quantify how much information is "too much" for freeway drivers to process. General thresholds include the following:

- No more than three guide signs at the same location,
- No more than two destination or street names on a single guide sign,
- No more than one destination or street name on a guide sign placed next to other guide signs, and
- Only one guide sign in the vicinity of an exit gore (*6*).

Signing generally does not influence ramp and interchange spacing. Geometric and operational needs usually require exit ramps to be spaced far enough apart that they can adequately be signed without overloading drivers with too much information. However, this may not be the case if interchanges are complex, more information than usual needs to be presented for a given exit, or there are several successive exit ramps without corresponding entry ramps such as in a central business district.

With complex interchanges and high exit ramp density, signing needs may determine if an alternative is feasible or help dictate the corresponding ramp spacing dimensions.

Case Studies 1 and 2 illustrate situations where it can quickly be determined that a new interchange can easily be signed and relatively little analysis of signing is necessary. Case Study 5 illustrates a complex environment with many exits, including a major fork. In that situation, a complete layout of signing extending several interchanges upstream and downstream of the proposed interchange helps assess whether the proposed interchange is feasible. Ultimately, signing requirements influenced the interchange form selected in this Case Study.

3.9.4.1 ADVANCE GUIDE SIGNS

MUTCD Chapter 2E: Guide Signs for Freeways and Expressways provides specific sign location information. The MUTCD addresses three specific signing considerations that may influence ramp and interchange spacing considerations: Minimum sign spacing between signs, advance guide sign placement, and driver workload associated with processing sign content. The MUTCD states the spacing between sign locations should be a minimum of 800 ft (*6*). The signs should integrate with other information that is presented to the driver and should be located within the driver's visual field to allow for easy decision making and adequate time to maneuver.

The MUTCD recommends that at least three advance guide signs are added to an interchange at the following locations:

- 1 mile,
- 0.5 mile, and
- Exit Gore (*6*).

Chapter 5 offers guidelines on how closely successive exit ramps can be spaced while still satisfying signing needs.

If spacing allows, an additional advance guide sign could be placed two miles in advance of the exit (*6*).

In practice, two or three advance guide signs are generally placed upstream of the exit gore as recommended by the MUTCD, but the distance upstream may vary on freeway segments with several closely spaced interchanges.

If possible, ramps and interchange should be spaced far enough apart to avoid the use of interchange sequence signs.

Where interchanges are too close together for a series of advance guide signs to be used, the MUTCD allows Interchange Sequence Signs (*6*). These signs may show the exit number, street name, and distance for up to three interchanges. These signs cannot display as much information per interchange as an advance guide sign, and they are not recommended except for at existing interchanges that otherwise could not be signed.

3.9.4.2 SIGNING AND MESSAGE UNITS

When interchanges are closely spaced, overhead signs are often used so that more than one sign can be placed at the same location. However, if too many signs containing too much information are placed at one location, drivers may not be able to read or comprehend all of the information that they contain. To prevent driver overload, signs should be spread out. The MUTCD states that no more than three guide signs should be displayed on a single overhead structure and support (*6*). Additionally, the exit direction sign should be the only sign placed in the vicinity of the gore. If ramp and interchange configurations and spacing alternatives require signing exceeding these limits, these alternatives should be ranked lower than others that can meet signing needs.

The ITE *Freeway and Interchange Geometric Design Handbook* (ITE *Freeway Handbook*) and the *Texas Freeway Signing Handbook* provide additional guidance on the maximum amount of information that should be presented to drivers at a single location. In addition to limits on the number of sign panels, these documents provide recommendations on the total number of message units (pieces of information) that should be presented to a driver at a sign structure. Examples of message units include city names, route numbers, exit numbers, and lane-use arrows. Exhibits 3-14 and 3-15 present recommended limits on sign panels and message units from the ITE *Freeway Handbook* and the *Texas Freeway Signing Handbook* (*8, 12*).

Alternative interchange or ramp design configurations that cannot meet MUTCD objectives should be ranked lower than alternatives that provide appropriate driver messages.

Exhibit 3-14 Message Unit Limits, ITE *Freeway Handbook* (*8*)

NUMBER OF SIGN PANELS IN SERIES AT ONE LOCATION		NUMBER OF MESSAGE UNITS*			
		MAX. PER SIGN		MAX. TOTAL ASSEMBLY	
NUMBER	APPLICATION	DESIRABLE	ABSOLUTE	DESIRABLE	ABSOLUTE
1 □	FREQUENTLY	5	6	5	6
2 □□	OCCASIONALLY	4	5	8	10
3 □□□	SPECIAL CASE	3	4	9	11
4 □□□□	NEVER	–	–	–	–

These Guidelines emphasize that while signing considerations do generally not influence ramp and interchange spacing, they can. A quick and simple check of sign sequencing and the number of message units should be performed in the earliest stages of concept development.

Exhibit 3-15 Message Unit Limits, *Texas Freeway Signing Handbook* (*12*)

	Units of Information per Structure	
Number of Sign Panels	Desirable	Maximum
2	12	16
3	16	18
4	18	20
5	Undesirable Design	20

* Source: McNees, R.W. and C.J. Messer. Reading Time and Accuracy of Response to Simulated Urban Freeway Guide Signs. in *Transportation Research Record 844*, Transportation Research Board, Washington, D.C, 1982.

In some cases, it is appropriate to modify interchange configurations to simplify signing requirements.

To remain within intended message unit limits, sign panels could be simplified or otherwise divided into multiple signs to better distribute advance messages. These signs and their placement would need to be considered within the context of existing or planned signs for the corridor. To increase comprehension of sign content, minimum sign spacing requirements may affect sign layout and placement. The desired layout may not be achievable in some contextual design environments. Similarly, complex signs increase driver workload to comprehend the message units and require increased time for drivers to perceive and react to the signs. Providing increased driver perception and reaction times between the displays and the downstream location where the action is required may influence ramp spacing decisions. In some cases, if signing becomes too complex professionals may elect to consider other roadway or interchange configurations to simplify overall signing needs.

3.9.4.3 EFFECT ON RAMP AND INTERCHANGE SPACING

The following two principles noted in the prior sections constrain the number of exit ramps that are desirable:

- At least two signs in advance of the exit gore (1 mile and ½ mile upstream are recommended) and
- No more than three sign panels at one location.

These constraints effectively create a limit of three exit ramps (for separate interchanges) within a one-mile freeway segment. Upstream or at the start of the one-mile segment, there would be a location with a sign panel for each of the three exit ramps. A fourth exit ramp could be added towards the downstream end of the segment if it served the same interchange as one of the other ramps. This would allow at least one of the advance guide signs for the forth ramp to be combined with the advance guide sign for the other ramp serving the same interchange. A pattern of three (or four as described above) exit ramps per mile could be repeated indefinitely. However, such designs are generally not feasible for issues unrelated to signing.

The threshold of three exit ramps per mile assumes that the exits do not require any type of special signing. System interchanges, exits signed with diagrammatic signs, and exits serving a large number of roadways or destinations are examples of situations where three ramps per mile may be infeasible and a more detailed analysis of sign and message unit requirements should be conducted. In these cases, in particular, designs may be infeasible due to signing requirements.

Chapter 4 Operational and Safety Considerations

This chapter provides an overview of the various operational considerations and elements that affect choices and decisions about ramp and interchange spacing. In general, traffic operations and safety evaluations should be included as an integral part of the initial geometric evaluations of potential ramp configurations.

4.1 TRAFFIC OPERATIONS OVERVIEW

Professionals need to conduct an appropriate level of traffic operations analysis commensurate with the stage of the project development process (planning, location, or final design) to support ramp and interchange spacing decisions. The analysis should be consistent with the data available, and data should be consistent with the analysis tools applied.

Operational considerations should begin at the earliest stage of project development and integrated with the geometric design considerations. This means evaluating lane numbers and arrangements along the highway and ramp series and considering the types of analyses that should be performed (i.e., ramp merge and diverge, mainline capacity, and weaving sections). In addition, this means considering ramp terminal intersection operations and understanding how predicted operations (lane numbers, arrangements, queuing, deceleration, and stopping sight distance to the back of queue) may influence the ramp and interchange layout.

Operational analysis for basic planning applications can likely be conducted with limited data that is often available during the planning stages of a project. Hourly ramp and freeway volumes, operating speeds, lane numbers, and ramp configurations should be assessed to guide geometric design decisions. The *Highway Capacity Manual* (HCM) and the ITE *Freeway Handbook* provide planning-level operational analysis procedures. Many state highway agencies provide general guidance concerning ramp and freeway service volumes and the number and arrangements of needed lanes. This guidance can be used to aid design decisions as ramp and interchange configurations are being developed. Some basic freeway-related capacity thresholds from the HCM are shown in Table 4-1.

Professionals could include total ramp density as a factor in evaluating interchange forms and ramp configurations.

Table 4-1 Approximate Capacity of Freeway-related Roadway Elements, 2010 HCM (*5*)

Element	Service Volume
Freeway Lane	2,250 – 2,400 passenger cars per hour
Single-Lane Ramp*	1,800 to 2,200 passenger cars per hour
Merge Influence Area (on-ramp plus right two lanes of freeway)	4,600 passenger cars per hour
Diverge Influence Area (off-ramp plus right two lanes of freeway)	4,400 passenger cars per hour

* Basic ramp segment only, does not consider ramp terminal operations.

The ITE *Freeway Handbook* also provides a tool for assessing merges and diverges. For both entry ramps and exit ramps, the handbook includes charts that require only freeway volume, ramp volume, and number of lanes as an input to determine if a ramp-freeway junction is below, near, or over capacity. Planning-level operational considerations can influence ramp and interchange configurations and, therefore, ramp spacing values.

4.2 HIGHWAY CAPACITY MANUAL PROCEDURES

These Guidelines are not intended to replace the use of the HCM in the interchange planning and design process. Instead, they are intended to bring traffic operations considerations into the planning process at an early stage to consider the operational considerations and associated influence on ramp spacing values.

Three HCM chapters are most relevant to ramp and interchange spacing: basic freeway segments, freeway weaving segments, and freeway merge and diverge segments.

The HCM addresses interchange and ramp spacing and density in discussions related to basic freeway segments, weaving segments, and ramp-freeway junctions. On a basic freeway segment, estimated free-flow speed decreases as the number of ramps per mile (total ramp density) increases. In a weaving section, speeds and level of service (LOS) decrease as the segment shortens. At a ramp-freeway junction, the presence of an adjacent ramp influences the density and LOS in some cases.

An overview of 2010 HCM procedures from the three chapters most relevant to ramp and interchange spacing are presented in the following subsections. Although not detailed in these Guidelines, service interchange ramp terminal intersections should also be evaluated using HCM and other traffic engineering procedures to understand how ramp terminal intersection operations influence lane numbers and arrangements and queue lengths.

These can influence overall ramp design configurations and ramp spacing values.

4.2.1 Basic Freeway Segments

The mainline, or basic, freeway segment occurs between ramp merge and diverge areas and can include basic lanes, auxiliary lanes, or high-occupancy vehicle lanes. Free-flow speed (FFS) is the performance metric for basic freeway segments, and is defined as the average speed of passenger cars on a uniform freeway segment with moderate volume. Interchange spacing and ramp density influences a freeway's estimated FFS.

FFS on a basic freeway segment decreases as more ramps are added. However, the spacing between the ramps does not impact estimated FFS. FFS may be measured or estimated with equation 4.1 (*5*):

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84}$$

To predict FFS, the HCM assumes a base free-flow speed of 75.4 mph and applies reductions based upon lane width (f_{LW}), right-side lateral clearance (f_{LC}), and total ramp density (TRD). TRD is expressed in terms of ramps per mile and is measured over a six-mile segment of freeway—three miles upstream and three miles downstream of the point on the freeway being studied. Both onramps and offramps are included. The researchers who developed the FFS prediction equation considered including interchange density, onramp density, and offramp density instead of TRD, but ultimately found that TRD best predicted FFS (*25*).

According to the HCM, the number of ramps impacts FFS, but ramp spacing does not. Total ramp density has the greatest impact on FFS.

Exhibit 4-1 shows the impact of ramp density on FFS using the prediction model in the 2010 HCM. A freeway with three-mile diamond interchange spacing would have two ramps every three miles, or 0.67 ramps per mile. This ramp density will decrease predicted FFS by 2.3 miles per hour compared to an "ideal" six-mile section of freeway that has no ramps. A freeway with one-mile diamond interchange spacing, as is common in many urban areas, will have two ramps per mile and decrease predicted FFS by 5.8 mph in comparison to an ideal segment. One-mile spacing of full cloverleaf interchanges (four ramps per mile) would decrease predicted FFS by 10.3 mph.

Complete HCM analyses should be conducted as applicable reflecting the relative accuracy of the level of engineering detail available while using the analysis results to guide and influence geometric design considerations.

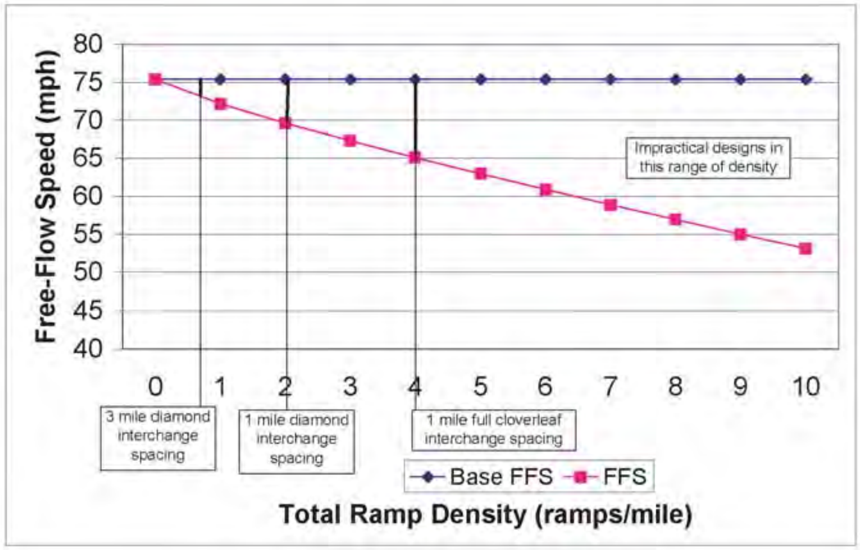


Exhibit 4-1 Impact of Total Ramp Density on Basic Freeway Segment Free-Flow Speed (*5*).

4.2.2 Freeway Merge and Diverge Segments

Merge and diverge areas exist at ramp-freeway junctions at which a lane is not added or dropped. Operationally, it is desirable to separate merge and diverge influence areas to the extent possible so the combination or overlap of these two areas does not cumulatively degrade mainline performance. Therefore, ramp and interchange spacing dimensions can be affected by attempting to separate or reduce the overlap of these influence areas. Exhibit 4-2 schematically presents these conditions.

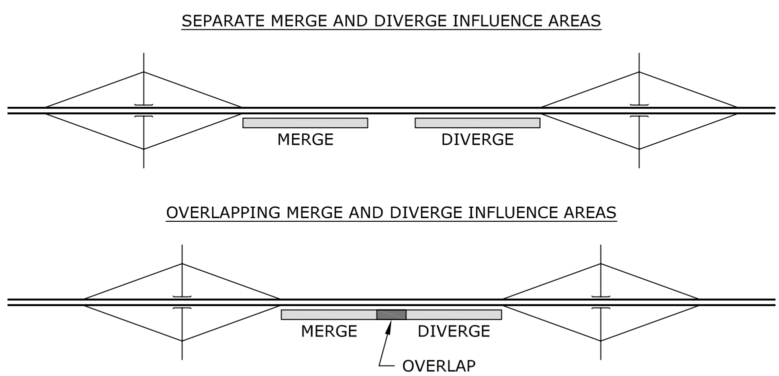


Exhibit 4-2 Merge and Diverge Influence Areas

Merge and diverge areas are limited by definition to the right two lanes of the freeway and the associated acceleration or deceleration lane because studies have shown that this is where most turbulence occurs (*5, 23*). The methodology of the HCM identifies influence areas to be approximately

1,500 ft in length. However, certain designs could increase this length. For example, two-lane ramps which are developed with auxiliary lanes may exert an influence on the freeway as far upstream/downstream as the auxiliary lane extends.

In moderate- to high-volume freeway or ramp conditions, increased ramp spacing may be considered to separate merge and diverge overlap areas. In locations of extreme volumes and low capacities, the ramp spacing may have little influence on traffic operations since the individual merge and diverge condition or freeway mainline capacity limitation may dominate the influence of ramp spacing values.

The 2010 HCM provides separate merge and diverge procedures for four-, six-, and eight-lane freeways. On six-lane freeways, merge segment operations improve as the distance to an adjacent downstream offramp increases or as the distance to an adjacent upstream offramp decreases. Also, on a six-lane freeway, diverge segment operations improve as the distance to an upstream onramp or a downstream offramp increases. The following two paragraphs discuss the reasons for this. Although these basic relationships would intuitively apply to all freeways, data used to create the HCM procedures only indicated this trend on six-lane freeways. As a result, HCM merge and diverge analysis procedures only take adjacent ramps into consideration on six-lane freeways. The HCM does not specify an upper boundary for what is considered "adjacent," but, in general, the HCM models are not sensitive to adjacent ramps that are more than one mile apart regardless of volume.

For six-lane freeways, HCM merge and diverge procedures are sensitive to adjacent ramps, and therefore, ramp spacing values become a key operational consideration.

For a merge, a greater distance to a downstream exit ramp results in fewer vehicles in the merge influence area (fewer vehicles have changed to right side lane in preparation for the exit) and improved ramp-freeway junction operations. Likewise, a shorter distance to an upstream exit ramp also results in fewer vehicles in the merge influence area and improved operations. In the case of the downstream exit ramp, the volume of the ramp plays a role in merge influence area operations (greater volume decreases operational performance) in addition to the distance to the ramp (*5, 26*)

Ramp spacing is one of many factors that determine weaving segment LOS. Target LOS can influence ramp spacing dimensions.

For a diverge, a greater distance to an upstream entrance ramp or a greater distance to a downstream exit ramp will result in fewer vehicles in the diverge influence area and thus improve operations. In both cases, greater volume on the adjacent ramp also decreases operational performance.

4.2.3 Weaving Segments

Weaving segments are formed when a merge area is closely followed by a diverge area and the resulting lane configuration requires two or more traffic streams to cross. The means of determining what is "close" are discussed in the following paragraphs. The length of the weaving segment (the spacing between the entry and exit ramp) is one of many factors that determines the operation of the segment. Generally speaking, the speeds and LOS within a weaving segment decrease as the segment shortens.

These Guidelines and the 2010 HCM use a different definition of weaving segment length than past editions of the HCM

Historically, many weaving segments were between loop ramps and the length of a weaving section was defined in terms of criteria specific to loop ramp design (*27*). This length was measured from a point at the merge gore where the right edge of the highway shoulder lane and left edge of the merge lanes are 2 ft apart to a point at the diverge gore where the two edges are 12 ft apart. The maximum length for which the weaving analysis was conducted was 2,500 ft. Beyond this distance, the merge and diverge areas were considered separately regardless of traffic volume or other factors. Because this description was applied for many years, a number of transportation agencies may still include this method of measuring weaving length in their documentation.

In reality many weaving segments today are between adjacent interchanges rather than loop ramps within the same interchange. Research conducted in the past few years and incorporated into the 2010 HCM focused on weaving between non-loop ramps and considered several ways of defining weaving segment length (*27*). Exhibit 4-3 and Table 4-2 present these different measurements, and the corresponding AASHTO event points.

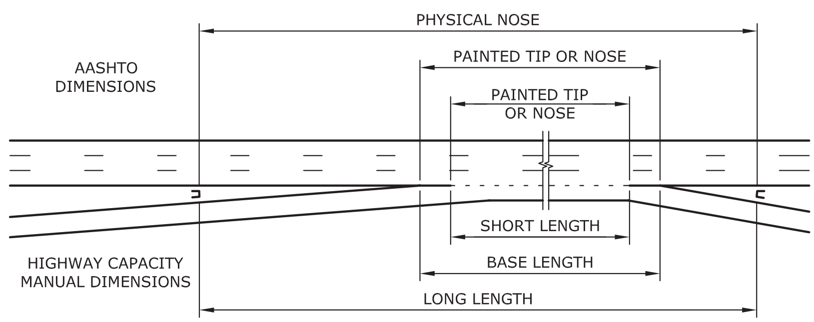


Exhibit 4-3 Definitions of Weaving Segment Length (*4, 5*)

Table 4-2 Design Event Points in Resource Documents

Description	HCM	AASHTO
The distance between the end points of any barrier markings that prohibit or discourage lane changing.	Short length	“painted tip” or “painted noses”
The distance between points in the respective gore areas where the left edge of the ramp travel lanes and the right edge of the highway travel lanes meet.	Base length	“painted tip” or “painted noses”
The distance between physical barriers marking the ends of the merge and diverge gore areas.	Long length	“physical noses”

Of the three potential definitions of weaving segment length depicted above, the researchers developing the weaving procedures for the 2010 HCM found the "short length" best predicted weaving operations (*27*). The short length is measured between the end points of barrier markings (such as solid white stripes) that prohibit or discourage lane changes. This definition is different than the one used in these Guidelines. These Guidelines define ramp spacing as the distance between painted gores, which is shown in Exhibit 4-3 as the "base length." If barrier markings do not exist, then short length is measured between the painted gores. In such a case, the spacing definition in the HCM and these Guidelines is the same.

To provide planning-level tools to understand how weaving may or may not influence ramp spacing decisions, these Guidelines contain some high-level aids that provide insights about the presence of weaving using procedures from the HCM. To determine if ramps are "close enough" for a weaving segment to exist, one must count the number of lanes from which a weaving maneuver may be made with one or no lane changes (N_W). In order to have weaving, there will always be two lanes ($N_W = 2$). For major weaves, N_W will equal two or three. Exhibit 4-4 depicts a weaving section where one of the weaving movements requires two lane changes.

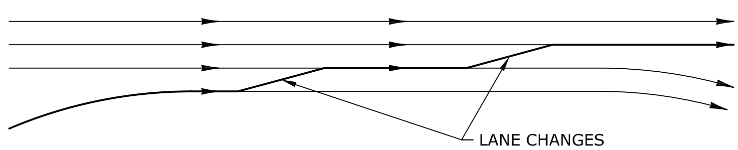


Exhibit 4-4 Weaving Segment With Two Lane Changes for One of the Weaving Movements

If ramps get "far enough" apart, the freeway segment between them will operate as a basic segment rather than a weaving section. Exhibit 4-5, which was developed from the HCM equation that determines maximum weaving segment length, can be used to check if this condition exists. For example, if an entry ramp and exit ramp with an auxiliary lane are spaced 2,000 ft apart and there are 800 weaving vehicles out of 2,000 total vehicles in the section (ratio of 0.4), an HCM weaving analysis should be performed.

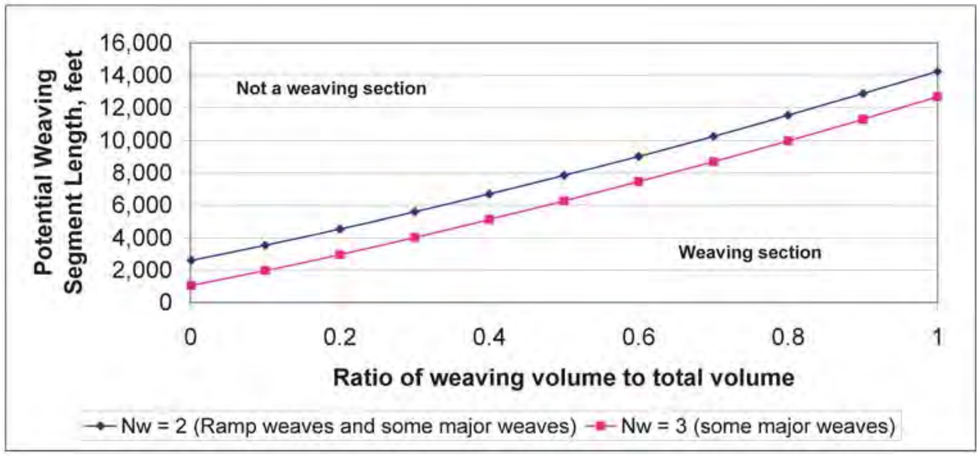


Exhibit 4-5 Maximum Weaving Segment Length. Adapted from (5).

Planning-level tools can aid professionals in the types of operational analysis that might be needed to support informed ramp and interchange spacing decisions.

If Exhibit 4-5 indicates that a weaving segment exists for the location under study, then a full weaving analysis should be conducted using the HCM's methodology to evaluate the weaving segment operations. This aid can be used at the earliest planning level to understand the range of traffic operations analyses that might be needed to confirm ramp spacing decisions.

4.3 OTHER PLANNING-LEVEL OPERATIONAL GUIDELINES

The HCM provides analysis procedures for many common ramp and interchange forms and designs, but not all possible situations. In particular, the HCM provides little guidance on how the spacing between two ramps impacts freeway speed. In developing these Guidelines, this relationship was investigated through simulation modeling and the limited information in the HCM.

4.3.1 Simulation Modeling

Simulation modeling of four freeway lanes in each direction (eight lanes total) with consecutive entry ramps and an entry ramp followed by an exit ramp (without an auxiliary lane) found that ramp spacing usually had little impact on freeway speeds at low to moderate freeway volumes (1,500 vehicles per hour per lane (vphpl) or less). Entry-exit ramp combinations when exit-ramp volumes are near capacity (1,750 vphpl) are an exception to this. During these modeling scenarios, ramp spacing did have a significant impact (up to 15 mph) on freeway speed at low to moderate freeway volumes.

At higher freeway volumes (1,750 vphpl), decreased spacing between ramps had a significant impact on freeway speeds. For entry-exit ramp combinations the impact was up to 15 mph, and for entry-entry ramp combinations the impact was up to 10 mph. Spacing impacts of entry-exit ramp combinations are shown in Exhibit 4-6.

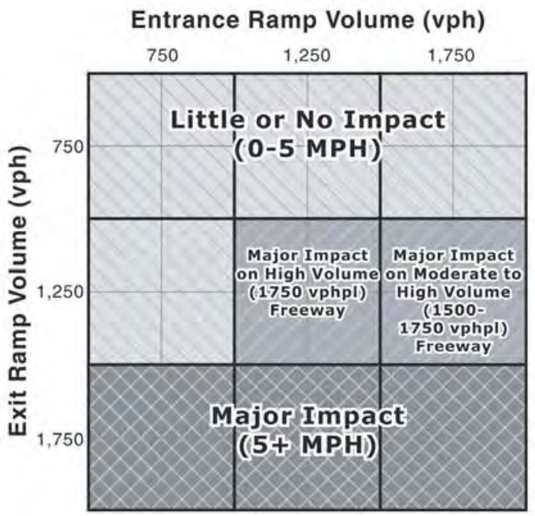


Exhibit 4-6 Impact of EN-EX Ramp Spacing on Freeway Speed. "Major" Impact defined as 5+ MPH

Decreased ramp spacing generally has a significant impact on freeway speeds when the freeway is operating with high volumes.

In general, entry-exit ramp combinations have a greater impact on freeway speed than entry-entry ramp combinations. Also, for entry-exit ramp combinations, increased exit ramp volume has a greater impact on freeway speed than increased entry ramp volume.

Ramp spacing generally has little influence on freeway speeds when the freeway has low to moderate volumes and the entrance and exit ramps operate below capacity.

The HCM provides a procedure for analyzing closely spaced entry-exit ramp combinations with auxiliary lanes (weaving segments), but does not provide information on the performance of a weaving segment in comparison to a closely spaced entry-exit combination without an auxiliary lane. Simulation modeling identified that adding an auxiliary lane between an entry ramp and an exit ramp is operationally beneficial. Regardless of ramp spacing, adding an auxiliary lane generally improved freeway speed by 5 mph or more if at least one of the ramps had moderate to near-capacity volume (1,500-1,750 vphpl) as shown in Exhibits 4-7 and 4-8.

The HCM does not provide an analysis procedure for closely spaced entrance-exit ramps without auxiliary lanes. Simulation quantified the operation benefits of auxiliary lanes.

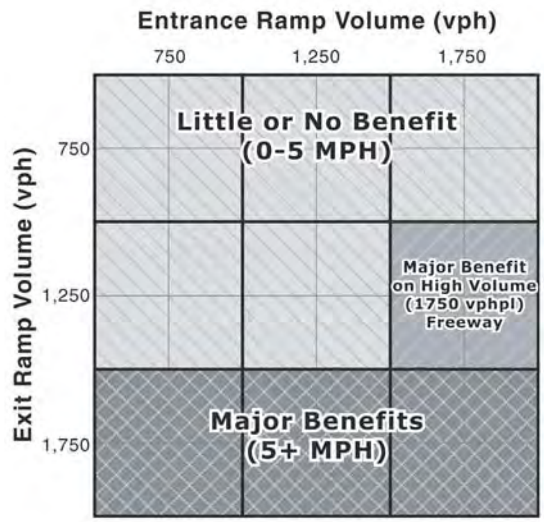


Exhibit 4-7 Benefit of Auxiliary Lane on Freeway Speed with 1000' ramp spacing. "Major" Benefit defined as 5+ MPH

Regardless of ramp spacing values, adding an auxiliary lane generally will improve freeway speeds compared to a no-auxiliary-lane condition.

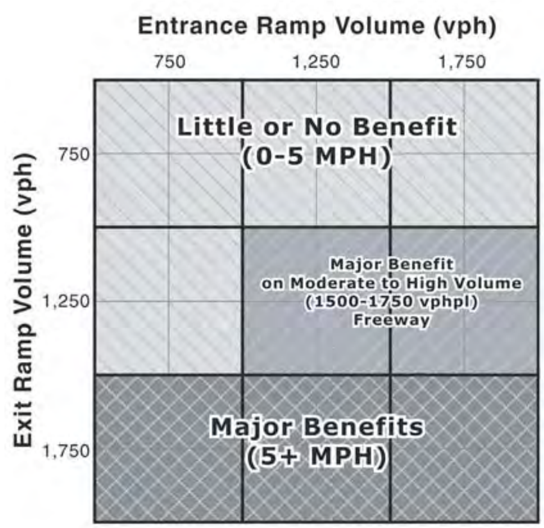


Exhibit 4-8 Benefit of Auxiliary Lane on Freeway Speed with 2500' ramp spacing. "Major" Benefit defined as 5+ MPH

4.3.2 Planning-Level Application of HCM Procedure

In most cases, there is little flexibility with the spacing of exit-entry ramp combinations because the ramps are part of the same interchange and spacing is generally determined by interchange form. Of the remaining ramp combinations, entry-exit is the most common. Using the merge analysis procedures and traffic volumes for the freeway and ramps, the minimum ramp spacing needed for a desired LOS can be determined for six lane freeways.

Exhibit 4-9 is a chart developed from a HCM merge procedure for six-lane freeways (three lanes in each direction). This chart can be used to consider ramp and freeway volumes to evaluate whether approximate entry-exit ramp spacing values will create a design that achieves a desired LOS. Such charts can be used in a project's initial planning stages to quickly test whether conceptual designs are feasible from a traffic operations perspective. The chart shown in Exhibit 4-9 is for LOS D. Charts developed for LOS C, D, and E are included in Appendix B.

Chart users should begin by finding the volume of the freeway being studied on the x axis. Users should then find the set of curves associated with the volume on the entry ramp. In Exhibit 4-9, curves are provided for entry ramp volumes of 500 vehicles per hour (vph) and 1,750 vph for ease of presentation. For example, with a one-direction, three-lane freeway volume of 3,000 vph and an entrance ramp volume of 1,750 vph, proposed ramp spacing of 3,500 ft should result in LOS D or better operation on the freeway regardless of the volume on the downstream exit ramp.

Planning-level tools can help correlate various target levels of service with ramp spacing values.

However, with the same freeway and entrance ramp volumes, if the proposed ramp spacing was only 2,500 ft, LOS D or better operation would be achieved with a downstream exit ramp volume of 800 vph, but not with a downstream exit ramp volume of 1,200 vph or 1,750 vph. For entrance and exit ramp volumes not shown in Exhibit 4-9, users can interpolate between ramp volumes.

These tools can assist users in quickly assessing various freeway interchange or ramp spacing alternatives and assess how these alternatives meet various levels of service targets.

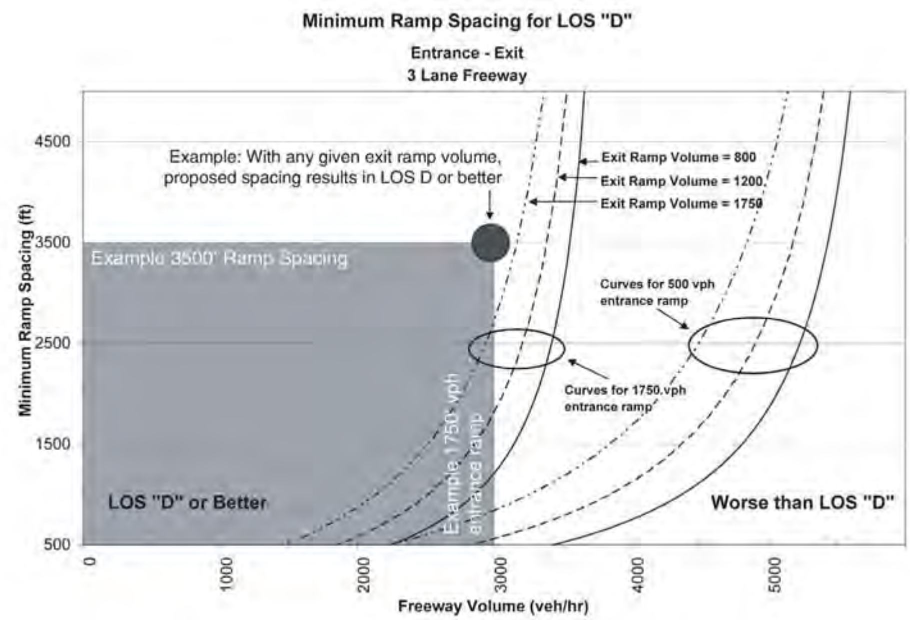


Exhibit 4-9 Example of Minimum Ramp Spacing Guidance Developed from HCM Ramp-Freeway Junction Procedure

Charts for other target levels of service are presented in Appendix A.

The charts shown in Exhibit 4-9 and Appendix B are not replacements for a complete HCM analysis. These charts are based on assumptions of some inputs into the ramp-freeway junction procedures (such as the peak-hour factor, the vehicle mix, and acceleration lane length). Exhibit 4-9 is intended to give planners and designers a means of assessing whether interchange concepts are likely to be feasible at the earliest stage of project development. Concepts that are likely feasible would warrant further investigation using complete HCM procedures.

4.4 MICROSIMULATION

Microsimulation is the most detailed and data-intensive analysis that could be conducted for estimating the traffic operations on a highway and at an interchange. There are multiple types of microsimulation tools and some are more effective at estimating highway operations than others. Microsimulation tools require an extensive amount of data that is often not available for all types of projects. Therefore, these types of analysis tools should be applied appropriately, given the amount and type of data available and the specific needs of the project. Microsimulation tools can be helpful in investigating complex ramp sequencing scenarios and the queue interactions of ramp terminal intersection traffic control or ramp metering relationships.

4.5 SAFETY

This section provides an overview of relationships between ramp spacing and safety. A traditional, criteria-based view of the ramp spacing/safety relationship is followed by a discussion of a substantive safety approach to ramp spacing. These Guidelines are consistent with safety analysis approaches in AASHTO's Highway Safety Manual (HSM). This section compares interchange spacing and ramp spacing dimensions in the context of safety analysis. Also, this section includes a description of observed and modeled relationships between ramp spacing and safety for three ramp scenarios: (1) an entrance ramp followed by an exit ramp, (2) two consecutive entrance ramps, and (3) an exit ramp followed by an entrance ramp.

Freeway interchange ramps, by definition, coincide with increased vehicle lane changing, acceleration, and deceleration adjacent-to and on the freeway mainline. Observable operational measures, including density, average speed, and speed differentials, as well as the higher cognitive and decision-making demands on drivers at, near, and between interchange ramp locations are often used as surrogates to deduce lower expected levels of safety on freeway segments with increased ramp presence. Historically, expected crash patterns at ramp locations, including crash frequencies, crash severities, and crash types, were relatively unknown.

4.5.1 Traditional View of Ramp Spacing and Safety

The transportation profession has traditionally taken a nominal approach to safety analysis; a design alternative either meets all geometric design criteria or does not. Acceptable safety performance, measured by having low crash risk, is presumed to result from attaining desired design criteria. If the criteria is achieved, the design is presumed "safe." If minimum values are not attainable, the design is presumed "unsafe." This idea, applied to ramp spacing, is illustrated in Exhibit 4-10.

Actual values for minimum spacing have been based on recommendations in the AASHTO Green Book (see Exhibit 3-13). The AASHTO values are intended to represent general guidance that should be supplemented with more detailed geometric, operational, safety, and signing analyses. However, the values are often applied as "absolute minimums" in early stages of interchange planning.

The binary result (i.e., above minimum or below minimum, safe or unsafe) of a nominal safety approach is interpreted as an indicator of acceptable or unacceptable design. Unacceptable designs are associated with visions of poor driving performance and high frequencies and severities of crashes. These generalizations oversimplify driver behavior and complex interactions between roadway geometrics, traffic operations, and safety. They also oversimplify the definition of safety itself and the trade-offs that often exist between crash frequencies and severities.

Traditional approach to investigating the safety of ramp spacing decisions followed an all or nothing philosophy. Either ramp spacing values were acceptable or not.

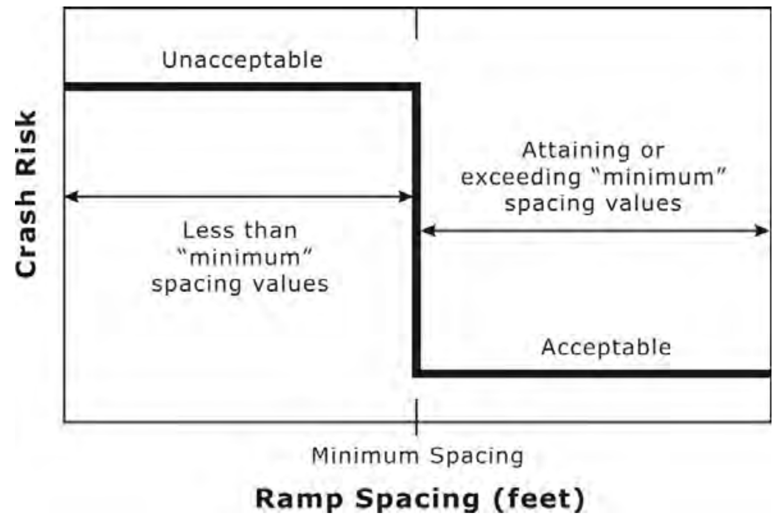


Exhibit 4-10 Nominal Safety Approach to Ramp Spacing. Adapted from (25).

4.5.2 Defining Substantive Safety

These *Guidelines* provide a means of investigating the "continuum of safety" associated with ramp spacing values.

The HSM assists professionals in taking a substantive approach to safety, where expected crash frequencies and outcomes for different design alternatives can be predicted and analyzed. These substantive safety measures result in more informed decision making, but a more complex decision making environment. Instead of a traditional binary approach ("safe" or "unsafe"), designers now have a continuously changing safety function readily available for their use. Exhibit 4-11 illustrates a non-binary approach to considering the safety continuum. It is difficult to recommend absolute minimum dimensions from the expected safety outcomes themselves, but it is possible to conduct more meaningful trade-off analysis that considers a variety of important transportation, environmental, societal, and cost factors.

These *Guidelines* present a substantive safety discussion of ramp spacing.

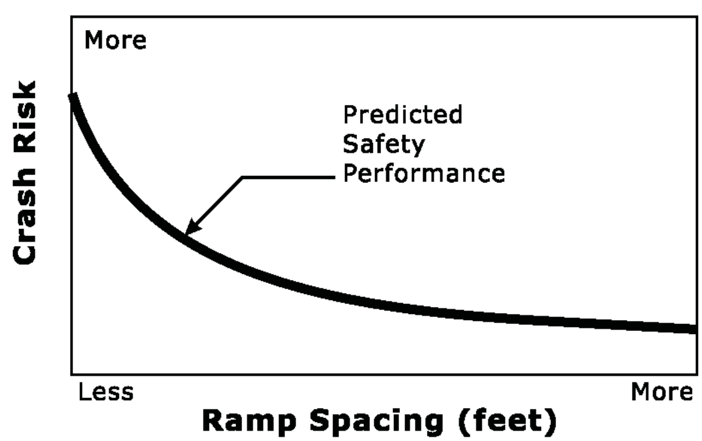


Exhibit 4-11 Substantive Safety Approach to Ramp Spacing. Adapted from (*28*).

These Guidelines present a substantive safety discussion of ramp spacing, with safety defined as:

The number of crashes, or crash consequences, by type and severity, expected to occur on an entity during a specified time period (*29*).

This safety definition is comprised of three main components that are consistent with the HSM:

- crash number,
- crash type, and
- crash severity.

Professionals should consider all three components when assessing alternate ramp and interchange concepts. For example, knowing that the total number of predicted crashes increased is not enough to say safety has decreased; changes in crash severities must also be known. Additionally, knowledge of crash types is necessary to link safety outcomes with specific design decisions and to identify effective safety improvements. Relationships between ramp spacing and safety are most meaningful and informative when discussed in terms of crash numbers, crash types, and crash severities.

Crash number is the total number of crash events, regardless of crash type or severity. The total number of crashes serves as a baseline to compute crash type and crash severity proportions. It can be used as a safety performance measure with the idea that design decisions or safety countermeasures that reduce the total crash count are effective (i.e., if a crash does not occur, then there is no chance of a traffic fatality or injury). However, total crash counts alone do not provide a complete understanding of the safety associated with alternative ramp spacing values, particularly in the ramp spacing context where there are complex interactions between design features, traffic operations, and safety.

Crash type refers to the manner of vehicle collision. At the highest level, crash types are classified by the number of vehicles involved in the crash. Single-vehicle crash examples include overturn and fixed object collisions. Multiple-vehicle crash examples include same-direction-sideswipe, opposite-direction-sideswipe, rear-end, head-on, and angle collisions.

Multiple-vehicle crashes become more prevalent than single-vehicle crashes as traffic volumes and levels of congestion increase. They are also common at locations where conflicting traffic movements interact, including entrance ramps, exit ramps, and weaving areas. Head-on and angle collisions are generally associated with higher crash severities (increased likelihoods of occupant injuries and fatalities). The severity of sideswipe and rear-end collisions depends on the impact speeds of the involved vehicles and the presence of vehicle occupants near the impact location.

These guidelines provide tools to assess crash number, crash type, and crash severity for various ramp spacing dimensions.

Crash severity is a measure of the crash outcome with respect to occupant health following the collision. The recorded crash severity refers to the most severe injury to any vehicle occupant involved in the collision. For example, a collision involving two vehicles, each vehicle having a driver and two passengers (i.e., six total occupants involved in the crash), will be recorded in a crash database as an injury crash if only one occupant sustained an injury and the remaining five occupants were unharmed. Fatal and injury crashes are often combined into one crash category, referred to as *severe* crashes or *fatal-plus-injury* crashes.

Crash severity is strongly related to the change in speed a vehicle and its occupants experience during a collision (see Exhibit 4-12). Understanding this phenomenon is critical to analyzing and interpreting ramp spacing and safety relationships. A given crash is more likely to be severe during free-flowing conditions (i.e., "better" levels of service) when vehicles are traveling at higher speeds. Crashes during congested conditions, often associated with high volumes and short ramp spacing, are more likely to result in property-damage-only within the boundaries of the congestion. However, crashes are more likely to be severe at the end of queues formed upstream of these areas, where there is an abrupt transition from high to low speeds. Crash severity is also strongly linked to driver and vehicle factors, particularly occupant ages and the weights of vehicles involved in the crash (*30*).

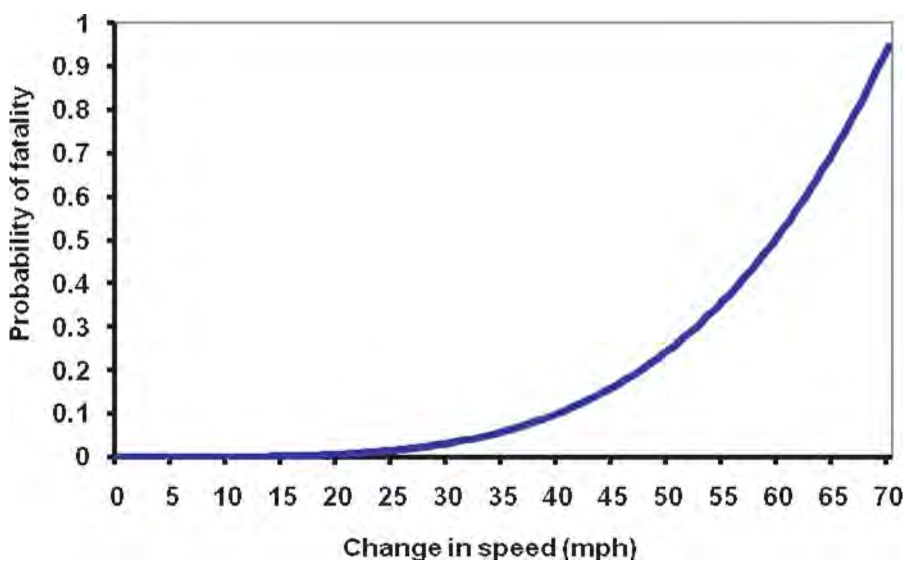


Exhibit 4-12 Relationship between Crash Severity and Change in Vehicle Speed during a Collision (*31*).

4.5.3 Interchange or Ramp Spacing when Discussing Safety

Interchange spacing, defined from cross-street-centerline to cross-street-centerline, is not as meaningful as ramp spacing, defined from painted gore to painted gore, from a safety modeling and analysis standpoint. For a given interchange spacing, the freeway segment between the cross streets may have different numbers, types, combinations, and spacings of interchange ramps. In addition, cross streets associated with some interchange ramps are difficult to identify for atypical interchange types, and may not be centered between exit and entrance ramps. As a result, the safety discussions in these Guidelines focus on relationships between ramp spacing and safety. The relationships can be aggregated to determine interchange spacing effects for different interchange forms if desired.

Ramp spacing provides a more meaningful evaluation than interchange spacing. These *Guidelines* focus on ramp spacing value, safety relationships.

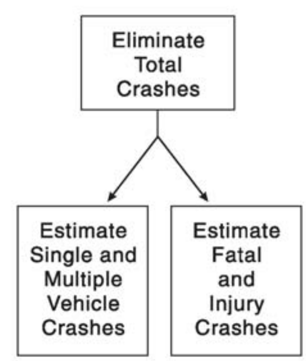
4.5.4 Relationships between Ramp Spacing and Safety

Past studies of ramp spacing and safety have generally indicated an increase in the total number of crashes (of all types and severities) as ramp spacing decreased, all else being equal. Findings on crash severity have been inconclusive, but hinted that the proportion of crashes resulting in a fatality or injury decreased as ramp spacing decreased. Tools for analyzing the relationship between ramp spacing and safety have been developed through research leading to these Guidelines. Research was conducted for the following ramp combinations:

Research indicates crashes generally increase as ramp spacing decreases. However, fatal and injury crash trends are less clear.

- an entrance ramp followed by an exit ramp (EN-EX), both with and without an auxiliary lane connecting the ramp terminals;
- an entrance ramp followed by another entrance ramp (EN-EN); and
- an exit ramp followed by an entrance ramp (EX-EN).

Safety Analysis Elements



The EN-EX scenario was studied at the greatest level of depth in developing these Guidelines. This is a commonly occurring ramp-sequence scenario and one in which operational analyses are frequently conducted and safety information is frequently needed. The Guidelines *present* safety performance functions (SPFs) and ramp spacing accident modification factors (AMFs) for the EN-EX ramp combination. The EN-EN and EX-EN were explored less vigorously; trends between crash frequencies and ramp spacing for different volume levels were developed without controlling for other potential safety influencing features.

The safety analysis tools to conduct quantitative assessments of ramp spacing on freeway mainline safety are presented in Section 5.3.3, and their application is illustrated in the Case Studies. The remainder of this section summarizes the general findings of the research conducted to develop these Guidelines, including observed trends between ramp spacing and crash frequencies, types, and severities.

Safety analysis tools to quantitatively assess ramp spacing alternatives are presented in Section 5.3.3

4.5.4.1 ENTRANCE RAMP FOLLOWED BY EXIT RAMP (EN-EX)

As discussed in Chapter 1, ramp spacing is defined as the distance between the painted tips of the entry ramp and the exit ramp. However, entering and exiting vehicles can cross striped areas, so any safety analysis limited to the area between painted tips might omit crashes that occurred between the physical gores and the painted tips. Safety analysis conducted as part of the development of these Guidelines considers all crashes that occur between physical gores, while still defining ramp spacing as the distance between painted tips. This is illustrated in Exhibit 4-13. Safety analysis tools do not address rear-end crashes that may occur far upstream of the entrance gore as a result of queue formation during congested conditions.

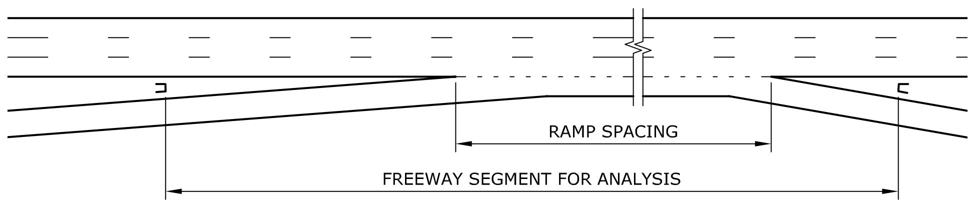


Exhibit 4-13 Freeway Segment Definition for Safety Analysis of an Entrance Ramp Followed by an Exit Ramp

4.5.4.1.1 EN-EX Ramp Spacing versus Crash Frequency

The sensitivity of total crashes to ramp spacing becomes higher as ramp spacing decreases. The sensitivity of total crashes to ramp spacing becomes close to negligible for spacing values greater than about 2,600 ft.

The expected number of crashes increases as ramp spacing decreases, all else being equal. This trend is illustrated in Exhibit 5-5. The sensitivity of total crashes to ramp spacing becomes higher as ramp spacing decreases. For example, reducing ramp spacing from 1,400 to 1,200 ft (200 foot reduction), is associated with a larger increase in crash frequency than reducing ramp spacing from 2,400 to 2,200 ft (also a 200 foot reduction). The sensitivity of total crashes to ramp spacing becomes close to negligible for spacing values greater than about 2,600 ft; in other words, the safety performance of the segment between the ramps approaches that of a basic freeway segment with no ramps. Tools to estimate the impact of ramp spacing on crash frequency are provided in Section 5.3.3.1.

4.5.4.1.2 EN-EX Ramp Spacing versus Crash Type

The expected number of crashes involving more than one vehicle increases as ramp spacing decreases. As ramp spacing decreases and lane change intensity increases, a crash is much more likely to involve at least two vehicles and be a sideswipe or rear-end collision. The rate of increase is higher than for total crashes. In other words, the percentage of total crashes classified as multiple vehicle increases as ramp spacing decreases. This trend is quantified in Exhibit 5-7.

Tools to estimate the percentage of total crashes that are multiple vehicle crashes as a function of ramp spacing are provided in Section 5.3.3.1. The percentage of total crashes involving more than one vehicle is approximately 90% at a 600 ft ramp spacing value. The proportion reaches 65% at a ramp spacing of 3,000 ft and remains at approximately 65% for all larger spacing values.

4.5.4.1.3 EN-EX Ramp Spacing versus Crash Severity

The expected number of crashes resulting in a fatality or injury to at least one vehicle occupant increases as ramp spacing decreases. The rate of increase is lower than for total crashes. In other words, the percentage of total crashes that result in at least one fatality or injury decreases as ramp spacing decreases as quantified in Exhibit 5-7. The general speed/severity trend is illustrated in Exhibit 4-12. Traffic speeds are likely to be lower in urban areas with higher volumes and shorter ramp spacing values. While the likelihood of crashes increases in these areas, the probability of a severe crash decreases due to the slower speeds. This finding is applicable to crashes occurring on the freeway mainline between the physical gore of the entrance ramp and the physical gore of the exit ramp. It is not applicable to rear-end crashes that may occur far upstream of the entrance gore as a result of queue formation during congested conditions. These crashes are likely to be severe when the relative speed differences between colliding vehicles are large.

Tools to estimate the percentage of total crashes expected to result in a fatality or injury to at least one vehicle occupant as a function of ramp spacing are provided in Section 5.3.3.1. The percentage of total crashes expected to be severe is approximately 20% at a 600 ft ramp spacing value. The proportion reaches 30% at a ramp spacing of 2,000 ft and remains at approximately 30% for all larger spacing values.

4.5.4.1.4 EN-EX Ramp Safety with Auxiliary Lanes

The presence of an auxiliary lane between an entrance ramp and an exit ramp corresponded to approximately 20% fewer expected crashes for a given ramp spacing and traffic volume level. The expected 20% overall reduction is the result of a reduction in multiple vehicle collisions. The presence of an auxiliary lane has no effect on single vehicle collisions. The reduction applies almost equally to both fatal plus injury crashes and property damage only crashes. Equation 5.1 and Exhibit 5-7 can be used to estimate crash frequencies and severities with and without an auxiliary lane. The process is demonstrated in Case Study 3

> An auxiliary lane between an entrance and an exit ramp corresponded to about 20% fewer crashes.

4.5.4.2 ENTRANCE RAMP FOLLOWED BY ENTRANCE RAMP (EN-EN)

Like entry-exit safety analysis, entry-entry safety analysis defines ramp spacing as the distance between painted tips but also considers crashes that occur outside of the area. Specifically, entry-entry safety analysis considers all crashes that occur between the physical gore of the first entry ramp and the end of the acceleration lane taper of the second ramp. This is illustrated in Exhibit 4-14.

The expected number of crashes increases as ramp spacing decreases, with the sensitivity become negligible for spacings greater than 2,200 feet.

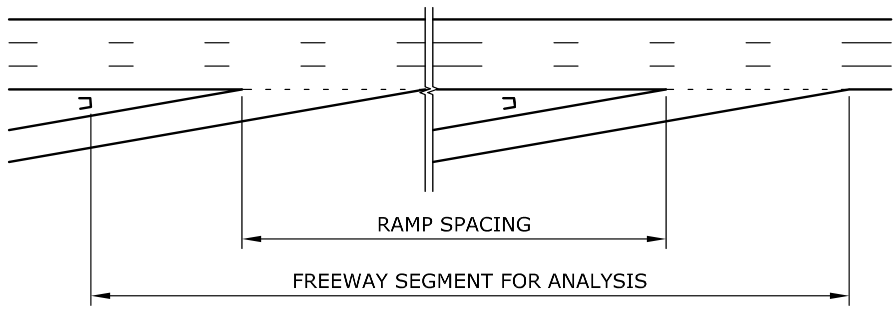


Exhibit 4-14 Freeway Segment Definition for Safety Analysis of an Entrance Ramp Followed by an Entrance Ramp

Data and sample sizes are relatively limited for the entry-entry ramp combinations compared to the entry-exit combinations. Safety analysis tools consider only freeway and ramp volumes in addition to segment length and ramp spacing; variable definitions are provided in Section 5.3.3.2. The remainder of this section summarizes observed relationships between ramp spacing and safety for the EN-EN scenario.

4.5.4.2.1 EN-EN Ramp Spacing versus Crash Frequency

Crash frequency is defined by the total number of crashes (all severities and types) expected to occur between the physical gore of the first entrance ramp to the end of the acceleration lane taper of the second entrance ramp. The expected number of crashes increases as ramp spacing decreases. The sensitivity of crash frequency to ramp spacing for the EN-EN is similar to, but slightly less than, the sensitivity for the EN-EX combination. The trend is illustrated in Exhibit 5-8. The sensitivity of total crashes to EN-EN ramp spacing becomes close to negligible for spacing values greater than about 2,200 ft; in other words, the safety performance of the segment approaches that of a basic freeway segment with no interchange ramps. The value is slightly less than the 2,600 ft value for the EN-EN. The relative differences are in agreement with the geometric analysis, which showed a slightly smaller dimension for the EN-EN than the EN-EX in which geometrics are likely not feasible (see Section 5.3.1).

Regardless of the spacing dimension, about three quarters of crashes at entry-entry ramp combinations involve multiple vehicles. The percent of crashes that are severe at entry-entry ramp combinations increases as ramp spacing decreases.

Tools to estimate the impact of EN-EN ramp spacing on crash frequency are provided in Section 5.3.3.2.

4.5.4.2.2 EN-EN Ramp Spacing versus Crash Type

A majority of crashes on segments with an entry-entry ramp combination involve more than one vehicle. The percentage of total crashes classified as multiple-vehicle varies between 70% and 80% and is relatively insensitive to the ramp spacing dimension.

4.5.4.2.3 EN-EN Ramp Spacing versus Crash Severity

The expected number of crashes resulting in a fatality or injury to at least one vehicle occupant increases as ramp spacing decreases. The rate of increase is lower than for total crashes. In other words, the percentage of total crashes that result in at least one fatality or injury decreases as ramp spacing decreases. The magnitude and direction of this relationship is the same as that for the EN-EX ramp combination. Therefore, the fatal plus injury curve in Exhibit 5-7 can be used to predict the percentage of the total crashes on the EN-EN segments expected to be severe. Explanations and limitations of these findings are the same as for the EN-EX combination (see Section 4.5.4.1.3).

EN-EX ramp combinations do not show an increase in crashes as ramp spacing decreases.

4.5.4.3 EXIT RAMP FOLLOWED BY ENTRANCE RAMP (EX-EN) AND EXIT RAMP FOLLOWED BY EXIT RAMP (EX-EX)

Research conducted to develop these Guidelines did not show an increase in crashes associated with a decrease in ramp spacing for the EX-EN ramp combination. Most data were from EX-EN combinations within the same interchange, which is different than an exit ramp followed by an entrance ramp servicing grade separated ramps (ramp braids). The geometric analysis should be a primary factor in the spacing assessment until additional safety information becomes available (see Section 5.3.1.4).

The safety characteristics of the EX-EX combination are expected to be consistent with the EX-EN results (i.e., no relationship between ramp spacing and safety). Without quantitative safety findings, the geometric analysis (Section 5.3.1.3) and signing considerations (Section 5.3.4) are the primary factors for the EX-EX spacing assessment.

Chapter 5 Spacing Guidance

This chapter presents an overarching framework to support ramp and interchange spacing evaluations and decisions. The information supporting the framework builds upon the information of previous chapters to help guide the user though steps to evaluate ramp and interchange configurations. This chapter provides information to highlight "interchange spacing" and "ramp spacing" relationships and emphasizes that ramp spacing should be the primary consideration of ramp and interchange spacing considerations. This chapter includes qualitative, and where available from project data, quantitative input on minimum ramp and interchange spacing values. This chapter provides a simplified four step assessment method to aid the user in understanding how ramp spacing values may or may not be influenced by design, operational, safety, and signing considerations. This chapter is supported by Appendix A, which provides case studies to apply the guidelines framework and four step process outlined in this chapter and supported by the resource information in Chapters 2, 3, and 4.

5.1 GUIDELINES FRAMEWORK

This section provides a simplified framework for applying the content of Chapters 2, 3, and 4 to understand a project context, consider and evaluate a range of solutions, and support efforts to select optimal ramps and interchanges for the project conditions.

Exhibit 5-1 presents a framework to considering ramp and interchange configurations and illustrates how ramp and interchange spacing assessments contribute to making project decisions. The interchange spacing assessment process addresses three basic areas: *Getting Started*, *Considering Solutions*, and *Selecting a Plan*. The framework and subsequent tabular information integrate information from Chapters 2, 3, and 4 into a generalized sequence that can guide a user through ramp and interchange spacing assessments.

Ramp and interchange spacing assessments should begin with a broad understanding of the needs of each particular project context.

The framework upon which ramp and interchange spacing decisions are made begins with establishing a broad understanding of the opportunities, constraints, and needs of a particular project context. This information helps a user understand the issues associated with the facility and helps identify the range of potential solutions. As possible solutions evolve from broad concepts to alternatives to completed designs, they become increasingly more detailed. However, as these solutions are advanced, the opportunities to affect and influence ramp and interchange spacing values diminishes.

Subsequent subsections expand upon the three basic areas and tables within these subsections outline contextual, design, operational, safety, and signing considerations that can help guide ramp and interchange spacing assessments and decisions.

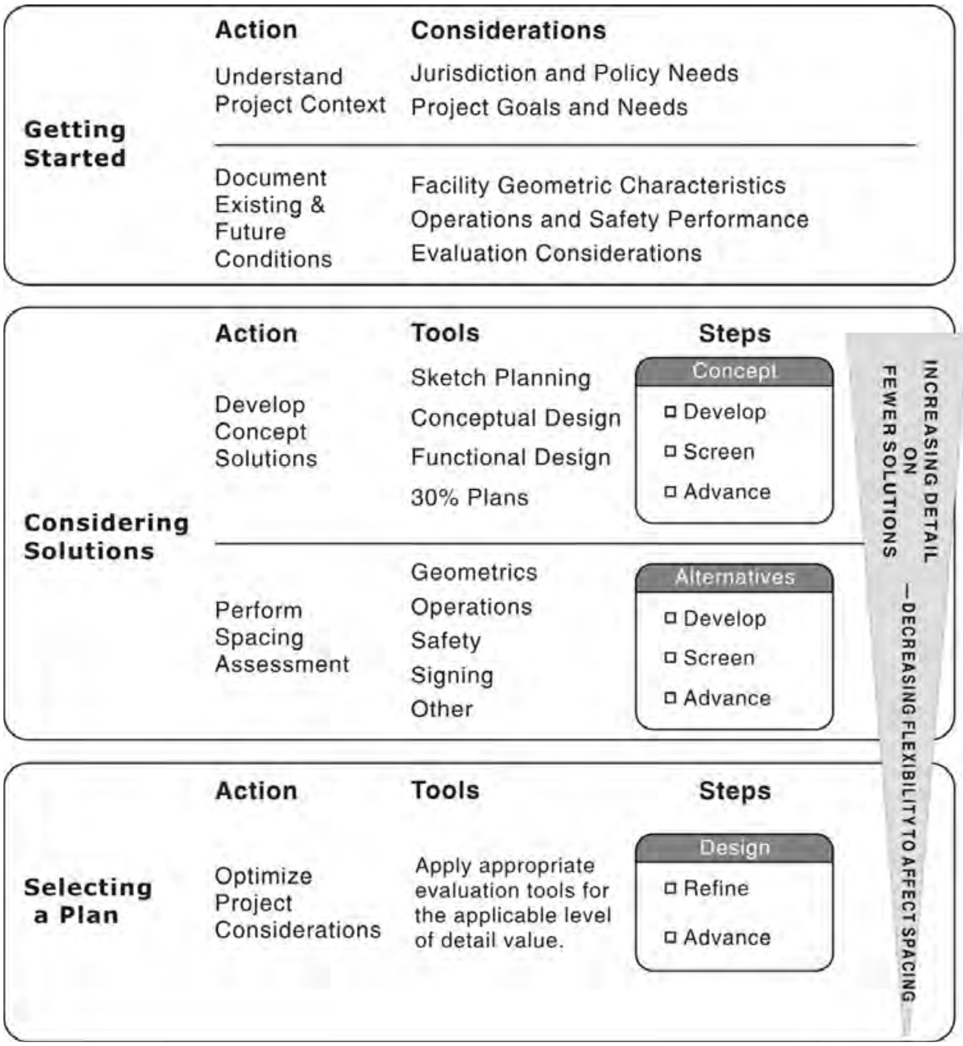


Exhibit 5-1 Interchange Planning and Design Framework

5.1.1 Getting Started

	Action	Considerations
Getting Started	Understand Project Context	Jurisdiction and Policy Needs Project Goals and Needs
	Document Existing & Future Conditions	Facility Geometric Characteristics Operations and Safety Performance Evaluation Considerations

There are numerous factors that influence project needs and decisions. Prior to developing and considering ramp and interchange configurations the user must understand the contextual design environment for the mainline and existing interchanges or ramps, if present. The project context can influence decisions on how proposed ramp and interchange spacing configurations can help alleviate existing facility operational or safety deficiencies. A key objective is to understand how proposed ramps and interchanges and their spacing, compared to adjacent constraints, may affect or may be affected by current and forecast conditions.

> It can be challenging to provide ramp and interchange configurations in complex freeway networks (especially in constrained environments) that meet spacing needs and provide desired traffic and safety performance.

The project development stage, project type, area, policy, and facility characteristics can influence the approach and ability to make ramp and interchange spacing decisions. Once the context is established, gathering the available evaluation data is critical to initiating preliminary assessments and evaluations that will guide the alternative development and refinement processes.

The following describes some of the project context considerations that can greatly influence freeway, interchange, and ramp design decisions.

5.1.1.1 JURISDICTION AND POLICY

FHWA and state agencies provide methodologies to consider new or modified access to freeways. Federal and state policy considerations are presented in Section 2.2 and their application is illustrated in Case Study 1. At the broadest level, a primary objective of these methodologies is to understand the traffic operational effects of adding or modifying a freeway access. In addition to quantifying forecast conditions with and without the proposed ramp or interchange, the methodologies generally identify a range of considerations that users must consider before access is granted.

The traffic operations and safety evaluations called for by federal and state policies can extend beyond the subject freeway segment and include analyzing the adjacent roadway network to better understand arterial network and freeway traffic operations and safety relationships. The overall intent is to consider how potential changes in ramp and interchange configurations might affect the freeway being considered. This is coupled with identifying a range of ramp and interchange solutions that are consistent and integrated with broader transportation system improvements.

In addition to traffic and design evaluations, federal and state approval processes usually require understanding the socio-economic and environmental constraints of the improvement under consideration. Meaningful public and stakeholder outreach are valuable contributors to any successful transportation project, and two-way outreach to share information and understand concerns and input from the public and project stakeholders is a cornerstone of a successful project.

5.1.1.2 PHYSICAL ATTRIBUTES

The user must understand the physical constraints of the environment and be prepared to generate potential concepts within those constraints. This requires understanding three dimensional geometric design requirements and factors that influence the ramp and interchange spacing ranges. Chapter 3 presents a number of these attributes and discusses how professionals should consider them when assessing ramp and interchange spacing. Professionals should apply tools and guidance to help them understand how sensitive system performance is to variations in design decisions associated with ramp and interchange spacing.

> The relationship between geometric design choices and resulting traffic operations is an iterative process in which forecast volumes support lane determinations and geometric configurations affect traffic operations.

5.1.1.3 EXISTING AND FUTURE TRAFFIC OPERATIONS

There is an iterative and dynamic relationship between geometric design choices and resulting traffic operations. Existing conditions and the contributing factors to existing traffic operations must be understood before identifying proposed solutions. Forecast traffic volumes should be used to support lane determination assessments that help establish the operational foundation of the design concepts.

Alternative geometric configurations, in turn, affect predicted traffic operations as alternative designs are developed, assessed, and screened. Ramp and interchange design features will directly affect resultant traffic operations. Professionals should first establish and address appropriate basic freeway, interchange, and ramp design configurations and then evaluate how traffic operations may or may not be sensitive to ramp spacing values. Chapter 3 provides an extensive discussion on geometric design and operational relationships. Traffic operations play a key role in ramp spacing assessment in Case Studies 3, 4, and 5.

5.1.1.4 IMPACTS TO SAFETY

Understanding the safety impacts associated with new or modified access alternatives to a freeway supports informed interchange and ramp spacing decisions. The general term "safety" should be considered based on crash frequency, type, and severity. General safety-related issues are presented in Section 4.4 of these Guidelines. Safety relationships of various ramp spacing parameters have been developed for these Guidelines and provide a useful aid to consider possible safety tradeoffs from various ramp and interchange configurations. Safety considerations in evaluating possible ramp and interchange evaluations are included in Case Studies 1, 2, 3, and 4.

5.1.1.5 SIGNING

Professionals should consider signing at the early stages to assess its role in ramp spacing decisions. Signs needs can influence potential solution concepts.

Geometric design and traffic operations needs often require ramps and interchanges to be far enough apart that the MUTCD's signing requirements can be satisfied. However, this is not always the case and signing needs should be considered early in the alternatives development stages. Complex or unusual interchange forms can require complex signing with a large number of message units or sign panels. The MUTCD notes no more than three should be placed at the same location; therefore, in such cases, ramp spacing may need to be increased from minimum geometric and operational dimensions to accommodate signing that is adequate and not overwhelming to drivers. Signing considerations are presented in Section 3.9 of these Guidelines and signing evaluations are included in Case Studies 1, 2, 3, and 5. Case Study 5 illustrates a situation in which a proposed alternative is determined to be infeasible because it cannot be adequately signed consistent with MUTCD criteria

5.1.1.6 PROJECT CONTEXT SUMMARY

Table 5-1 summarizes just some of the elements associated with establishing a project's context. The table is not exhaustive and is intended to represent some common considerations. The Case Studies in these Guidelines were developed to provide an array of project conditions and contexts.

Table 5-1 Understand Project Context

Project Development Stage	Project Type	Area
Planning Preliminary Design Final Design Implementation	New interchange and new facility New interchange on an existing facility Extensive modifications to an existing interchange on an existing facility	Type Urban Rural Suburban Issues Environmental Physical Social
Reason for Modification	**Facility Type**	**Policy Considerations**
New development Capacity Access Safety	Interstate State facility County City	Justification reports Interchange handbooks Design standards and guidelines Resource documents

Table 5-2 provides a summary of facility geometric characteristics that can influence concept solutions and ramp and interchange spacing decisions.

Whether it is the type of interchange form being evaluated or a desire to ensure lane continuity or the principle of lane balance, facility characteristics and considerations will form the basis for project solutions. These and other design considerations are presented in Chapter 3. Case Study 5 includes an example of how one alternative concept would have led to unacceptable mainline lane conditions.

Table 5-2 Facility Geometric Characteristics

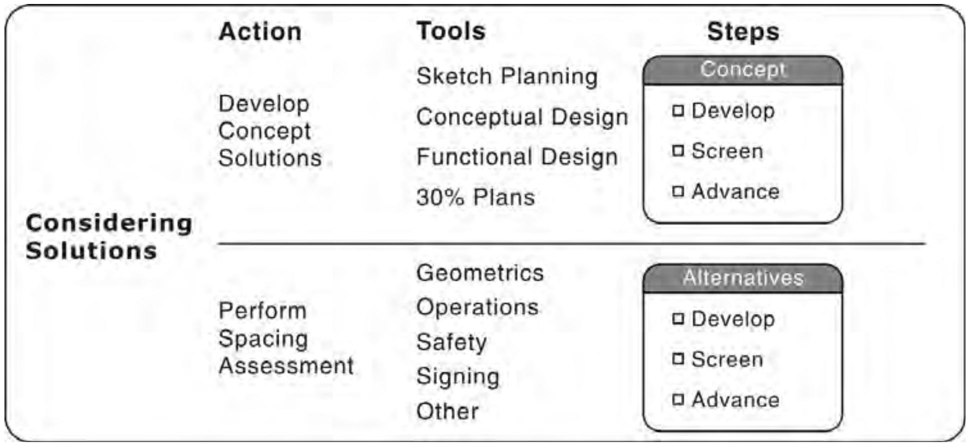
Interchange type and form	Ramp Combination	Lanes	Mainline	Network
"T", "Y", and "X" System All directional Directional with loops Service Diamond Cloverleaf Partial Cloverleaf	EN-EX EN-EN EX-EX EX-EN	Number Basic Auxiliary Balance Continuity	Freeway Highway	Adjacent network Connections to public roads Isolated interchange Consistent series of interchanges (e.g., 1-mile spacing) Inconsistent interchange spacing

In addition to understanding elements about the project's context and facility type, there are a variety of data needs that could influence ramp and interchange configurations and, therefore, spacing. Table 5-3 includes a partial list of the types of operational data and characteristics that might influence project decisions for ramp and interchange forms.

Table 5-3 Evaluation Considerations

Traffic	Speed	Crash History	Design Vehicle
Volumes Existing Design Forecast Composition Trucks Passenger cars Recreation vehicles Purpose Commuter Recreation Freight	Upstream Design Posted Operating Downstream Design Posted Operating	Type Frequency Severity Location Isolated System	Type Percentage

5.1.2 Considering Solutions



As solutions evolve from sketch-planning concepts to 30-percent plans, the same spacing assessments should occur, but at increasing levels of detail that are consistent with the information available.

Concept solutions should be developed based upon the overarching context considerations that might drive project documentation and decision making. During the initial sketch-planning stages of alternative development and evaluation, professionals should consider a wide range of possible solutions to compare and screen less promising alternatives. Ramp and interchange spacing limitations may directly influence screening decisions.

Developing, comparing, and selecting a preferred alternative is an iterative process that integrates geometric design, operational testing, signing evaluations, and safety analyses. As more detail is available throughout the process, evaluation tools and techniques can be applied at increasing detail to aid in project decision making. For example, Section 5.3.3 includes tools to support safety assessments at two levels: A planning level assessment that considers trade offs based on ramp spacing only and a planning/preliminary design level assessment that considers key variables that should be available as the concept design evolves in increasing design detail.

Table 5-4 provides an overview of the types of information that might be considered as potential solutions evolve from conceptual development to the alternative selection (sketch planning to 30% design).

Table 5-4 Alternatives Development and Refinement

Alternative Development/ Evaluation	Comparing Alternatives	Selected Alternative
Other Possible Solutions? Network Capacity Improvement Programmed Improvement Plan Select Appropriate Configurations Ramp and Interchange Form Prepare Interchange and Ramp Layout Design Alternatives Assess Conceptual Signing Needs	Ramp terminal layout Parallel Taper Profile considerations Schematic sign layout Message Sequence placement	Preliminary Design Refine design concepts based on governing agency Ramp and interchange spacing tradeoffs Final signing
Operational Testing		
Per lane capacity values Ramp/Freeway capacity charts and tables	Highway Capacity Software Ramp (Capacity, merge/diverge) Mainline (Segment, Weaving)	Analysis iterations Microsimulation, if needed
Safety Analysis		
Ramp combinations Short spacing highly sensitive to crash frequency	Preliminary safety assessment tool	Safety performance functions Crash modification factors

In some cases, ramp and interchange needs and constraints simply do not allow for conventional ramp or interchange designs that meet operational and safety objectives. Professionals may be faced with challenging decisions about accepting sub-optimal ramp spacing versus alternative solutions that may be more costly and have a greater impact. Collector-distributor (C-D) roadways are effective in protecting a freeway mainline by locating merge, diverge, and weaving movements onto a secondary roadway. However, C-D roadways clearly have facility cross-section impacts and may require a more extensive longitudinal evaluation of a mainline segment.

Information on C-D roads and grade separated ramps is presented in Case Study 5. These design features are sometimes needed to meet project needs.

Ramp braids (grade separated ramps) are alternatives to closely spaced ramps. These configurations may also be physically impacting, costly, and aesthetically unappealing. While much is written about interchange and ramp planning and design considerations, relatively little guidance is provided to support planning and design recommendations for C-D roadways or ramp braids as options to increase ramp spacing values.

Geometric and signing information is presented in Chapter 3. Operations and safety information is presented in Chapter 4.

A preliminary assessment of the capacity, geometrics, safety, and signing of each alternative should be conducted to understand the existing conditions and future facility needs. The desired outcomes are preliminary ramp and interchange configurations, an understanding of their spacing characteristics, and their likely resultant performance.

Table 5-5 provides an overview of the fundamental considerations in assessing ramp and interchange configurations. Their considerations are presented in Section 5.3 as sequential steps to support ramp and interchange spacing decisions. Each of the Case Studies guides the user through applications of the spacing assessment steps.

Information on C-D roads and grade separated ramps is presented in Case Study 5. These design features are sometimes needed to meet project needs.

Table 5-5 Fundamental Spacing Assessment Considerations

Geometric	Traffic Operations	Safety	Signing
Mainline Proper Basic Lanes Lane Balance Lane Continuity Route Continuity Interchange form Single-Exit Design Exits in Advance of the Cross Street No Left Exits Ramps Combinations (EN-EX, etc.) Type (loops, diagonal, etc.)	Freeway Number of lanes Weaving Merge/diverge capacity Closely spaced ramps Ramps Terminal Intersection Ramp-Freeway Junction Network Cross Streets Parallel Roads Adjacent Intersections	Isolated Ramp Terminal System/Network Upstream or downstream effects	Logical destination Sequencing Spacing Message units

These fundamental considerations form the basis of four sequential steps for assessing ramp and interchange spacing alternatives.

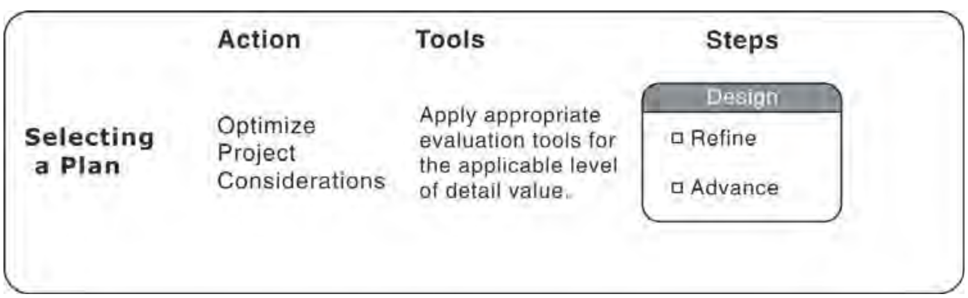
As concepts are screened and options advanced to schematic-level design, more detail and information is known about specific cross-sectional elements, the horizontal and vertical geometry and configuration of the ramps, and the number and arrangement of lanes on the mainline facility. The approximate ramp-freeway junction concepts may be more refined to reflect ramp terminal design features (taper versus parallel design and gore geometry, converge and diverge angles, gore dimensions).

At this stage, the specific ramp spacing measurements can be more carefully considered, and a more thorough evaluation of the projected operational and safety performance of the ramp and mainline can be conducted. With more detailed operations analysis results, users can assess tradeoffs for various ramp and interchange spacing alternatives. A schematic sign layout for messages, sequencing and placement could be established to aid in evaluating and refining the design alternative. Specifically, users should consider how ramp configurations and ramp and interchange spacing dimensions affect expected operations and safety performance. During these evaluations and comparisons, inferior alternatives may be screened to advance only the most promising solutions.

After thoroughly comparing the potential alternatives, the selected alternative is typically moved into the preliminary (30-percent) design phase. The design and operational concepts are refined based on governing agency guidelines and standards. The various ramp and interchange spacing tradeoffs are fully identified and reviewed. Operational analysis is likely to become more refined with additional highway capacity analyses and, in some cases, by applying microsimulation models. Ramp and interchange spacing values can be optimized and refined based on traffic operations analysis results. With detailed preliminary design and operational analysis results, signing requirements can be refined, and collectively, all of the information should be used to select the most promising alternative(s).

This stage generally includes preparing and completing documentation needed for a particular governing agency, such as FHWA or state or local governments, to make project approval decisions. Additional documentation for environmental review evaluations, design deviations and possible design exceptions can be completed at this time.

5.1.3 Selecting a Plan



Upon completing project documentation, project solutions are refined and advanced to the final design stages. At this stage, there is very little flexibility to influence ramp and interchange spacing decisions. As the designs are refined and advanced, minor revisions for right-of-way, utilities, or other project constraints may be necessary, but major revisions are less practical.

5.2 "INTERCHANGE" VERSUS "RAMP" SPACING

This section provides information to highlight "interchange spacing" and "ramp spacing" relationships and emphasizes that ramp spacing should be the primary consideration of *ramp and interchange spacing decisions. This section provides information on how design, operations, safety, and signing may influence ramp and interchange spacing assessments*

Ramps, more so than interchanges, should be the focus of spacing evaluations. Interchange spacing dimensions generally provide limited value in most interchange and ramp spacing evaluations.

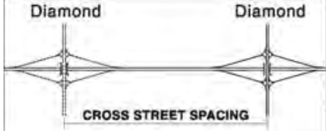
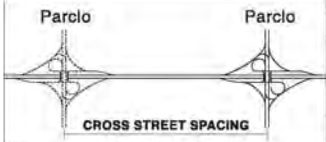
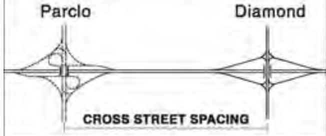
Ramp spacing values should be the primary consideration in making interchange and ramp spacing technical decisions. "Interchange" spacing addresses the dimensions between freeway cross street centerlines. Ramp spacing addresses the dimensions of sequential ramps that are to be configured to meet geometric design, operational, safety, and signing needs. Interchange spacing dimensions generally provide limited value in most interchange and ramp spacing evaluations and should not, on their own, guide project decisions.

5.2.1 Geometric Design: Interchange Form Considerations

Interchange forms may influence interchange spacing assessment results.

Considering ramp element dimension ranges from Chapter 3 and how those ramp elements are applied to various service interchange forms, it is possible to conceptually assess how interchange form may influence or be influenced by cross street spacing. Interchange forms influence the length of ramp components and the type of interchange may influence spacing assessments. For example, a single exit design for a partial cloverleaf form may result in longer ramps than a diamond interchange. The interchange form should be selected before performing a spacing assessment. In turn, a spacing assessment may help determine that some interchange forms are better suited for an available interchange spacing dimension.

Exhibit 5-2 presents the cross street spacing feasibility of three pairs of different forms of service interchanges based upon the interchange spacing. Exhibit 5-2 is based on geometrics only and does not account for traffic operations, safety, signing, or other factors that play a role in interchange spacing decisions.

Interchange Form	Cross Street Spacing			
	4,000' – 4,500'	4,500' – 5,000'	5,000' – 5,500'	5,500' – 6,000'
Diamond / Diamond 	POTENTIALLY GEOMETRICALLY FEASIBLE	POTENTIALLY GEOMETRICALLY FEASIBLE	LIKELY GEOMETRICALLY FEASIBLE	LIKELY GEOMETRICALLY FEASIBLE
Parclo / Parclo 	LIKELY NOT GEOMETRICALLY FEASIBLE	LIKELY NOT GEOMETRICALLY FEASIBLE	POTENTIALLY GEOMETRICALLY FEASIBLE	LIKELY GEOMETRICALLY FEASIBLE
Parclo / Diamond 	LIKELY NOT GEOMETRICALLY FEASIBLE	POTENTIALLY GEOMETRICALLY FEASIBLE	LIKELY GEOMETRICALLY FEASIBLE	LIKELY GEOMETRICALLY FEASIBLE

Assumes single entrance and exit design for configurations with the loop in advance or beyond the cross street. Assumes ramp braids or C-D roadways are not used.

Exhibit 5-2 Interchange Spacing Feasibility

The generalized ranges of values in Exhibit 5-2 reflect conventional ramp configurations. Interchanges may be spaced more closely than the ranges indicted in this exhibit if ramp braids or C-D roadways are included. The spacing values of ramps that access the ramp braids or collector distributor roadway and other adjacent interchanges should be considered using the principles and tools included in this chapter.

System interchanges are not included in Exhibit 5-2 and spacing needs should be assessed on a case-by-case basis. In general, interchange spacing values between system interchanges or between system and service interchanges will exceed (sometimes greatly) the ranges of Exhibit 5-2. In some cases these spacings may exceed two or more miles. Closer interchange spacing may be allowable if ramp braids and C-D roadways are included. In general, system interchange spacing needs should focus on ramp spacing considerations for supporting project decisions.

System interchange forms have unique characteristics that generally increase "interchange spacing" dimensions over service interchange forms.

Factors influencing ramp and interchange spacing include the orientation and "levels" of the intersection freeways and the number of levels a particular ramp must change. For example, a ramp changing only one level will have a completely different profile than a ramp changing three or four levels. System interchanges may include double or triple lane exits or branch type connections. The geometric design needs and associated resulting spacing needs for ramp terminal configurations of system interchanges will vary greatly based on system interchange form, ramp design, turning roadway design, and lane adds and drops.

In complex interchange environments, signing may become a critical consideration influencing alternative designs. Case Study 5 provides an example of complex signing needs influencing ramp spacing decisions

5.2.2 Traffic Operations Considerations

Table 5-6 highlights some of the relationships between "interchange" and "ramp" spacing values. This table may help users correlate interchange spacing discussions and planning level evaluations to ramp spacing considerations and evaluations.

Table 5-6 Interchange Spacing Effects

	Effects on ramp density	Effects on Volume	Effects on ramp design
Increased Interchange Spacing	Lower ramp density (fewer ramps per mile)	More volume per ramp	Increased exit ramp length to avoid queue spillback Multilane ramps
Decreased Interchange Spacing	Higher ramp density (more ramps per mile)	Less volume per ramp	Possible application of shorter ramp lengths for queue storage

Interchange spacing and ramp density influences a freeway's estimated free-flow speed (FFS). As interchanges are added within a segment (thus increasing ramp density), there is a corresponding decrease in FFS. The effects of the *spacing* between the added interchanges and ramps on FFS speed are less clear.

5.2.3 Safety Considerations

The variability in interchange forms and the relatively subjective nature of spacing measurements between crossroad centerlines makes ramp spacing a better means of considering safety. The safety tradeoffs between various interchange spacing dimensions is best quantified by considering safety analysis tools of section 5.3.3 and assessing the predicted safety performance of the estimated *ramp* spacing values between the subject interchanges.

5.2.4 Signing Considerations

Exit ramp placement and location is the primary factor in any signing assessment. The spacing between interchanges is of less importance with regard to signing.

5.3 RAMP SPACING ASSESSMENTS

This section provides guidance to support ramp and interchange spacing decisions and assess their adequacy. The intent is to characterize the geometric design, traffic operations, safety, and signing considerations that influence the activities depicted in the Guidance Framework of Exhibit 5-1. The steps outlined in these Guidelines represent an approach to integrate design, operations, safety, and signing considerations in ramp and interchange spacing decisions.

Ramp and interchange spacing design requires an iterative approach to blending geometric design, traffic operations, safety, and signing considerations within a project's contextual design environment. Each of these four fundamental elements is interrelated and optimizing solutions comes as a byproduct of balancing and integrating the elements. "Ideal" projects result in a balance of the four elements, however, in reality, sometimes projects focus on optimizing the relationship between two or more elements.

Interchange and ramp designs are complex, and no sequential process is sufficient to address a particular contextual design environment. The user is responsible for adapting and adjusting the approach provided in these Guidelines to meet project-specific needs.

For example, one project's conditions may require an extensive effort to balance geometric design and traffic operations considerations; another project may require emphasizing geometric design and signing considerations. Exhibit 5-3 provides graphical representation of the interdependence of the four fundamental elements and highlights examples that focus on the selected specific considerations (geometric design/traffic operations and geometric design/signing).

The Case Studies consider all of these relationships

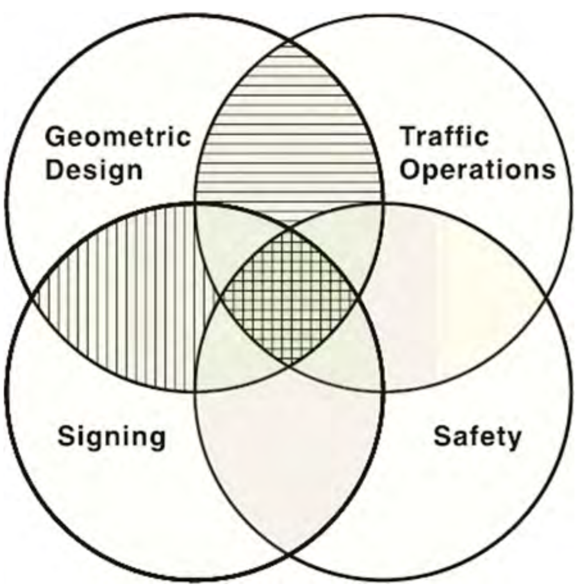


Exhibit 5-3 Ramp and Interchange Considerations Relationships

There are many ways professionals can conduct ramp and interchange spacing assessments and numerous ways to develop ramp and interchange concepts. These Guidelines suggest four fundamental, sequential steps and at the same time, note the importance of flexibility in the approach for any particular project need. In addition, users should be aware of the iterative nature of the assessment process as they accomplish the activities outlined in the Interchange Planning and Design Framework of Exhibit 5-1.

The four sequential steps address the following:

- Geometric Design,
- Traffic Operations,
- Safety, and
- Signing.

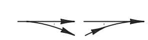
Unless stated otherwise, these Guidelines assume that ramp spacing values are between interchanges rather than within a single interchange.

The fundamentals that should be included in these steps are provided in Chapters 3 and 4. Appendix A contains five project case studies depicting a range of hypothetical projects that apply the concepts presented throughout this Guidelines document.

AASHTO guidance has not specifically correlated the relationship between ramp spacing, interchange spacing, and interchange form. Some ramp combinations are likely to occur within the same interchange and this will dictate their spacing. Table 5-7 provides insights into the influencing factors that affect ramp spacing values. Users of these Guidelines should consider these key influencing factors as they assess ramp and interchange geometric design options.

Appendix A includes five case studies that apply the sequential ramp assessment steps to a range of hypothetical project types.

Table 5-7 Factors Influencing Minimum Ramp Spacing

	EN-EX 	EN-EN 	EX-EX 	EX-EN 
Primary Considerations in Spacing Evaluations	Geometry Traffic Operations Safety	Traffic Operations Safety	Signing	Geometry
Relationship to Interchange Spacing	Greatly influences crossroad (interchange) spacing	Single entrance designs may increase spacing to adjacent interchanges	Single exit designs may increase spacing to adjacent interchanges	Typically none

The following subsections build upon the design and signing information in Chapter 3 and the operations and safety information in Chapter 4. Where possible, quantitative thresholds can aid professionals in integrating geometric design, traffic operations, safety, and signing considerations into ramp and interchange spacing evaluations and decision making.

5.3.1 Geometric Design

As presented in Chapters 1, 2, and 3, the ramp and interchange geometric design is based upon factors such as the following:

- Traffic volumes,
- Interchange Form,
- Terrain, and
- Agency standards and preferences.

These factors greatly influence interchange design from one location to another. Users must consider three-dimensional roadway design relationships to develop appropriate ramp and interchange configurations. These configurations should consider and reflect desired traffic operations. Upon understanding system and service interchange forms and basic ramp design elements (ramp-freeway junctions, ramp proper, ramp terminal intersections), a user should be familiar with the possible applications of other potential interchange elements such as turning roadways, C-D roads, and braided ramps.

Understanding and applying three dimensional roadway geometric design principles, approximate dimensions (as presented in Chapter 3) can be used as a starting point in laying out interchanges and the associated ramp components. These dimensions address three dimensional geometric design principles for relatively simplified site constraints and do not consider traffic operations. These dimensions apply to single lane ramps and users can apply these principles to investigate the influence of two lane entrance ramps.

> Approximate ramp design dimensions presented in Chapter 3 reflect simplified site constraints. Users must apply the principles of the Chapter 3 design information to their specific project context.

5.3.1.1 ENTRANCE RAMP FOLLOWED BY EXIT RAMP (EN-EX)

Tables 5-8 and 5-9 indicate the potential feasibility of an entry-exit ramp combination based upon the spacing between single lane diamond interchange ramps and partial cloverleaf ramps, respectively. As discussed in Chapter 1, ramp spacing is measured between painted gore stripe tips.

Dimensions presented in the "potentially geometrically feasible" range generally correlate to the ability to apply these ramp configurations within one-mile cross street spacing.

Table 5-8 Diamond Interchange Ramp Entrance-Exit Ramp Combination

Ramp Spacing Dimension	Feasibility
Less than 1,600 ft	Likely Not Geometrically Feasible
1,600 ft to 2,600 ft	Potentially Geometrically Feasible
Greater than 2,600 ft	Likely Geometrically Feasible

Table 5-9 Partial Cloverleaf Interchange Entrance-Exit Ramp Combination

Ramp Spacing Dimension	Feasibility
Less than 1,600 ft	Likely Not Geometrically Feasible
1,600 ft to 1,800 ft	Potentially Geometrically Feasible
Greater than 1,800 ft	Likely Geometrically Feasible

Assumes single entrance and exit design for configurations with the loop in advance or beyond the cross street.

5.3.1.2 ENTRANCE RAMP FOLLOWED BY ENTRANCE RAMP (EN-EN)

Table 5-10 indicates the potential feasibility of an entrance-entrance ramp combination. The values are primarily influenced geometrically by the freeway entrance ramp terminal design with the smallest values attributed to sharper convergence angles compared to flatter entrance designs. The smallest theoretical dimension would be when the completed entrance taper coincides with physical gore of the second entrance ramp.

Table 5-10 Entrance-Entrance Ramp Combination

Ramp Spacing Dimension	Feasibility
Less than 1,400’	Likely Not Geometrically Feasible
1,400’ to 1,800’	Potentially Geometrically Feasible
Greater than 1,800’	Likely Geometrically Feasible

5.3.1.3 EXIT RAMP FOLLOWED BY EXIT RAMP (EX-EX)

Table 5-11 indicates the potential feasibility of an exit-exit combination. The values are primarily influenced geometrically by the freeway exit ramp terminal design with the smallest values attributed to sharper divergence angles compared to flatter exit designs. The smallest theoretical dimension would occur when the diverge of the second exit coincides with the physical gore of the upstream exit. Note that minimum sign spacing values of 800 ft between exit-exit combinations would become a critical control if exit-exit spacing values of less than 900 ft are being considered.

Table 5-11 Exit-Exit Ramp Combination

Ramp Spacing Dimension	Feasibility
Less than 900’	Likely Not Geometrically Feasible
900’ to 1100’	Potentially Geometrically Feasible
Greater than 1100’	Likely Geometrically Feasible

5.3.1.4 EXIT RAMP FOLLOWED BY ENTRANCE RAMP (EX-EN)

There are two primary scenarios of an exit-entrance combination. The shortest dimension would be that of an exit followed by the entrance for a “button hook” design where the freeway ramps are serving a local street parallel to the freeway versus a local street crossing the freeway as an over- or underpass. This interchange form is not desirable and this combination is an unlikely configuration. Should this configuration be considered, other operations and interchange and ramp configuration policy or criteria will likely need to be considered.

The second scenario would be when an exit ramp and subsequent entrance ramp are servicing grade separated ramps (ramp braids). Based on the concept depicted in Exhibit 3-6 for ramp braid vertical and horizontal relationships, the spacing values are presented in Table 5-12. The minimum values reflect a condition where both ramp profiles are changing.

Table 5-12 Exit-Entrance Ramp Combination (Braided Ramps)

Ramp Spacing Dimension	Feasibility
Less than 1700’	Likely Not Geometrically Feasible
1700’ to 2300’	Potentially Geometrically Feasible
Greater than 2300’	Likely Geometrically Feasible

5.3.2 Traffic Operations

The spacing dimensions presented previously are based on the lengths of the various components of ramps and interchanges. They do not account for traffic volumes and may result in geometrics that do not adequately serve forecast volumes. Fundamental traffic operations and capacity considerations should be considered in the earliest stages of developing interchange and ramp configurations.

Chapter 3 provides an overview of the many ways traffic operations can be evaluated using a variety of techniques at the earliest planning stages through more detailed geometric design evaluations.

The following elements should be evaluated and the findings incorporated into geometric layouts. As alternatives are refined, evaluated, and screened, ramp and interchange configurations should be refined, and these elements should be re-evaluated using tools and techniques at increasing levels of detail.

Appendix A provides a variety of planning level operational analysis tools to assess possible tradeoffs of ramp spacing values

- Mainline Freeway—The overarching design and operational relationships of Section 3.1 (lanes and uniformity) should first be assessed and fundamentals incorporated into the earliest geometric configurations. Interchange and ramp configurations for proposed improvements should be prepared within the objectives of the preserving basic lanes, lane continuity, lane balance, and other lane elements noted in section 3.1.1. Traffic operations for the mainline must address basic segment capacity needs. As noted in Table 4-1, the capacity of a single freeway lane ranges from 2,250 to 2,400 passenger cars per hour.
- Ramp Terminal Intersections—Ramp terminal intersection treatments affect capacity and queuing, and ramp terminal intersection evaluations should be conducted early in the evaluation process. Ramp terminal intersection queue lengths will vary based on the lane numbers and arrangements that are provided at that location. Stopping sight distance and deceleration lengths to the back of those queues directly affect ramp horizontal alignments and, ultimately, ramp-freeway junction locations.
- Isolated Merge or Diverge—Ramp-freeway junctions should be investigated in isolation to check basic capacity needs and as part of a system to check the impact of close spacing. As noted in Table 4-1, the capacity of a single merging or diverging influence area (ramp plus right two lanes of freeway) ranges from 4,400 to 4,600 passenger cars per hour.
- Closely Spaced Merges and Diverges—Research conducted when developing these Guidelines examined the impact of ramp spacing on mainline freeway speed. In general, ramp spacing has the greatest impact when traffic volumes (of the freeway, the ramps, or both) are near but not at capacity. Under low to moderate volume, changes in ramp spacing generally have little effect on freeway operations. At capacity, a freeway will operate poorly regardless of ramp spacing. This general relationship is illustrated in Exhibit 5-4. Specific findings are presented in the following sections and in Appendix B.

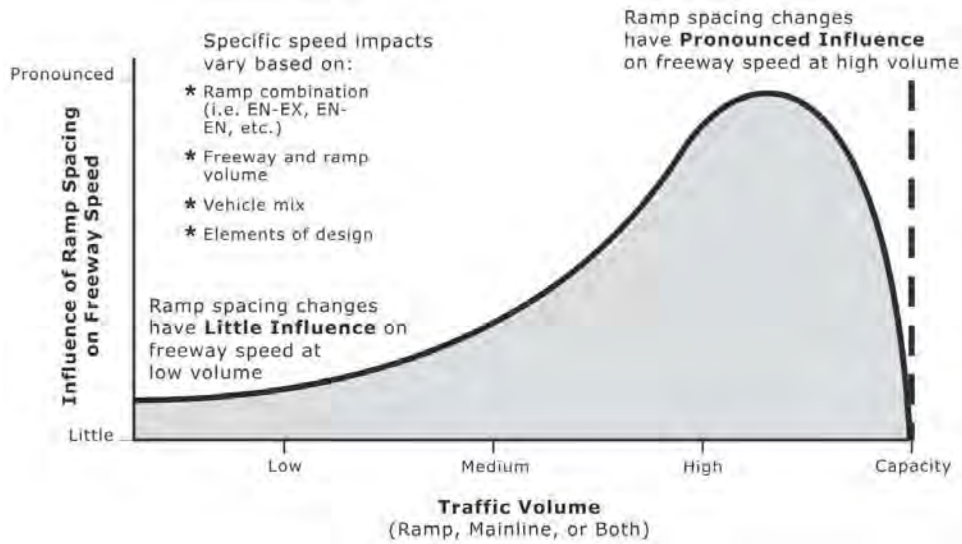


Exhibit 5-4 Conceptual Effect of Changes in Ramp Spacing on Freeway Speed

At low to moderate volumes, ramp spacing generally has little effect on freeway operation.

For entrance-exit ramp combinations without an auxiliary lane, research conducted in developing these Guidelines found that:

- Ramp spacing significantly affects mainline segment speed for mainline segments with low entering volumes and high exit-ramp volumes.
- Ramp spacing significantly affects mainline segment speed for mainline segments that have moderate and high mainline entering ramp volumes and moderate and high exit-ramp volumes.

Closely spaced entry-exit ramps may be designed with or without an auxiliary lane. If an auxiliary lane is present, an HCM weaving analysis is needed to evaluate operations. Any application of auxiliary lanes should include a review of lane balance provisions. Auxiliary lanes provide operational and safety benefits, and the benefit can potentially be maximized by providing lane balance at the down stream exit ramp.

The operational effects of auxiliary lanes are quantified in Section 4.3.1 and Appendix B.

Adding an auxiliary lane creates minor speed increases at low mainline and exit volumes. However, the increase becomes significant as traffic volumes increase. Adding an auxiliary lane to a longer ramp spacing generally has less benefit than adding an auxiliary lane to shorter ramp spacing.

For entrance-entrance ramp combinations, research conducted in developing these Guidelines found that:

- With low to moderate mainline volumes upstream of the first ramp, ramp spacing generally has little effect on mainline speed regardless of ramp volume levels.

- Ramp spacing has a significant impact on mainline segment speeds with high mainline volume upstream of the first ramp and moderate to high ramp volumes.

5.3.3 Safety

A comprehensive ramp spacing safety assessment should consider:

- Safety impacts on the freeway mainline (addressed in this section);
- Safety associated with speed-change lane presence and design (can be addressed with HSM or ISAT—see the following discussion);
- Safety along the ramp proper (can be addressed with ISAT);
- Safety at ramp terminal intersections (can be addressed with ISAT); and
- Safety on surrounding highways and streets (capabilities that intertwine travel demand modeling and safety are somewhat limited).

Users should access published safety documents and tools to make comprehensive evaluations of freeway and interchange design alternatives to augment the tools developed for these Guidelines. This includes:

A complete safety assessment of proposed ramps and interchanges should include more than spacing impacts, as discussed in Section 4.5

- Applying the HSM crash modification factors for designing interchanges with crossroads above (versus below) the freeway, speed change lane lengths, and modifying lane arrangements at merge and diverge areas (*7*). Professionals should also access the qualitative safety discussions to guide decisions regarding ramp type/configuration, right-side versus left-side entrances and exits, interchange spacing, weaving area length, ramp proper alignment and width, and the provision of bicycle and pedestrian facilities at ramp terminals.
- Using FHWA's Interchange Safety and Analysis Tool (ISAT) safety performance functions for predicting crash frequencies along the freeway mainline, at freeway-ramp terminals, at ramp-cross street terminals, and along the ramp proper (*32*). Like the HSM, ISAT will continue to evolve and expand as supplemental research findings become available over time.

Reductions in ramp spacing are generally associated with an increase in crashes along the freeway mainline (all else, including measures of exposure, being equal).

Research conducted in developing these Guidelines identified a consistent trend: reductions in ramp spacing are generally associated with an increase in crashes along the freeway mainline (all else, including measures of exposure, being equal).

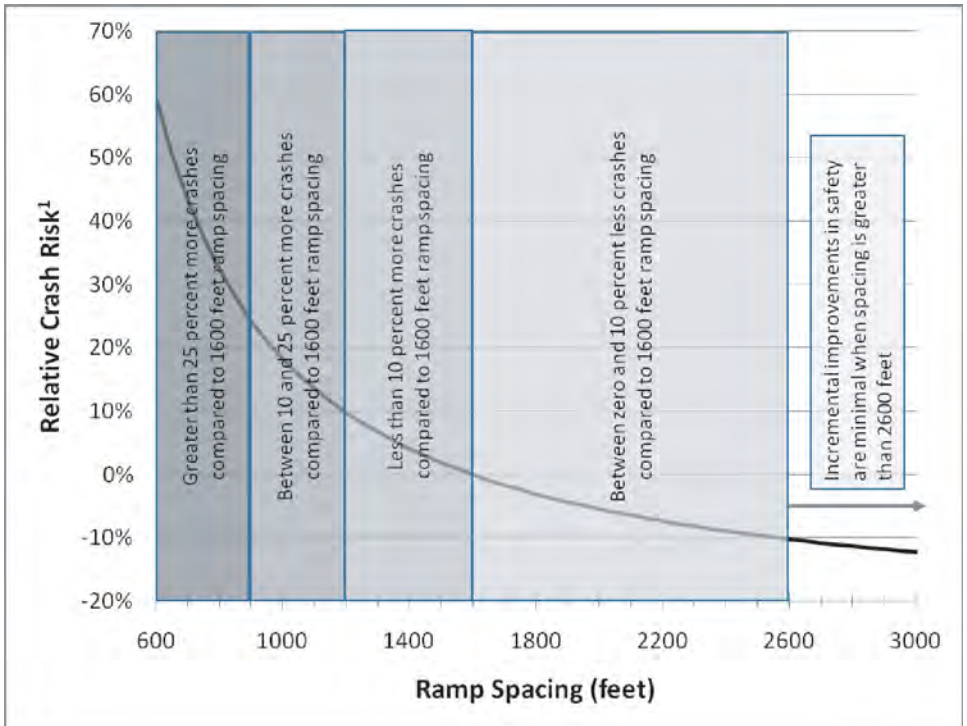
Similar to the previous planning-level information for considering geometric design requirements, users may estimate ramp spacing safety impacts for specific ramp combinations. This information may be used to provide insights into the safety considerations and potential trade offs of alternative ramp and interchange spacing values. The tools do not address rear-end crashes that may occur far upstream of the entrance gore as a result of queue formation during congested conditions.

5.3.3.1 ENTRANCE RAMP FOLLOWED BY EXIT RAMP (EN-EX)

The information provided in these Guidelines can be used to conduct a ramp spacing safety assessment at two levels: An early planning level assessment and a planning/preliminary design level assessment.

The *planning level tool* depicting the relationship between EN-EX ramp spacing and relative crash risk is shown in Exhibit 5-5. The relative safety impacts of ramp spacing alternatives can be assessed without gathering data on freeway volumes, ramp volumes, and detailed geometrics. Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,600 ft. The shaded regions of Exhibit 5-5 graphically summarize the following:

- Up to 10% more crashes are expected for ramp spacing values between 1,200 and 1,600 ft when compared to the baseline of 1,600 ft;
- Between 10-25% more crashes are expected for ramp spacing values between 900 and 1,200 ft when compared to the baseline of 1,600 ft;
- More than 25% more crashes are expected when ramp spacing is less than 900 ft when compared to the 1,600 ft baseline;
- The incremental safety benefits of ramp spacing values greater than 1,600 ft are relatively minor
- Up to 10% less crashes are expected for ramp spacing values between 1,600 and 2,600 ft when compared to the 1,600 ft baseline;
- The incremental safety benefit of providing ramp spacing values longer than 2,600 ft are relatively negligible.



[1] Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,600 ft

Exhibit 5-5 Preliminary Safety Assessment Tool for Ramp Spacing, Entrance Ramp Followed by Exit Ramp

The use of Exhibit 5-5 in the context of analyzing impacts of a new interchange on a freeway between two existing interchanges is illustrated in Case Studies 1, 2, 3 and 4.

The solid line behind the shaded regions can be used to compare relative crash risk of two specific ramp spacing values. For example, a ramp spacing of 2,000 ft corresponds to a relative crash risk (value on the y-axis) of -5%. A ramp spacing of 1,600 ft corresponds to a relative crash risk of zero percent (the baseline). Therefore, one could expect 0 - (-5) = 5% more crashes for a ramp spacing of 1,600 ft than for a ramp spacing of 2,000 ft.

Case Study 3 presents a detailed illustration of the spacing and auxiliary lane interaction

As more detailed preliminary design information is available, users may apply a *planning/preliminary design* tool to conduct a more detailed safety assessment of ramp spacing than Exhibit 5-5, with explicit consideration of freeway volumes, ramp volumes, and the presence of an auxiliary lane between the entrance ramp and exit ramp. The key variables for this level of safety analysis are defined below and illustrated in Exhibit 5-6:

- L = segment length (in miles) defined from the physical gore of the entrance ramp to the physical gore of the exit ramp;
- S = ramp spacing (in feet) defined from the painted entrance gore to the painted exit gore;
- DADT = the average daily traffic (in vehicles per day) on the freeway mainline upstream of the entrance gore in the analysis direction;

- ADT_{EN} = the average daily entering traffic (in vehicles per day);
- ADT_{EX} = the average daily exiting traffic (in vehicles per day);
- AuxLn = a variable indicating whether there is a continuous auxiliary lane between the entrance ramp and exit ramp provided for weaving (1 = auxiliary lane present; 0 = auxiliary lane not present); and
- TOTAL = number of crashes (of all types and severities) expected to occur between the physical entrance gore and physical exit gore on the freeway mainline

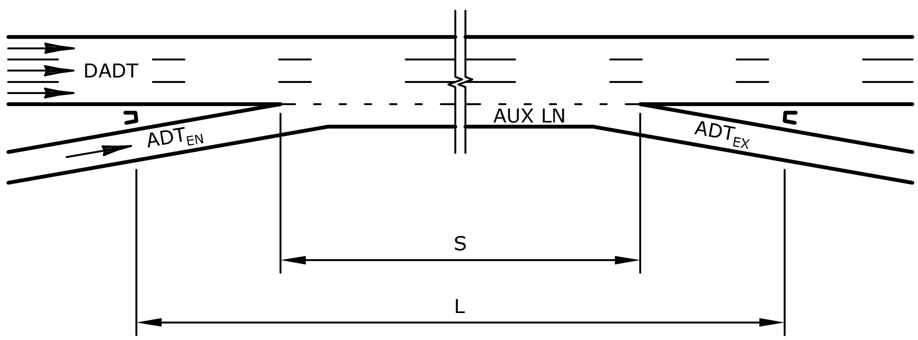


Exhibit 5-6 Key Variables for Planning and Preliminary Design Safety Assessment

Professionals may use Equation 5-1, developed for these Guidelines, to estimate the total number of crashes (of all types and severities) that might be expected to occur between the physical entrance gore and physical exit gore on the freeway mainline research with all variables defined previously.

$$TOTAL = 9.7 \times 10^{-6} L^{1.0} (DADT)^{1.12} (ADT_{EN})^{0.18} (ADT_{EX})^{0.02} \exp\left(\frac{450}{S} - 0.23 \times AuxLn \right)$$

Equation 5-1
Estimating the total number of crashes between an entrance and exit

The relationship between ramp spacing and crash type is discussed in Section 4.5.4

A complete safety picture requires understanding crash type and severity as discussed in Section 4.5.4. Crash type refers to the manner of vehicle collision. At the highest level, crash types are classified by the number of motor vehicles involved in the crash. Single-vehicle crashes involve only one motor vehicle. Examples include single-vehicle, overturn and single-vehicle, and fixed object collisions. Multiple-vehicle crashes involve more than one vehicle. Examples include same-direction-sideswipe, opposite-direction-sideswipe, rear-end, head-on, and angle collisions.

Once total expected crashes are estimated by Equation 5.1, a professional can estimate the expected percentage of predicted total crashes that will involve more than one vehicle, with the remaining percentage being single-vehicle crashes. Exhibit 5-7 (developed for these Guidelines) graphically summarizes the following:

Case studies 3, 4, and 5 illustrate the use of Exhibit 5-7.

- The expected percentage of total crashes that will involve more than one vehicle, with the remaining percentage being single-vehicle crashes. For example, approximately 66% of crashes are expected to be multiple vehicle collisions when the ramp spacing equals 2,000 ft; approximately 77% are expected to involve more than one vehicle when ramp spacing equals 1,000 ft.
- The expected percentage of severe (injury or fatal) crashes. For example, approximately 30% of crashes are expected to result in at least one fatality or injury when the ramp spacing equals 2,000 ft; approximately 26% are expected to be a fatal or injury crash when ramp spacing equals 1,000 ft.

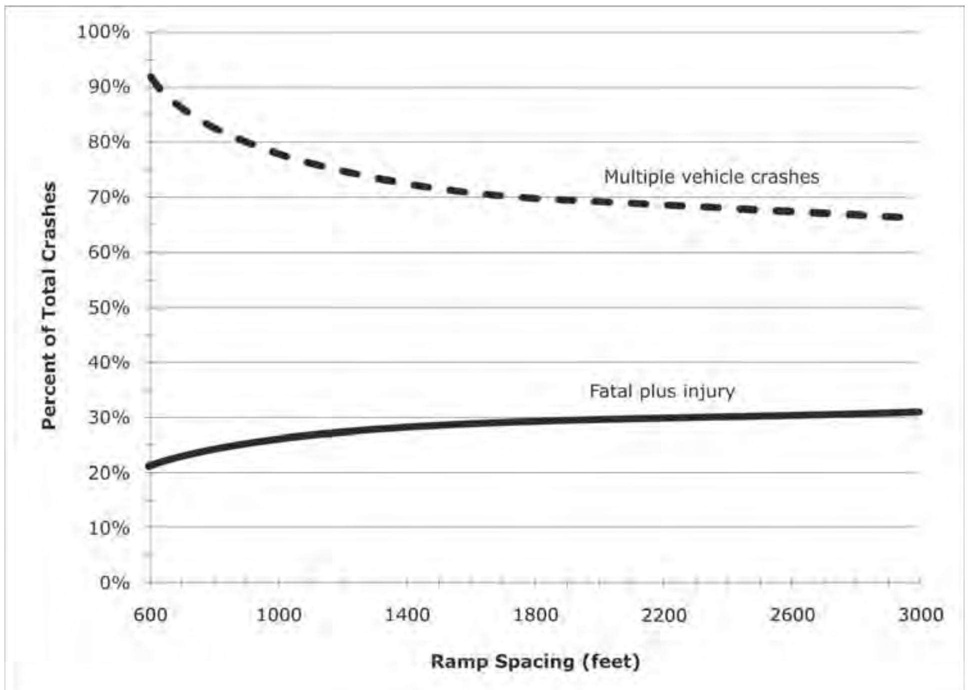


Exhibit 5-7 Crash Type and Severity Distributions as a Function of Ramp Spacing

Closely spaced EN-EX ramp combinations may be designed with or without an auxiliary lane, and Exhibit 5-5 includes data from both situations. However:

- The presence of an auxiliary lane corresponded to approximately 20% fewer expected crashes for any given ramp spacing and projected level of traffic volumes. This overall reduction in crashes is due to reduction in multiple vehicle collisions.

- The presence of an auxiliary lane has no effect on single vehicle collisions. The presence of an auxiliary lane was also found to have an equal reduction in injury and non-injury crashes.

In the example comparing 2,000 foot and 1,600 foot spacing, the larger expected number of crashes for the 1,600 foot spacing is likely to be offset if an auxiliary lane is provided.

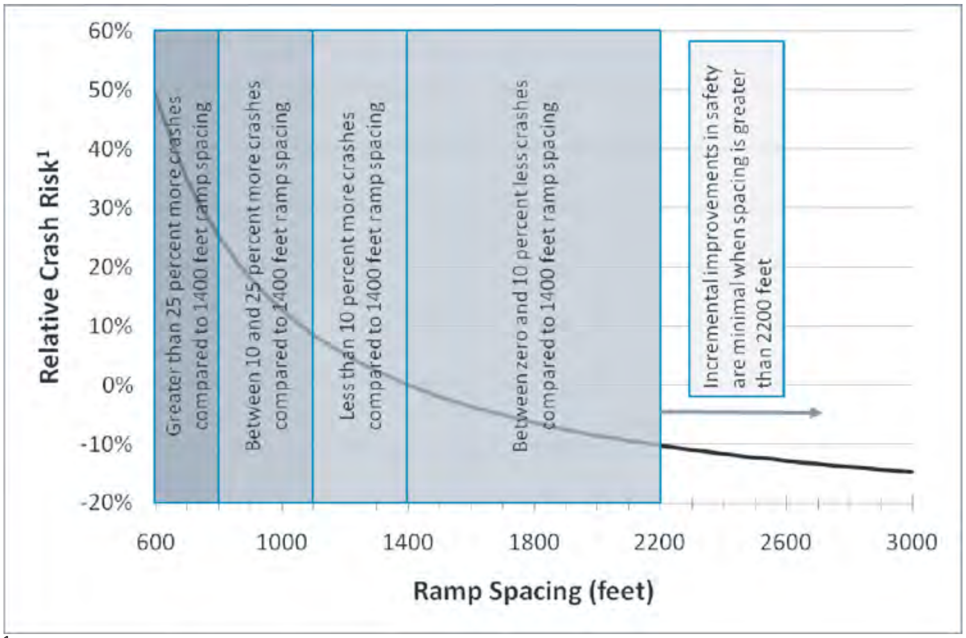
The combined applications of equation 5.1 and Exhibit 5-5 to perform safety assessments of ramp spacing alternatives are illustrated in Case Studies 3, 4, and 5.

The information provided in this section can be used to conduct a ramp spacing assessment for two consecutive entrance ramps.

5.3.3.2 ENTRANCE RAMP FOLLOWED BY ENTRANCE RAMP

A *planning level tool* depicting the relationship between EN-EN spacing and relative crash risk is shown in Exhibit 5-8. The exhibit can be used in the same way as Exhibit 5-5. The shaded regions of Exhibit 5-8 graphically summarize the following relationships between EN-EN spacing and crash frequency:

- Up to 10% more crashes are expected for ramp spacing values between 1,100 and 1,400 ft when compared to the baseline of 1,400 ft;
- Between 10-25% more crashes are expected for ramp spacing values between 800 and 1,100 ft when compared to the baseline of 1,400 ft;
- More than 25% more crashes are expected when ramp spacing is less than 800 ft when compared to the 1,400 ft baseline;
- Up to 10% fewer crashes are expected for ramp spacing values between 1,400 and 2,200 ft when compared to the 1,400 ft baseline;
- The incremental safety benefits of providing ramp spacing values longer than 2,200 ft are relatively small.



[1] Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,400 ft

Exhibit 5-8 Preliminary Safety Assessment Tool for Ramp Spacing, Entrance Ramp Followed by Entrance Ramp

Case Study 2 (Appendix A) applies Exhibit 5-8 in the context of analyzing impacts of a new interchange on a freeway between two existing interchanges, resulting in an EN-EN ramp sequence.

A *planning/preliminary design* tool to conduct a more detailed safety assessment of EN-EN ramp spacing is also available as Equation 5-2. The key variables for this tool are defined below and illustrated in Exhibit 5-9:

- L = segment length (in miles) defined from the physical gore of the first (upstream) entrance ramp to the end of the acceleration lane taper of the second (downstream) entrance ramp;
- S = ramp spacing (in feet) defined from the painted tip of the first entrance ramp to the painted tip of the second entrance ramp;
- DADT = the average daily traffic (in vehicles per day) on the freeway mainline upstream of the first entrance gore in the analysis direction;
- ADT_{EN-1} = the average daily entering traffic (in vehicles per day) from the first entrance ramp;
- ADT_{EN-2} = the average daily entering traffic (in vehicles per day) from the second entrance ramp; and
- TOTAL = number of crashes (of all types and severities) (crashes per year) expected to occur between the physical gore of the first

(upstream) entrance ramp to the end of the acceleration lane taper of the second (downstream) entrance ramp.

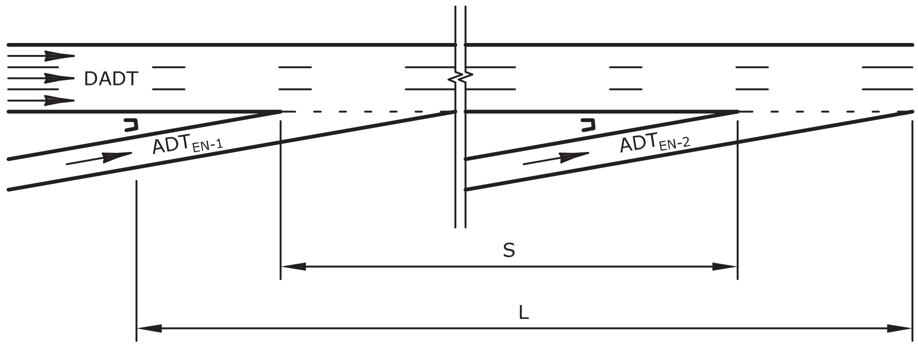


Exhibit 5-9 Key Variables for Planning and Preliminary Design Safety Assessment: Entrance Ramp followed by Entrance Ramp

Equation 5-2, developed for these Guidelines, may be used to estimate the total number of crashes (of all types and severities) expected to occur between the physical gore of the first (upstream) entrance ramp to the end of the acceleration lane taper of the second (downstream) entrance ramp.

$$TOTAL = 5.0\times10^{-5} L^{1.0} \left(DADT\right)^{0.81} \left(ADT_{EN-1}\right)^{0.34} \left(ADT_{EN-2}\right)^{0.09} \exp\left(\frac{420}{S}\right)$$

Equation 5-2
Estimating the total number of crashes between an entrance and entrance

The percentage of total crashes expected to be multiple vehicle on these segments changes very little as a function of ramp spacing and is generally between 70% and 80%. The expected percentage of severe (injury or fatal) crashes as a function of ramp spacing for the EN-EN sequence is similar to that for the EN-EX ramp sequence. Therefore, the fatal plus injury curve in Exhibit 5-7 can be used to predict the percentage of the total crashes on the EN-EN segments expected to be severe.

5.3.4 Signing

Upon evaluating geometric design, traffic operations, and safety evaluations, users should identify signing needs and placement options. A planning-level sign placement drawing, such as those shown in the Case Studies can help identify whether an interchange concept may require signing in excess of what a driver can process and thus potentially be an infeasible design. In some cases the analysis of signing will need to extend several interchanges upstream and downstream from the interchange in study. As illustrated in Exhibit 5-10, some designs are more likely than others to be impacted by signing considerations.

Exhibit 5-10 Impact of Signing on Ramp Spacing Decisions

Successive exit ramps should be at least 800 ft apart to meet basic signing needs.

Case Study 5 provides an example of how geometric design and signing considerations could ultimately influence ramp configuration project decisions. In that example, because signing needs can not be met, and there are other project alternatives, the configuration that could not be signed was recommended to be dismissed. Section 3.9 addresses signing needs for advance signing, and the number of message units can influence the effectives of communicating guidance and navigation tasks to drivers.

Signing needs primarily play two roles in spacing assessments, both of which involve exit ramps only.

5.3.4.1 SPACING BETWEEN SUCCESSIVE EXIT RAMPS

Exit ramps should be spaced at least 800 ft apart to satisfy the MUTCD's recommendation. In most cases, other factors such as interchange form and ramp/gore design will place successive exit ramps more than 800 ft apart.

Case Study 5 illustrates a situation in which signing determines ramp location

5.3.4.2 MAXIMUM NUMBER OF EXIT RAMPS ON A FREEWAY SEGMENT

As discussed in Section 3.9, the MUTCD recommends that a certain number of advance guide signs be placed prior to an exit and that no more than three sign panels be placed side by side. This effectively creates a limit of three single-exit interchanges per mile. If one of the three interchanges were a double-exit design, it could be possible to sign both exits of the interchange using a single advance guide sign, which would raise the limit to four exit ramps per mile.

In most cases, signing needs will not determine ramp spacing requirements, and factors such as geometry and traffic operations will not permit three or four exit ramps per mile. However, there are cases where signing needs are more complex than usual and are more likely to dictate ramp spacing.

The thresholds of three or four exit ramps per mile assume that the exits do not require any type of special signing. System interchanges, exits signed with diagrammatic signs, and exits serving a large number of roadways or destinations are examples of situations where three ramps per mile may be infeasible and a more detailed analysis of sign and message unit requirements should be conducted. Case Study 5 illustrates such a situation.

5.4 SPACING GUIDANCE SUMMARY

Evaluating a proposed ramp and interchange concept is an iterative, multiple stage process. As presented in Figure 5-1, the actions in the process are the following:

1. Understand Project Context,
2. Document Existing and Future Conditions,
3. Develop Concept Solutions,
4. Perform Spacing Assessment, and
5. Optimize Project Considerations.

Developing concept solutions and performing spacing assessments is an iterative process. In the earliest stages of planning, spacing assessments can be performed with limited data. Interchange spacing assessment tools such as those in Exhibit 5-2 may be appropriate at an initial planning stage. As concepts are refined, more in-depth analyses of spacing should be performed. Due to the wide variety of interchange forms and a multitude of project-specific ramp design features, ramp spacing assessments are more useful than interchange spacing assessments and will play a larger role in determining the adequacy of a ramp or interchange concept. Ramp spacing assessments, discussed in Section 5.3, should include analyzing geometric design, traffic operations, safety, and signing. Such analyses should be performed before the final design stage, as there is little flexibility with spacing at this point. Five scenario-based Case Studies in Appendix A illustrate how to conduct ramp spacing assessments.

Appendix A
Scenario Based Case Studies

This appendix presents five scenario-based case studies that demonstrate how to apply the various ramp and interchange spacing principles within the evaluation framework presented in Chapter 5. The case studies generally follow the conceptual design to refined alternative steps outlined in Chapter 5. Each case study consists of different geometric, operational, safety, and signing characteristics to provide the user with a range of contextual design environments from which to apply the principles presented in these Guidelines. These case studies include site descriptions, photos, and step-by-step discussions on how these Guidelines could be applied. Users should apply professional judgment and adhere to local practice when considering and recommending interchange and ramp spacing values for their own projects.

The case studies include the following project scenarios:

- Case Study 1: New interchange on a divided highway being upgraded to a full freeway (rural);
- Case Study 2: New interchange on a freeway (suburban);
- Case Study 3: New interchange on a freeway in a metropolitan area with a one-mile spaced arterial grid (suburban);
- Case Study 4: Modernizing an interchange on a vintage freeway (suburban); and,
- Case Study 5: New interchange near a system interchange on a high-volume freeway with many ramps (urban).

Case Study 1

Case Study 1 walks users through the process of assessing ramp and interchange spacing. In the case study, ramps and interchanges are spaced far apart and traffic volumes are low. Users are introduced to concepts which indicate that a new interchange can easily be accommodated on the facility.

BACKGROUND

General

A state transportation agency is upgrading an existing four-lane divided highway (US 32) to a full freeway and removing at-grade intersections. The roadway is in a rural part of the state and far from any large metropolitan areas. Austin Road currently intersects the divided highway at a two-way stop-controlled intersection. The state wants to maintain access to Austin Road after the freeway upgrade is complete by constructing a diamond interchange. A diamond form will have lower costs than other interchange forms considered for this location, and the diamond form will be consistent with the other interchanges in the corridor.

Adjacent Interchanges

The two existing interchanges are almost four miles apart (crossroad to crossroad) and traffic volumes are low. Placing a new interchange between the two existing interchanges will be physically feasible.

To the east, the nearest interchange is at SR 56, 12,200 ft away from Austin Road (measured between the centerlines of each crossroad). To the west, the nearest interchange is at SR 248, 8,300 ft away. Both interchanges are diamond forms, and there are no at-grade intersections on US 32 between Austin Road and either interchange. Austin Road will likely be relocated approximately 800 ft to the east when the interchange is constructed to remove the small radius reverse horizontal curves and to simplify the new interchange's design and construction while maintaining the existing Austin Road intersection during construction. The relocation would increase the distance to SR 248 and decrease the distance to SR 56. These roads and interchanges are shown on the site map in Figure 1-1.

Traffic Volumes and Characteristics

US 32 currently has two lanes in each direction and a peak-hour volume of approximately 2,500 vehicles in each direction. The SR 248 interchange has ramp volumes of 400-600 vehicles during the peak hour. The SR 56 interchange has ramp volumes of 200-400 vehicles during the peak hour. The Austin Road interchange is forecast to have ramp volumes of 200-300 vehicles during the peak hour. Heavy vehicles account for 15% of the volume on the divided highway, and 5-10% of the volume on all interchanges, including the planned Austin Road interchange. Terrain in this area is level.

CASE STUDY 1
SITE MAP

FIGURE
1-1

AGENCY REQUIREMENTS

The state in which this project is located has an operating guideline of LOS C for rural multilane highways and freeways. The highway and all ramp-highway junctions in the project are currently operating at LOS C or better. The new interchange should not result in any components of the new freeway operating below LOS C.

RAMP SPACING CONSIDERATIONS

The following ramp spacing assessment follows the sequence outlined in Section 5.3:

- Geometry considerations,
- Traffic operations,
- Safety, and
- Signing.

STEP 1—Geometric considerations:

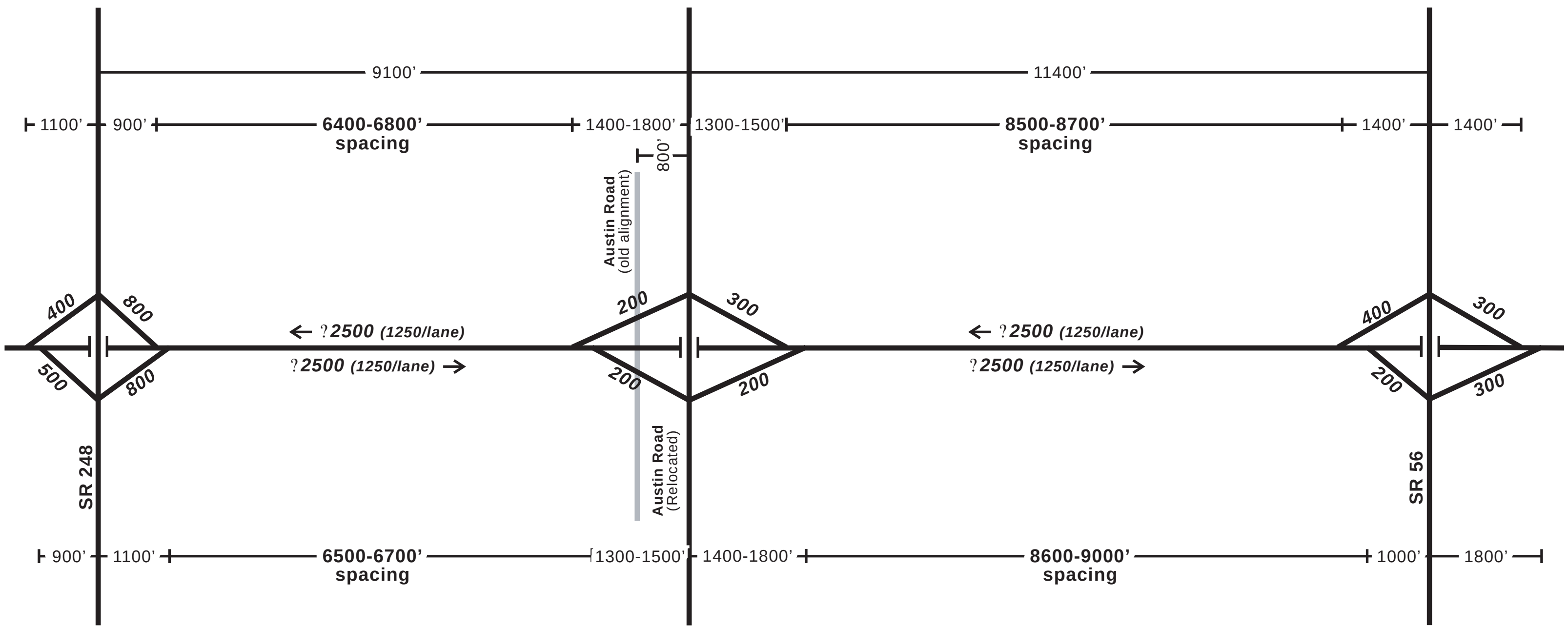
The first step is to conceptually determine the interchange footprint and approximate length of the ramps at the Austin Road interchange based on three-dimensional roadway design considerations.

At a concept level and starting point in laying out diamond interchange ramps, physical entry and exit ramp gores are approximately 1,000 ft in length from the crossroad. This distance generally meets vertical alignment needs for making appropriate grade changes and incorporating desired ramp geometry. On an entrance ramp, the distance between the physical gore and the painted merging tip typically varies from 400-800 ft based upon the horizontal curvature of the ramp and whether a taper or parallel entrance is used. On an exit ramp, the distance from the painted diverging tip to the physical gore typically varies from 300-500 ft for similar reasons. This results in the distance from a painted diverging tip to the crossroad generally ranging from 1,300-1,500 ft, and the distance from the crossroad to the painted merging tip generally ranging from 1,400-1,800 ft. These dimensions are further discussed in Chapter 3 of the Guidelines and shown in Exhibit 3-8. Ramp spacing dimensions under consideration in this case study (and all others) will be measured from the painted merging tip to the painted diverging tip.

Although ramp lengths cannot be determined until the project enters the preliminary engineering phase, a range of approximate ramp lengths and resulting ramp spacing values can be used to determine if issues related to traffic operations, signing, or safety are anticipated.

At this point in the planning process, no special conditions that could significantly impact ramp length have been identified at the Austin Road interchange. Dimensions similar to those noted above can be expected.

Figure 1-2 shows approximate dimensions of all existing and proposed ramps in the project area, as well as centerline-to-centerline roadway spacing and



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 1
RAMP SPACING AND TRAFFIC VOLUMES

FIGURE **1-2**

design-hour traffic volumes. After these ramp configurations and spacing values have been developed from a geometric design perspective, the next steps are to consider the influence these spacing values may have on traffic operations, signing, safety, and other aspects.

STEP 2—Traffic Operations:

All ramp spacing dimensions between the existing interchanges and the proposed Austin Road interchange are greater than 6,000 ft, as depicted in the diagram in Figure 1-2. As discussed in Chapter 4 of the Guidelines, ramp spacings of this length have virtually no impact on traffic operations. If each ramp-freeway junction operates acceptably when analyzed in isolation, it is highly likely the entire freeway system will as well, and operations at any particular ramp-freeway junction will not be affected by adjacent ramps.

The HCM does not have a procedure for analyzing an entrance ramp followed by an exit ramp on a two-lane freeway with no auxiliary lane. With ramp spacings of over 6,000 feet, though, operational impacts due to the spacing are unlikely.

The HCM provides basic capacity thresholds for various freeway and ramp components that are summarized in Table 4-1 of the Guidelines (reproduced below as Table 1-1). As shown in the table, the capacity of a merge on a two-lane (one direction) freeway is approximately 4,600 passenger cars per hour. At the Austin Road interchange, each of the ramp-freeway junctions will have a volume of approximately 2,700 vehicles per hour. Although a complete HCM analysis is needed to determine if the state agency's operating guideline of LOS C is satisfied, the ramp-freeway junctions will clearly be below capacity and potentially meet the LOS guideline.

Although it was previously determined that spacing is unlikely to have an impact on freeway speed under these conditions, the impact of each ramp in isolation should also be considered. The HCM provides capacity thresholds summarized in Table 4-1 that can be used here.

Table 1-1 Approximate Capacity of Freeway-related Roadway Elements, 2010 HCM (*5*)

Element	Service Volume
Freeway Lane	2,250 – 2,400 passenger cars per hour
Single-Lane Ramp*	1,800 to 2,200 passenger cars per hour
Merge Influence Area (on-ramp plus right two lanes of freeway)	4,600 passenger cars per hour
Diverge Influence Area (off-ramp plus right two lanes of freeway)	4,400 passenger cars per hour

* Basic ramp segment only, does not consider ramp terminal operations.

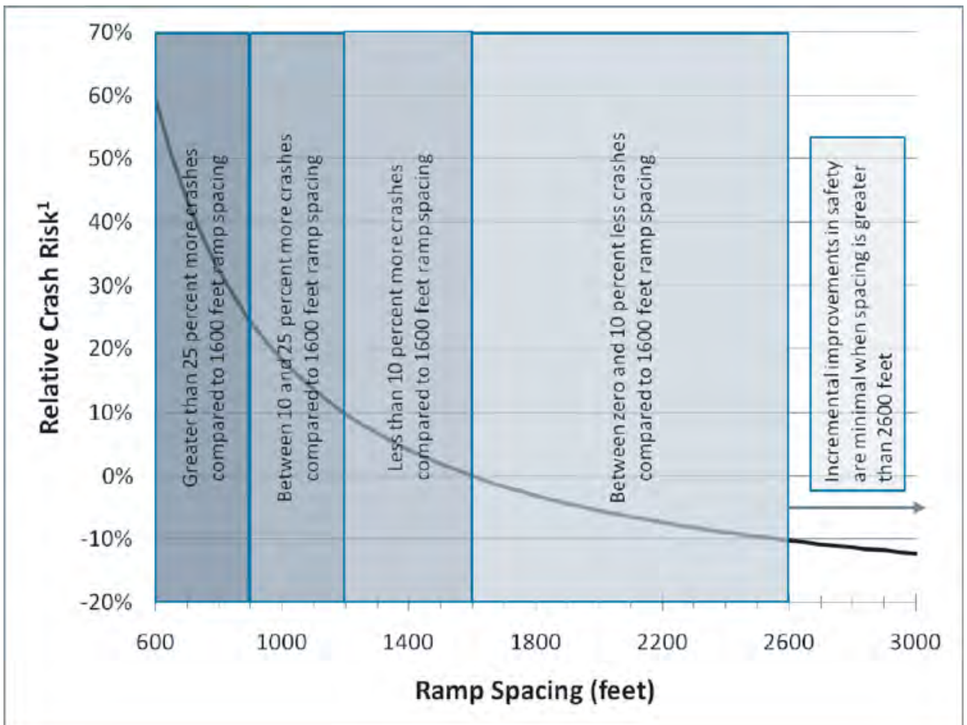
Based on this conceptual-level evaluation, ramp spacing dimensions will not have a significant impact on traffic operations. Furthermore, each ramp-freeway junction will operate well below capacity. When this project enters the preliminary design phase, traffic operations should be reevaluated. However, no issues are anticipated.

STEP 3—Safety:

The safety consequences of an Austin Road interchange may be explored at a planning level without direct consideration of traffic volumes. Ramp spacing, measured from merging tip to diverging tip, ranges from 17,600 to 19,000 ft on the freeway segment between SR 248 and SR 56 without the Austin Road interchange. Ramp spacing values are estimated to range from 6,400 to 9,000 ft if the Austin Road interchange is constructed. All ramp combinations of interest consist of an entrance ramp followed by an exit ramp (EN-EX).

Research conducted to develop the Guidelines indicated that the sensitivity of total crashes to EN-EX ramp spacing becomes close to negligible for spacing values greater than about 2,600 ft; in other words, the safety performance of the segment approaches that of a basic freeway segment with no interchange ramps. The finding is illustrated in Exhibit 5-5 (reproduced as Figure 1-3), where the solid line representing crash risk as a function of ramp spacing becomes fairly flat for spacing dimensions larger than 2,600 ft.

Section 4.5.4.1.1, Section 5.3.3.1, and Exhibit 5-5 of the Guidelines show that negligible differences in freeway mainline safety are expected between two ramp spacing dimensions that are both significantly greater than 2600 feet.



[1] Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,600 ft.

Figure 1-3 Preliminary Safety Assessment Tool for Ramp Spacing, Entrance Ramp Followed by Exit Ramp (Guidelines Exhibit 5-5)

STEP 4—Signing:

Signing should be considered at the earliest stages of concept development to assess the types and amount of information that will need to be presented and to consider the advance placement of signs. It may be necessary to consider more than one upstream and one downstream interchange because advance guide signs may be placed several miles before an interchange. At this location, there are no interchanges within four miles west of SR 248 or two miles east of SR 56. The area depicted in Figure 1-1 is effectively isolated from a signing perspective.

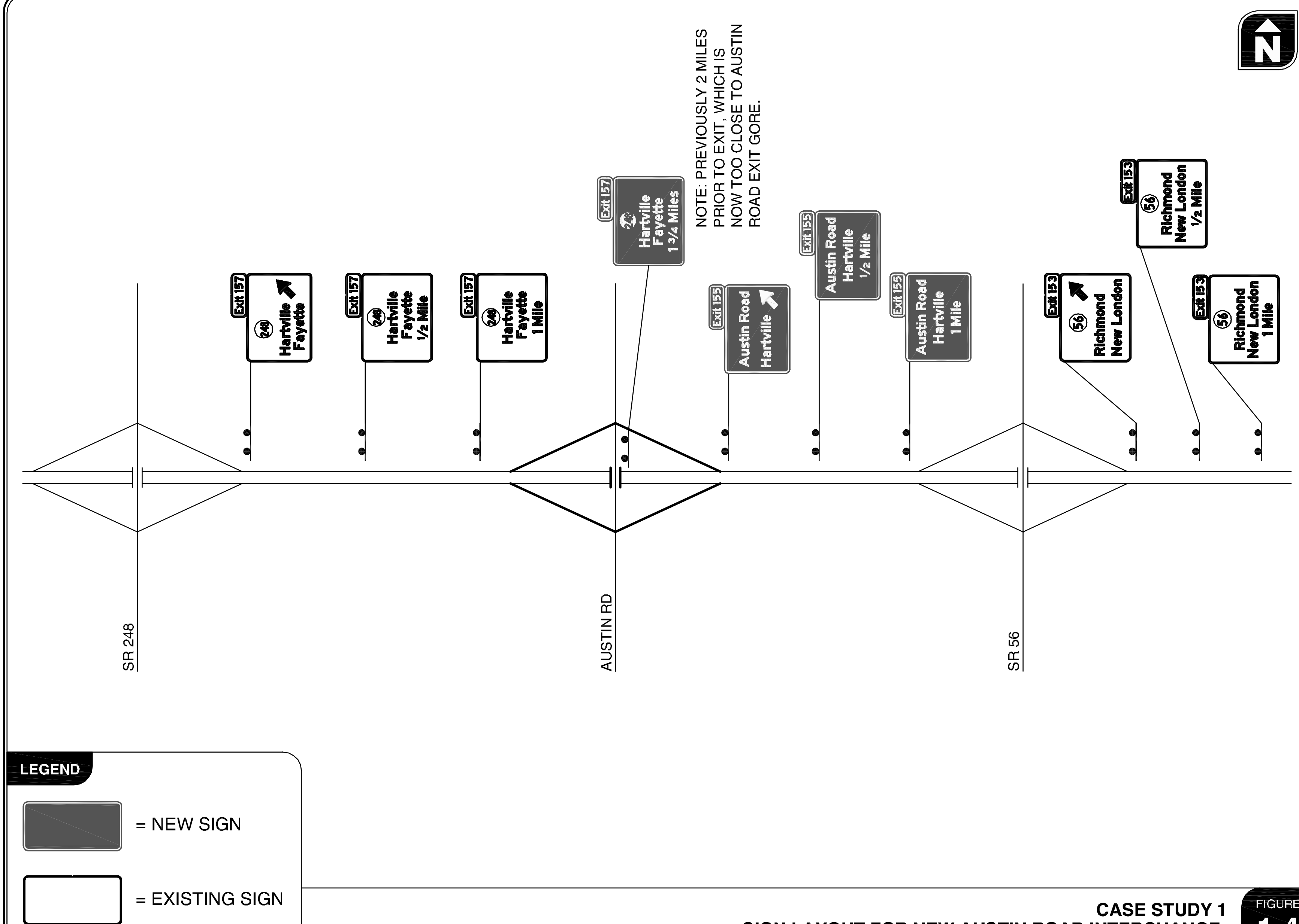
All three of these interchanges have a ramp ADT of more than 100 vehicles, and thus are classified by the MUTCD as "major" or "intermediate" interchanges. At major and intermediate interchanges, the MUTCD recommends an advance guide sign be placed ½ mile and one mile in advance of an exit, with a third guide sign placed two miles in advance of the exit if spacing permits. There are currently advance guide signs for SR 248 two miles prior to the exit in both directions, and the state wishes to maintain these two-mile advance signs due to the importance of SR 248 to its transportation network. Austin Road and SR 56 are not highways of regional importance or facilities where a high number of drivers unfamiliar with the area are expected. Therefore, this planning-level analysis will only consider the placement of advance guide signs ½ mile and one mile in advance of the Austin Road and SR 56 interchanges. If advance guide signs two miles prior to one or more of the interchanges is desired, a more detailed analysis can be completed at a later stage of the project. Placement of such signs would be optional.

Figure 1-4 shows a sign placement concept for the westbound direction of the freeway. Guide signs are placed one mile and ½ mile in advance of each offramp, as well as at the offramp itself. This figure depicts existing signs and new signs associated with the proposed interchange. The Austin Road exit gore will be located at approximately the same location as the existing two-mile advance guide sign for the SR 248 interchange. When close spacing of signs occurs, there are several signing options:

- The SR 248 advance guide sign and the Austin Road exit sign could be placed together on an overhead assembly. However, the MUTCD discourages the placement of other signs with an exit sign, so this is not recommended.

- Interchange sequence signs could be used. The MUTCD only recommends these signs in urban areas where multiple interchanges are spaced closely together. US 32 does not meet these criteria, so such signs are not recommended.

- The SR 248 advance guide sign could be moved downstream from the Austin Road exit. Placing the sign 1 ¾ miles in advance of the SR 248 exit would still provide advance notice of the exit to drivers, and is recommended.



CASE STUDY 1
SIGN LAYOUT FOR NEW AUSTIN ROAD INTERCHANGE

FIGURE **1-4**

Although one existing sign will need to be moved, the new interchange can easily be signed without presenting drivers with an excessive number of message units.

Overall, signing needs for US 32 in the westbound direction will not place more than two sign panels at the same location or create special conditions that would require an unusually high number of message units. For brevity, signing on US 32 eastbound is not illustrated in the case study but will be very similar to the westbound direction and will not affect the feasibility of the Austin Road interchange.

Signing principles of the MUTCD can be attained with the new Austin Road interchange. Signs related to these interchanges will not present drivers with more information than they are able to process; therefore, signing needs do not affect ramp spacing considerations.

FINDINGS

At the first stage of the concept development, a diamond interchange at Austin Road appears to be feasible from a ramp and interchange spacing perspective. Based on forecast ramp and freeway volumes and anticipated ramp spacing dimensions, no components of the freeway will be over capacity and the LOS C guideline is potentially achievable. Signing needs at this location appear consistent with MUTCD principles for sign placement and sign information content. At no location is more than one guide sign necessary. There is no expected reduction in safety along the freeway mainline after adding a diamond interchange at Austin Road because ramp spacing dimensions remain significantly larger than 2,600 ft. Ramp and interchange spacing considerations should be reevaluated as the concept developed enters preliminary design, although no issues are anticipated. Traffic operations should be refined and documented in the interchange evaluation document for this project.

Case Study 2

Case Study 2 introduces several conditions not found in Case Study 1. The project includes partial interchanges, and lies on the Interstate Highway System. The proposed interchange will create ramp spacing that is close enough to constitute a weaving section.

BACKGROUND

General

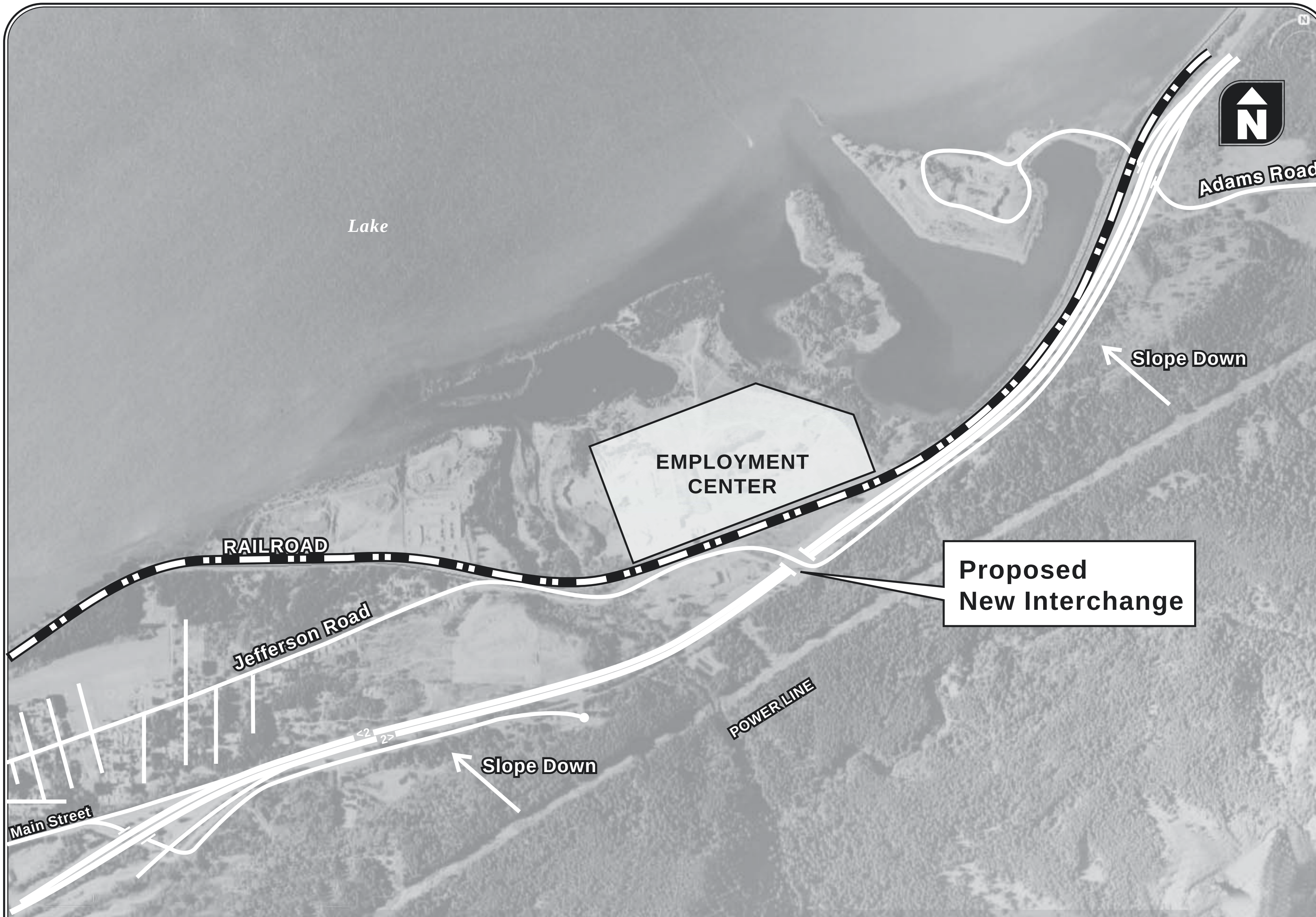
A new employment center is proposed in a historically rural community that is becoming suburbanized. The proposed site is located between Interstate 50 and a lake. A railroad runs parallel to the north side of the interstate (between the interstate and the lake), and a steep hillside and power line are on the south side of the interstate. The employment center will generate more traffic than the existing roadway network can accommodate, and a new diamond interchange is proposed at the existing Jefferson Road overpass on I-50. A diamond interchange will have a relatively narrow footprint compared to partial cloverleaf forms and will minimize impacts in this constrained site.

Adjacent Interchanges

To the east, the nearest interchange is at Adams Road, 5,100 ft away from Jefferson Road (measured between the centerlines of each crossroad). Adams Road has a half-diamond interchange, with the ramps on the east side away from Jefferson Road. To the west, the nearest interchange is Main Street, 6,900 ft away from Jefferson Road. Main Street also has a half-diamond interchange, with the ramps on the east side towards Jefferson Road. These roads and interchanges are shown on the site map in Figure 2-1.

Traffic Volumes and Characteristics

The freeway currently has two lanes in each direction and a peak-hour volume of approximately 2,500 vehicles in each direction. The Adams Road interchange has a peak-hour volume under 200 vehicles on each ramp. The Main Street interchange has a peak-hour volume of 400 to 600 vehicles on each ramp. When the employment center is fully built out, the Jefferson Road interchange is expected to have 500 peak-hour vehicles on the ramps to the east and 700 peak-hour vehicles on the ramps to the west. Heavy vehicles account for 10% of the interstate volume and less than 5% of the volumes on the existing ramps. The heavy-vehicle percentage on the ramps at the new interchange is forecast to be 5%. The interstate is generally level through this area, although there is a steep uphill slope on the south side.



Source: The U.S. Department of Agriculture, Service Center Agencies

CASE STUDY 2
SITE MAP

FIGURE
2-1

AGENCY REQUIREMENTS

The state in which the project is located has an operating guideline of LOS D for this type of location. The interstate and all ramp-freeway junctions in the project area are currently operating at LOS D or better, and the new interchange should not result in any components of the freeway operating below LOS D.

RAMP SPACING CONSIDERATIONS

The following ramp spacing assessment follows the sequence outlined in Section 5.3:

- Geometry considerations,
- Traffic operations,
- Safety, and
- Signing.

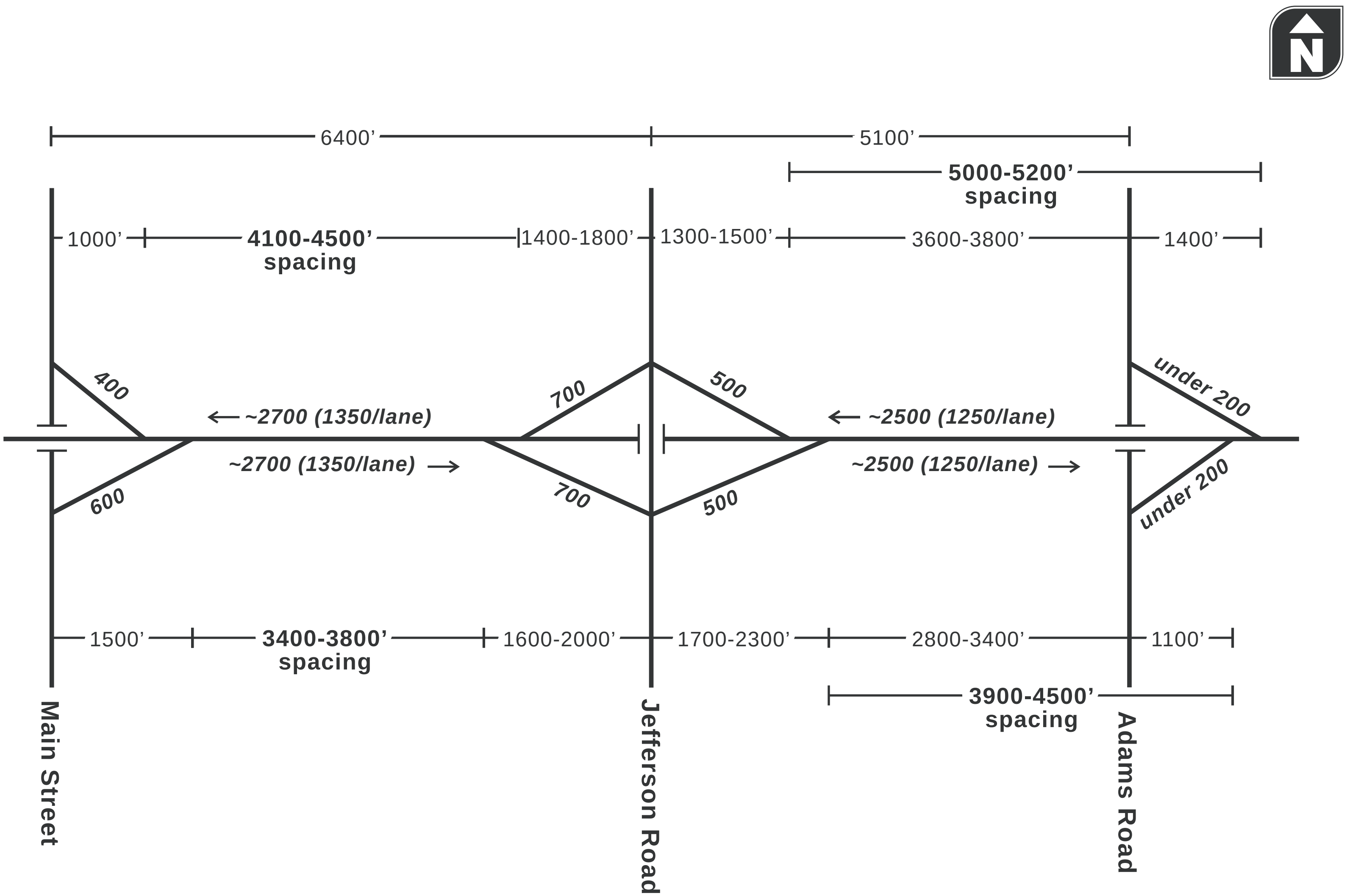
STEP 1—Geometric considerations:

The first step is to conceptually determine the interchange footprint and approximate length of the ramps at the Jefferson Road interchange based on three-dimensional roadway design considerations.

As discussed in Chapter 3 of the Guidelines and in Case Study 1, at a conceptual level and starting point in layout for diamond interchange ramps, physical entry and exit gores are approximately 100 ft in length from the crossroad. On an entrance ramp, the distance between the physical gore and the painted merging tip is typically 400-800 ft and, on an exit ramp, the distance between the painted diverging tip and the physical gore is typically 300-500 ft. Summing these dimensions, the distance from a painted diverging tip to the crossroad generally ranges from 1,300-1,500 ft, and the distance from the crossroad to the painted merging tip generally ranges from 1,400-1,800 ft.

As discussed in Chapter 1, ramp spacing dimensions under consideration in the case studies will be measured from the painted merging tip to the painted diverging tip.

Considering the site specific design needs at the Jefferson Road interchange, the length of the eastbound ramps may be impacted by the steep uphill slope on the south side of the interstate. An overpass is generally in the range of about 25 ft above a freeway, but the southern end of the Jefferson Street overpass may be closer to 40 ft above the elevation of I-50. This means the eastbound off- and onramps will need to be lengthened to accommodate the needed grade changes. Assuming a 4-6% grade and an additional 15 ft of elevation change, approximately the assumed distance between the cross street and the painted tips of the eastbound ramps should be lengthened by an additional 300-500 ft.



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 2
RAMP SPACING AND DAILY TRAFFIC VOLUMES

FIGURE 2-2

Figure 2-2 shows approximate dimensions of all existing and proposed ramps in the project area as well as centerline-to-centerline roadway spacing and design-hour traffic volumes. Note that ramps in the eastbound direction are expected to be 300-500 ft longer than ramps in the westbound direction to accommodate a greater grade change between the interstate and Jefferson Road.

After considering the ramp configurations and spacing values from a geometric design perspective, the next steps are to consider the potential influence that traffic operations, signing, and other considerations have on ramp spacing values.

STEP 2—Traffic Operations:

The Jefferson Road interchange will create the following four, closely spaced ramp combinations:

- Eastbound, upstream of Jefferson Road—Entry ramp (600 vehicles per hour (vph)) followed by exit ramp (700 vph). Ramp spacing of 3,400-3,800 ft.
- Eastbound, downstream of Jefferson Road—Entry ramp (500 vph) followed by entry ramp (under 200 vph). Ramp spacing of 3,900-4,500 ft.
- Westbound, upstream of Jefferson Road—Exit ramp (under 200 vph) followed by exit ramp (500 vph). Ramp spacing of 5,000-5,200 ft.
- Westbound, downstream of Jefferson Road—Entry ramp (700 vph) followed by exit ramp (400 vph). Ramp spacing of 4,100 to 4,500 ft.

There is little guidance available on operational analysis of closely spaced exit-exit or entry-entry ramp combinations. Exit-exit ramp combinations do not result in any vehicles entering the freeway, an act that is more disruptive to traffic flow than vehicles leaving the freeway. With a spacing of 5,000 ft or more between the Adams Road and Jefferson Road exit ramps on I-50 westbound, it is unlikely that any operational impacts will occur due to spacing. As discussed in the Section 4.3.1 of the Guidelines, simulation modeling has indicated that the spacing of entry-entry ramp combinations does not have a significant impact on freeway speed when the freeway volume is 1,500 vehicles per hour per lane or less. Volumes on I-50 eastbound are not this high, making it unlikely that the Jefferson Road and Adams Road entry ramps will create operational impacts on the freeway.

> Simulation results suggest the spacing of entry-entry ramps, with the volumes that will exist, will not have an impact on freeway speed.

In addition to checking operational impacts due to spacing, each ramp-freeway junction should be evaluated to see if, in isolation, it is near or under capacity. As discussed in Case Study 1, Table 4-1 of the Guidelines summarizes the HCM's capacity thresholds for various freeway and ramp components. The table shows that all ramp-freeway junctions on this segment of I-50 appear to be well below the capacity thresholds of the HCM. At a concept level, this indicates there are no obvious pronounced traffic operations concerns. Detailed traffic operations should be conducted as the geometry is being refined.

On I-50 between Main Street and Jefferson Road, a closely spaced entry-exit ramp combination will exist in both directions. Auxiliary lanes are being considered between each entry and exit ramp, which would create a weaving section. The AASHTO Green Book recommends auxiliary lanes to improve traffic operation between a successive entrance and exit terminal when the spacing between the ramp "noses" is 1,500 ft or less. The use of auxiliary lanes is not discouraged if greater ramp spacings exist, as is the case here. However, simulation modeling suggests that the benefits of an auxiliary lane may be limited at the Jefferson Road interchange. In each direction of I-50, less than 1,250 vehicles per hour per lane will be on the freeway upstream of each entry ramp. Simulation modeling of entry-exit ramp combinations with 1,250 vehicles per hour per lane on the freeway found that ramp spacing had no impact on freeway speed. Simulation modeling was only conducted with a four-lane (in one direction) freeway, so the findings should be used with caution.

> No operational guidelines or warrants for the use of auxiliary lanes exist. However, simulation model results suggest the benefits of adding one here may be limited.

Subsequently, in the next phase of the project, a complete HCM ramp-freeway junction analysis should be conducted to determine the LOS. If an auxiliary lane is added, the resulting segment will either be considered, for the purposes of HCM analysis, a weaving section or a basic freeway segment. To make this determination, Exhibit 4-5 of the Guidelines may be used. Use of this exhibit requires only three pieces of data–the ramp spacing (weaving segment length), ratio of weaving volume to total volume, and the number of lane changes to complete a weaving maneuver.

The eastbound direction of I-50 has a shorter ramp spacing dimension, the same freeway volume, and higher ramp volumes relative to the westbound direction of I-50. Therefore, the eastbound direction is the focus of the analysis presented below; similar analysis should be conducted for the westbound direction.

At this phase of the project, the origin and destination of vehicles in the weaving segment is not known. To account for worst-case conditions, it is assumed that all vehicles on the ramps make weaving maneuvers (there are no vehicles that enter at the first ramp and exit at the second ramp). Under such a scenario, there would be 1,300 (600 + 700) weaving vehicles and the ratio of weaving volume to total volume would be 0.48 (1,300/2,700). Using Exhibit 4-5 of the Guidelines (reproduced and marked up here as Figure 2-3), the Main Street entry ramp and the Jefferson Road exit ramp will be "close enough" together and have a "high enough" ratio of weaving to nonweaving volume that the weaving procedures of the HCM should be used for operational analysis.

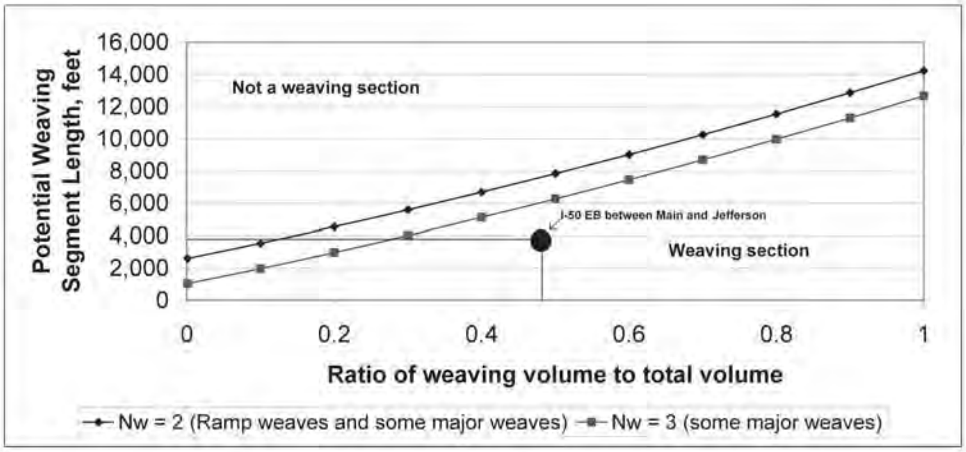


Figure 2-3 Determination of Analysis Procedure for I-50 Eastbound Between Main Street and Jefferson Road.

As shown in Figure 2-3, the section of I-50 between Main Street and Jefferson Road will fall into the realm of weaving, as defined by the HCM, if an auxiliary lane is added. However, this does not imply that operational problems will occur or a desired LOS cannot be achieved. Rather, it implies that the weaving procedures of the HCM, as opposed to the basic freeway segment procedures, should be used to analyze the section. In summary, the current configuration and weaving screening indicates the interchange should be evaluated as a weaving section (if an auxiliary lane is ultimately used), and this revelation can help guide the scoping for an appropriate range of traffic analyses as the interchange concepts are developed in more detail.

STEP 3—Safety:

The Jefferson Road interchange will create four ramp combinations of interest. The combinations, ramp spacing values, and applicable sections of the Guidelines for the safety assessment are summarized as the following:

Freeway mainline safety issues are not expected between entrance and exit ramps in either the eastbound or westbound directions following construction of the Jefferson Road interchange.

- Eastbound, upstream of Jefferson Road—Entry ramp followed by exit ramp; ramp spacing of 3,400-3,800 ft; Sections 4.5.4.1 and 5.3.3.1.
- Eastbound, downstream of Jefferson Road—Entry ramp followed by entry ramp; ramp spacing of 3,900-4,500 ft; Sections 4.5.4.2 and 5.3.3.2.
- Westbound, upstream of Jefferson Road—Exit ramp followed by exit ramp; ramp spacing of 5,000-5,200 ft; Section 4.5.4.3.

- Westbound, downstream of Jefferson Road—Entry ramp followed by exit ramp; ramp spacing of 4,100 to 4,500 ft; Sections 4.5.4.1 and 5.3.3.1.

The safety consequences of the Jefferson Road interchange can be explored at a planning level in this case study without direct consideration of traffic volumes. The ramp spacing for the EN-EX combinations will be 3,400-3,800 ft in the eastbound direction and 4,100-4,500 ft in the westbound direction. Research conducted to develop the Guidelines indicated that the sensitivity of total crashes to EN-EX ramp spacing becomes close to negligible for spacing values greater than about 2,600 ft; in other words, the safety performance of the segment approaches that of a basic freeway segment with no interchange ramps. The finding is illustrated in Exhibit 5-5, where the solid line representing crash risk as a function of ramp spacing becomes fairly flat for spacing dimensions larger than 2,600 ft.

Freeway mainline safety issues are also not expected between the consecutive entrance ramps in the eastbound direction following construction of the Jefferson Road interchange.

The ramp spacing for the eastbound EN-EN combination will range from 3,900-4,500 ft. Research conducted to develop the Guidelines indicated that the sensitivity of total crashes to EN-EN ramp spacing becomes close to negligible for spacing values greater than about 2,200 ft. The finding is illustrated in Exhibit 5-8, where the solid line representing crash risk as a function of ramp spacing becomes fairly flat for spacing dimensions larger than 2200 ft.

Freeway mainline safety issues for an EX-EX spacing between 5,000-5,200 feet are not likely given the relatively low volumes at the ramp-freeway junctions. The geometric analysis and signing considerations are the primary factors for the EX-EX spacing assessment.

The ramp spacing for the westbound EX-EX combination will range from 5,000-5,200 ft. The EX-EX combination was not studied from a safety perspective during research conducted to develop the Guidelines.

STEP 4—Signing:

Signing should be considered at the earliest stages of concept development to assess the types and amount of information that will need to be presented and to consider the advance placement of signs. It may be necessary to consider more than one upstream and one downstream interchange because advance guide signs may be placed several miles prior to an interchange. At this location, there are no interchanges within three miles west of Main Street or east of Adams Road. The area depicted in Figure 2-1 is effectively isolated from a signing perspective.

The existing interchanges and the proposed Jefferson Road interchange are all considered "major" or "intermediate" by the MUTCD. Advance guide signs should be placed ½ and one mile prior to each exit, with a third sign two miles in advance of the exit being optional. The Main Street and Adams Road interchanges do not currently have 2-mile advance guide signs, and such signs are not planned for the Jefferson Road interchange.

Figure 2-4 shows a sign placement concept for the westbound direction of the freeway. In the eastbound direction, there is only one exit ramp, and signing requirements will clearly be achievable.

As shown in Figure 2-4, the guide sign one mile in advance of the Main Street offramp is presently within a few hundred feet of the Jefferson Road diverging tip, at approximately the same location where a sign for the Jefferson Road offramp will need to be placed. There is limited flexibility with the location of the sign for the Jefferson Road offramp. However, the advance guide sign for Main Street could be placed at a location other than one mile in advance of the exit. The sign could be mounted on the Jefferson Road overpass ¾ mile prior to the Main Street exit, or it could be placed 1 ½ miles prior to the Main Street exit (at the same location as the ½ mile advance guide sign for the Jefferson Road exit). If the latter is chosen, an overhead sign structure would be needed.

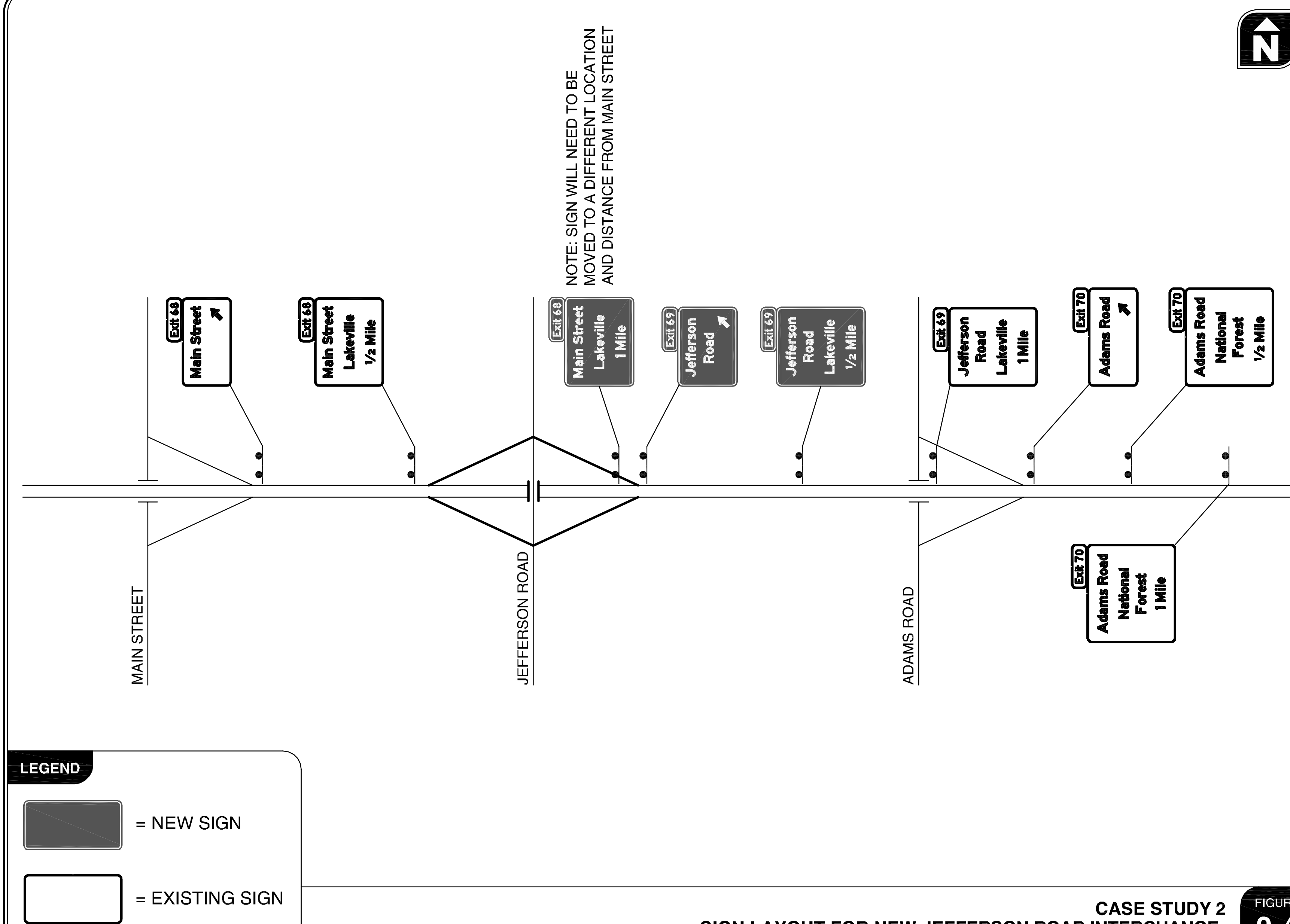
Both options can be explored in greater detail in the preliminary design phase of the project. However, it is clear that signing principles of the MUTCD can be satisfied, and no further analysis is necessary at this time. Signs related to these interchanges will not present drivers with more information than they are able to process; therefore, signing needs do not affect ramp spacing considerations.

Other Considerations:

The proposed interchange will be on the Interstate Highway System, and therefore must be approved by FHWA. As discussed in Chapter 2 of the Guidelines, FHWA considers eight points before granting or denying access. These points address the following issues:

1. The existing system is incapable of accommodating traffic demands;
2. All reasonable alternatives to a new interchange have been considered;
3. The proposal does not adversely impact the freeway;
4. A full interchange at a public road is provided;
5. The proposal is consistent with transportation plans;
6. A comprehensive interstate network study is prepared;
7. There is coordination with transportation system improvements; and,
8. The request needs to consider planning and environmental constraints.

The initial ramp spacing analysis conducted above will, in part, determine whether the third point is satisfied.



CASE STUDY 2
SIGN LAYOUT FOR NEW JEFFERSON ROAD INTERCHANGE

FIGURE **2-4**

FINDINGS

At the first stage of the concept development, a diamond interchange at Jefferson Road appears to be feasible from a ramp and interchange spacing perspective. Based on forecast ramp and freeway volumes and anticipated ramp spacing dimensions, the LOS D guideline for this facility appears achievable. Signing needs at this location appear consistent with MUTCD principles for sign placement and sign information content. At no location is more than one guide sign necessary. Safety is relatively insensitive to ramp spacing within the ranges expected for the EN-EX, EN-EN, and EX-EX combinations following construction of the Jefferson Road interchange. Ramp and interchange spacing considerations should be reevaluated as the concept developed enters preliminary design, and traffic operations analyses should be performed as the concepts are being refined.

Case Study 3

Case Study 3 presents a project where a proposed interchange will be one mile from adjacent interchanges in either direction. The proposed interchange is likely geometrically feasible, but the presence of high traffic volume creates operational and safety concerns. A preliminary analysis is conducted in this case study, and the need for additional analyses as the design is refined is highlighted.

BACKGROUND

General

Arterials in this area were built on a one-mile grid. Exhibit 5-2 indicates that, geometrically, the diamond forms can fit within the cross street spacing available at this site.

An eight-lane interstate (I-121) runs through a built-out suburban area where arterials are spaced one mile apart. To improve the transportation system, the state transportation agency is proposing a new interchange at 44th Street, one of the arterial streets on the one-mile grid. When the interstate was initially constructed, no interchange was constructed at 44th Street. A single-point diamond interchange is considered the most feasible interchange form for this location because it has a small footprint and is consistent with the other interchanges in the corridor. The state is considering adding auxiliary lanes between the ramps for the 44th Street interchange and ramps from adjacent interchanges. Auxiliary lanes have been used at some other locations in the I-121 corridor to improve operational performance.

Adjacent Interchanges

To the north, the nearest interchange is at 48th Street, 5,300 ft away from 44th Street (measured between the centerlines of each crossroad). To the south, the nearest interchange is at 40th Street, 5,400 ft away. Both interchanges are single-point diamonds. These roads and interchanges are shown on the site map in Figure 3-1.

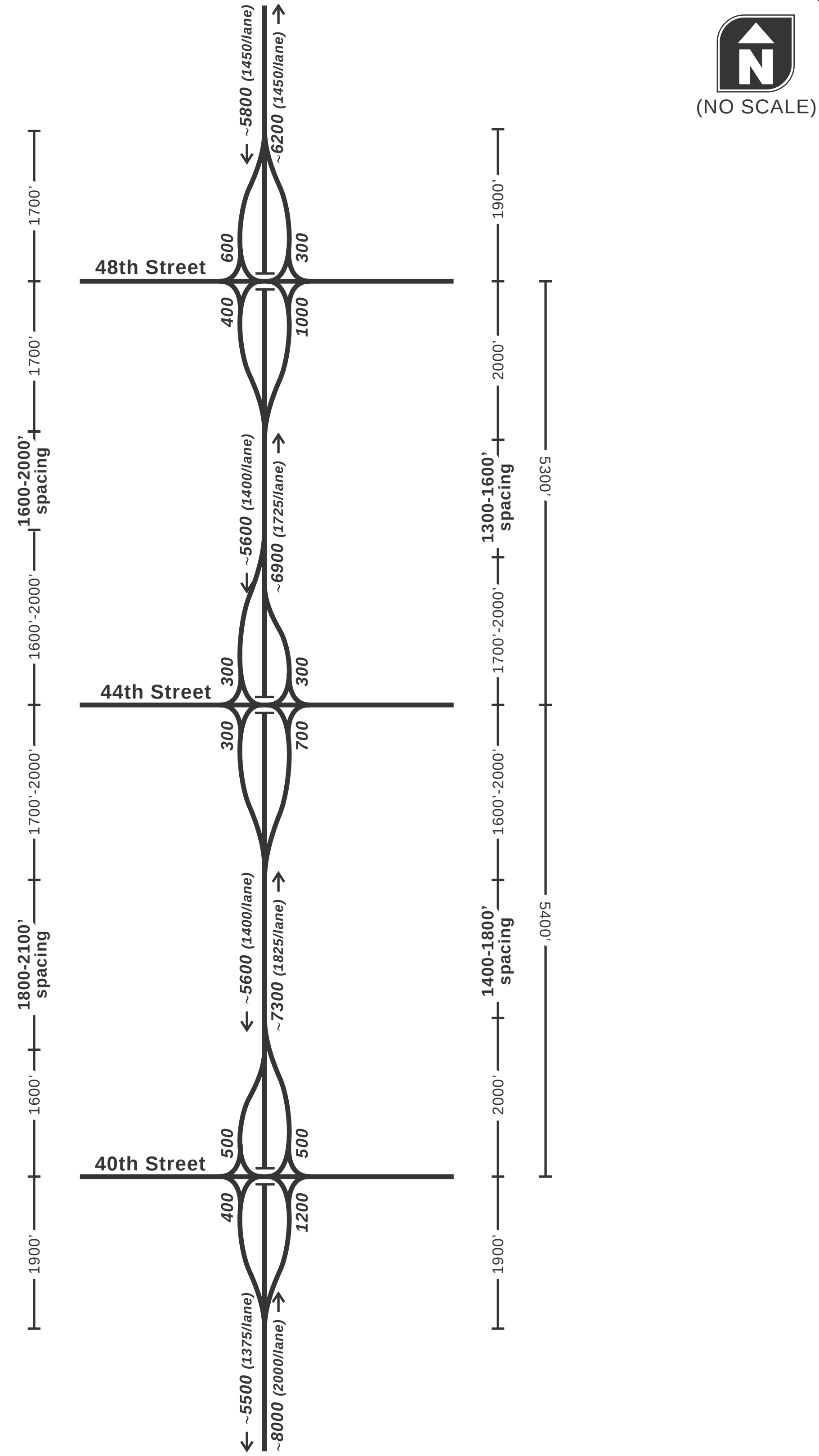
Traffic Volumes and Characteristics

For brevity, only one time period is analyzed within this case study. However, the a.m. peak hour and any other high-volume periods known to exist should also be analyzed.

I-121 currently has four lanes in each direction. The interstate is primarily used by commuters, and experiences a heavy directional split during the peak periods. Conditions during the p.m. peak, when overall volume is highest, are described below. During the p.m. peak, 8,000 vehicles (approximately 2,000 per lane) are travelling northbound on I-121 south of the 40th Street interchange. The 40th Street, 44th Street, and 48th Street interchanges will have 700-1,200 northbound vehicles exiting and 300-500 entering northbound vehicles. North of the 48th Street interchange, there will be 6,200 northbound vehicles on I-121. Heavy vehicles account for less than 5% of volume on the freeway and surrounding arterials, and terrain in this area is level. Volumes in the southbound direction, which are lower during this period, are shown in Figure 3-2.

CASE STUDY 3
SITE MAP

FIGURE
3-1



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 3
RAMP SPACING AND TRAFFIC VOLUMES

FIGURE 3-2

AGENCY REQUIREMENTS

The state in which this project is located has an operating guideline of LOS E for urban interstates. Additionally, state maintains the traffic signals at all ramp-terminal intersections and has an operating standard of LOS D for signalized intersections. The interstate and the existing ramp-terminal intersections are currently meeting these standards. The new interchange should not result in any components of the new freeway operating below LOS E or any ramp-terminal intersection operating below LOS D.

Analysis of ramp-terminal intersections will not be included in the conceptual evaluation presented in this case study but should be considered at the next phase of the project.

RAMP SPACING CONSIDERATIONS

The following ramp spacing assessment follows the sequence outlined in Section 5.3:

- Geometry considerations,
- Traffic operations,
- Safety, and
- Signing.

STEP 1—Geometric Considerations:

The first step is to conceptually determine the interchange footprint and approximate length of the ramps at the 44th Street interchange based on three-dimensional roadway design consideration. Conditions at the 44th Street interchange will be similar to those at the two adjacent interchanges. All interchanges will:

- Be single-point diamond form;
- Serve arterials with similar volumes of traffic as the adjacent interchanges;
- Have a transition from a single lane to multiple lanes on exit ramps and vice versa on entry ramps;
- Have metered entry ramps;
- Have the potential for long queues on the exit ramps; and
- Use the state's standard gore design.

Measured from the crossroad to the painted gore, the 40th and 48th Street interchanges have exit ramps that vary from 1,600-2,000 ft and entry ramps that vary from 1,700-2,000 ft. Since the design of the 44th Street interchange will be similar to these interchanges, these ranges of ramp lengths are used at the conceptual planning level of the 44th Street interchange. Ramp lengths are shown in Figure 3-2.

At the 44th Street interchange, the design of exit ramps will be heavily influenced by ramp-terminal intersection queues, and the design of entrance ramps will be heavily influenced by ramp meter queues.

On the 44th Street exit ramps, queues of several hundred feet in length can be anticipated during the p.m. peak hour. The ramp should be designed so that drivers can decelerate from the speed of the freeway to a complete stop by

Precise dimensions of the 44th Street ramps will be determined during the project's preliminary design phase. Approximate ranges of dimensions based upon the design of adjacent interchanges may be used at this stage of the project to make an initial assessment of the adequacy of ramp spacing.

the time the back of queue is reached. The FFS of the freeway can be used for a conservative design. However, if freeway volumes are high enough to create congestion at the same time peak queues are expected, a speed lower than FFS could be used when determining deceleration distance. Ultimately, queue considerations will likely dictate a ramp length that is greater than required due to grade change alone. A similar situation exists on the entrance ramp. The ramp meter will need to be placed far enough down the ramps that queues will not spill back onto 44th Street. After stopping at the meter, drivers will then need sufficient ramp length to accelerate to nearly the speed of the freeway onto which they are merging. Queue length and acceleration/deceleration length calculations should be performed during the project's preliminary design phase to determine actual ramp length dimensions. At this stage of the project, it is assumed the dimensions needed to achieve these characteristics at the 44th Street ramps will be similar to the ranges of dimensions that exist at the ramps at the adjacent interchanges.

After considering the ramp configurations and spacing values from a geometric design perspective, the next steps are to consider the potential influence that traffic operations, signing, and other considerations have on ramp spacing values.

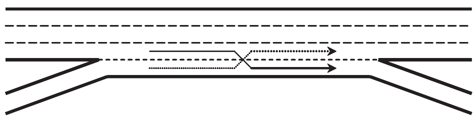
STEP 2—Traffic Operations:

The 44th Street interchange will introduce four ramp spacings of approximately 2,000 ft or less. AASHTO policy recommends auxiliary lanes when the distance between successive "ramp noses" is less than 1,500 ft, and this may be the case here. Simulation models of a four-lane freeway with 1,750 vehicles per hour per lane (the approximate volume on I-121 at 44th Street) have identified a freeway speed reduction of up to 20 mph when an auxiliary lane is not present between closely spaced ramps. However, under the range of ramp volumes at these interchanges, the expected speed reduction due to the lack of an auxiliary lane would be less than 5 mph. Auxiliary lanes are recommended between all four of the EN-EX ramp combinations that will be created.

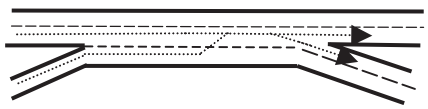
A complete weaving analysis for all four weaving sections being created by the 44th Street interchange should be conducted as the design is developed to a level of detail that better quantifies ramp length dimensions.

Ramp spacing dimensions in the range of 1,500-2,000 ft are short enough that, when an auxiliary lane is added between the ramps, a weaving section will be created regardless of what volumes are present, and an HCM weaving analysis should be conducted. The weaving section will be considered one-sided, since both ramps will be on the same (right) side of the freeway.

The one-sided weaving sections that will be created here may be designed in one of two ways. If designed as a ramp weaving, a lane will be added from a single-lane entry ramp, carried through the section, and dropped at a single-lane exit ramp. Designed as a major weave, a lane will be added from a single-lane entry ramp, carried through the section, and dropped at a double-lane ramp (where the second lane comes from a taper off of one of the freeway's basic lanes). These two options are illustrated in Exhibit 12-3 of the 2010 HCM (reproduced as Figure 3-3)



Ramp weave



Major weave with two-lane exit ramp

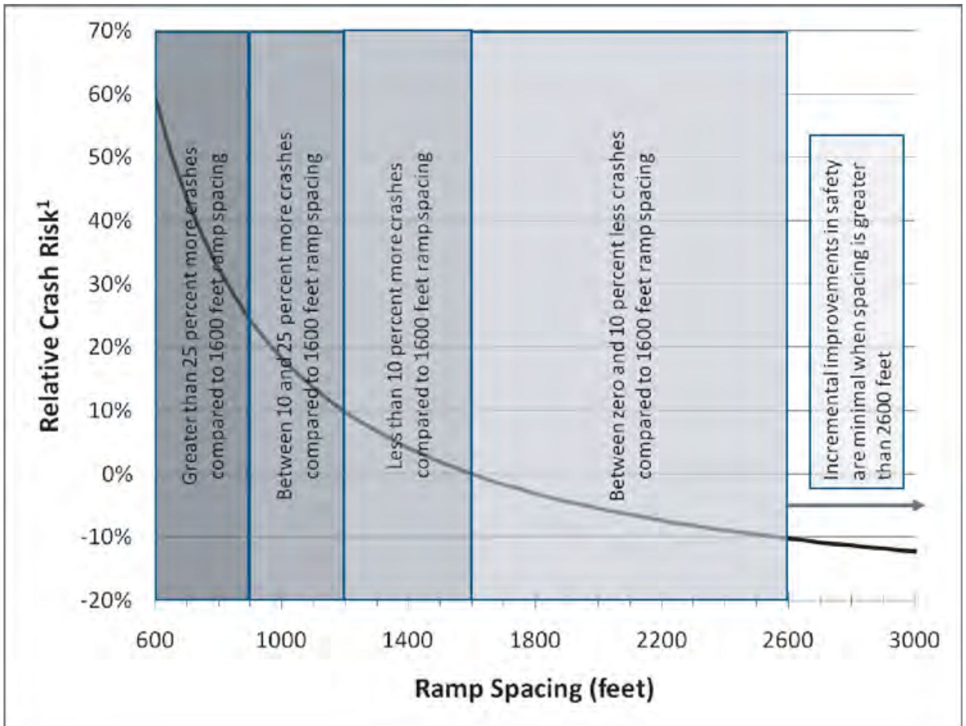
Figure 3-3 Types of One-Sided Weaving Segments (Reproduced from 2010 HCM).

Two-lane exit ramps will maintain the principles of lane balance. The number of lanes downstream of the diverge (on the freeway and the ramp combined) is one more than the number of lanes on the freeway prior to the diverge. Exiting vehicles coming from the freeway are not required to make a lane change, which will improve the operation of the weaving section. An HCM analysis can be used to quantify this improvement. However, two-lane exit ramps may not be required to achieve capacity and/or desired LOS. For weaving segments where the exit ramp already exists (i.e., a 40th Street or 48th Street exit), converting existing single-lane ramps into double-lane ramps will increase the scope and extent of this project.

> Ramp weaves with single-lane exits may be adequate for all weaving sections created by the 44th Street interchange. If they are not, major weaves with double-lane exits should be considered.

STEP 3—Safety:

The safety consequences of a 44th street interchange may first be explored at a planning level without explicit consideration of traffic volumes. Ramp spacing dimensions range from 6,000 to 7,400 ft without a 44th Street interchange; all ramp combinations of interest are EN-EX. Guidelines Exhibit 5-5 (reproduced below as Figure 3-4) indicates that spacing dimensions in this range generally correspond to safety performance of a freeway segment without interchanges. The relative crash risk "levels off" to about -12% for spacing dimensions beyond 3,000 ft.



[1] Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,600 ft

Figure 3-4 Preliminary Safety Assessment Tool for Ramp Spacing, Entrance Ramp Followed by Exit Ramp (Guidelines Exhibit 5-5)

Ramp spacing dimensions range from 1,300 to 2,100 ft with an interchange at 44th Street. Again, all ramp combinations of interest are EN-EX. Figure 3-4 shows a relative crash risk of about -6% for a spacing of 2,100 ft; +7% for a 1,300 ft spacing. Therefore, the expected number of crashes along the freeway mainline is estimated to increase by anywhere from 6 to 19% with the 44th Street interchange in place. These estimates assume all else is equal, including traffic volumes, and that no auxiliary lanes are used. Discussion in Guidelines Section 4.5.4.1.4 indicates the expected increase in crashes can be reduced, or possibly eliminated, if auxiliary lanes are provided between entrance and exit ramps.

Traffic patterns are likely to change following construction of the 44th Street interchange. In addition, safety impacts of adding auxiliary lanes between the ramps for the 44th Street interchange and ramps from adjacent interchanges need to be assessed in greater detail. A fuller safety assessment that addresses these issues by implementing Guidelines Equation 5-1 and Guidelines Exhibit 5-7 is illustrated next.

The total number of crashes expected to occur can be estimated with Guidelines Equation 5-1:

$$TOTAL = 9.7\times10^{-6} L^{1.0} \left(DADT\right)^{1.12} \left(ADT_{EN}\right)^{0.18} \left(ADT_{EX}\right)^{0.02} \exp\left(\frac{450}{S} - 0.23\times AuxLn\right)$$

Guidelines Equation 5-1: Estimating the total number of crashes between an entrance and exit

Equation variables are defined in Guidelines Section 5.3.3.1. Applications to the northbound direction of I-121 are demonstrated in this case study. A safety analysis of the southbound direction can be conducted using the same basic steps.

L represents the segment length, measured in miles. An analysis segment is defined from physical gore to physical gore. If exact locations of the physical gore are unknown, the analysis segment may be defined from cross street to cross street. The segment length without the 44^{th} street interchange is approximately 2 miles (the distance between 48^{th} and 40^{th} streets).

ADT_{EN} and ADT_{EX} represent the daily volumes of cars entering and exiting on the analysis segment. The volumes without the 44^{th} street interchange are shown in Figure 3-5. In the northbound direction, these numbers are 5,400 and 11,250 vehicles per day, respectively.

DADT is the daily volume on the freeway mainline upstream of the entrance gore in the analysis direction. This number for the northbound segment without the 44^{th} street interchange can be determined from Figure 3-6 as 67,000 – 13,000 = 54,000 vehicles per day.

S is the ramp spacing in feet, defined from painted merging tip to painted diverging tip. The spacing between the merging tip (from 40^{th} street) and diverging tip (to 48^{th} street) is 6,700 ft in the northbound direction (see Figure 3-5).

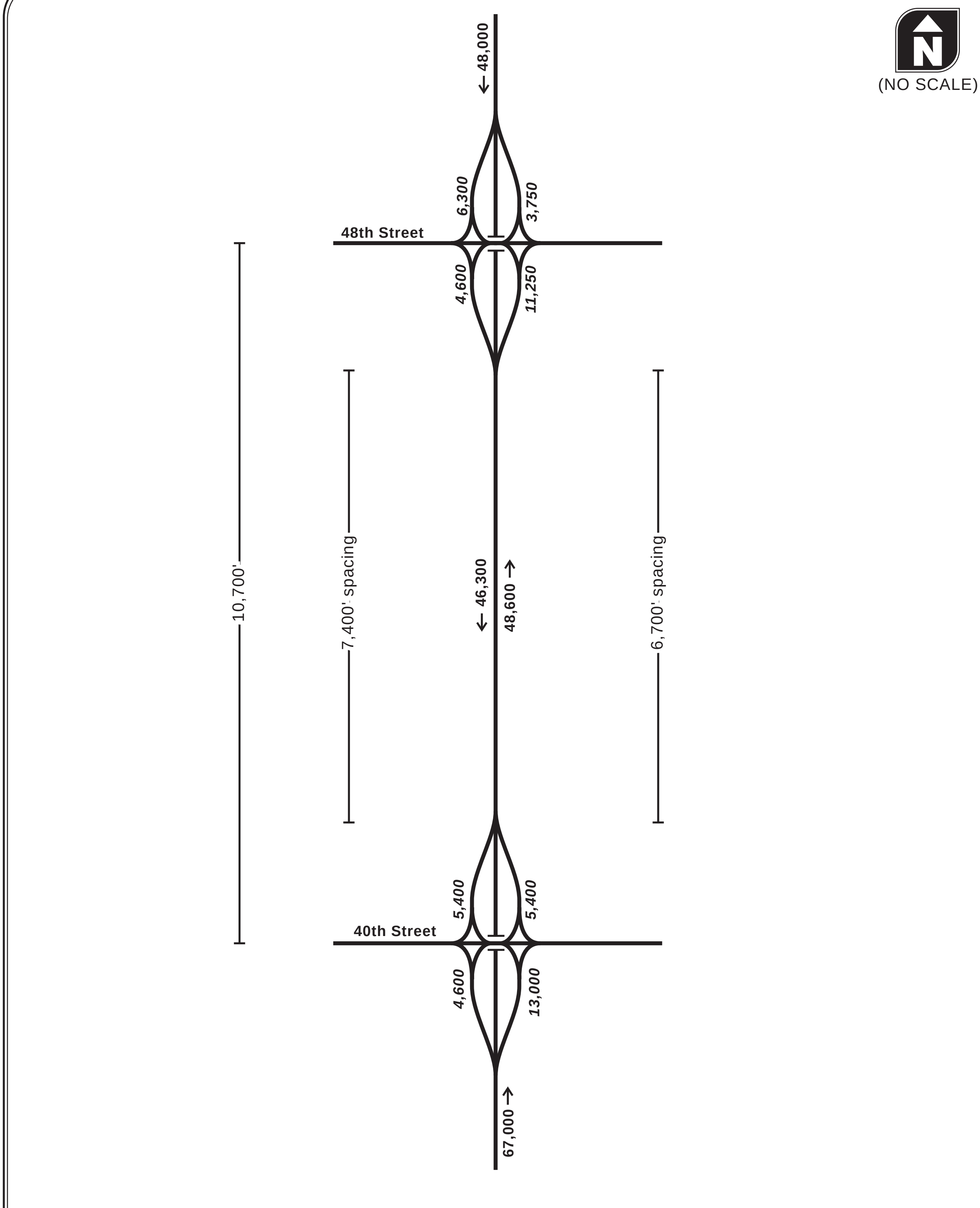
Therefore, 23 x 0.30 = 7 crashes per year are expected to be fatal plus injury on the northbound freeway mainline between 40^{th} Street and 48^{th} without the 44^{th} Street interchange.

No auxiliary lane is present in the current condition, so the variable ‘AuxLn’ is set to zero.

The total number of crashes expected on the northbound freeway mainline between 40th street and 48th street without a 44th street interchange is:

$$TOTAL = 9.7\times10^{-6} 2^{1.0} \left(54000\right)^{1.12} \left(5400\right)^{0.18} \left(11250\right)^{0.02} \exp\left(\frac{450}{6700} - 0.23\times0\right) \approx 23\ crashes/yr$$

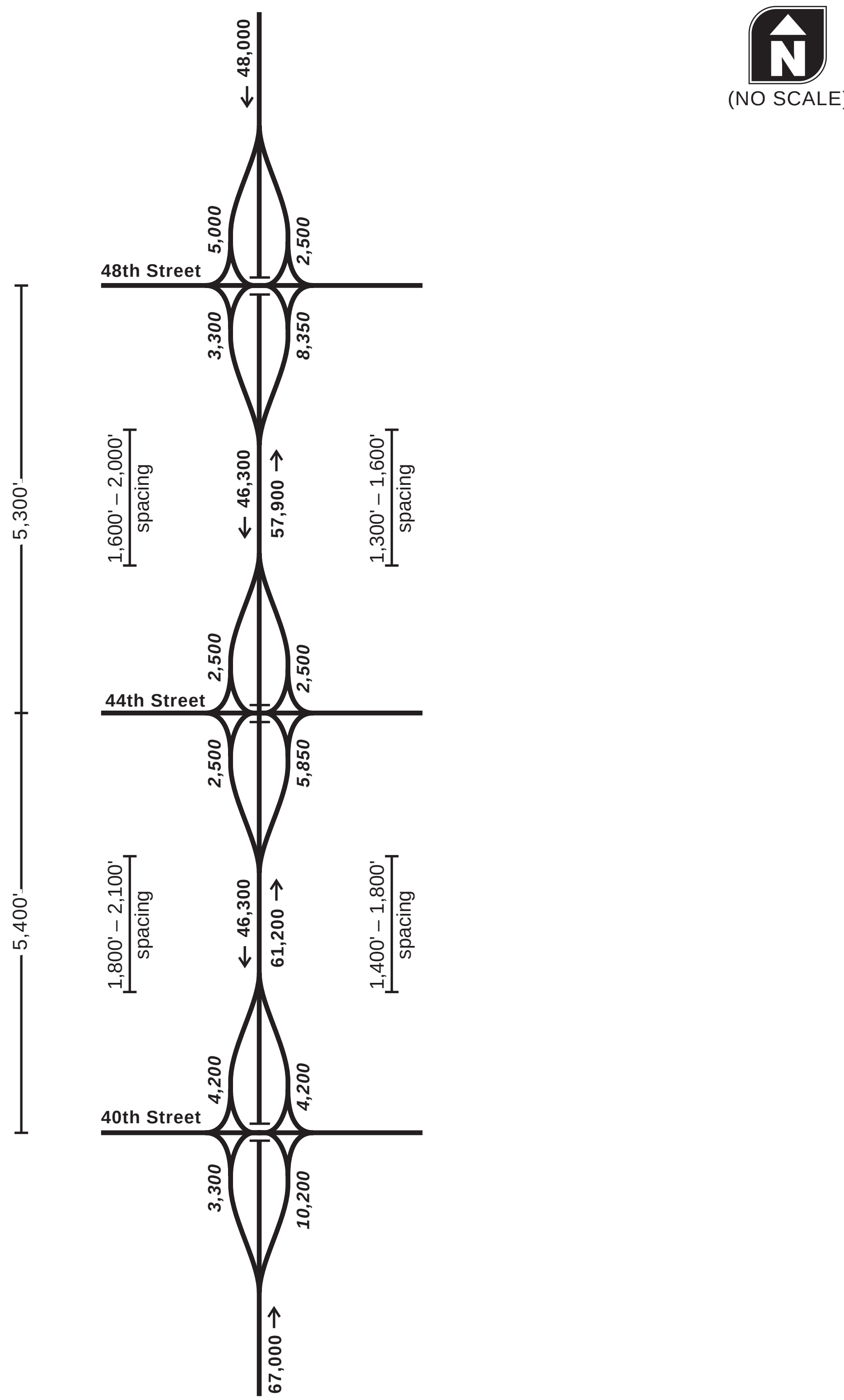
Guidelines Exhibit 5-7 (reproduced as Figure 3-7) shows that the percentage of crashes expected to result in a fatality or injury to at least one vehicle occupant levels off at 30% for ramp spacing values greater than about 1,800 ft.



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 3 RAMP SPACING AND DAILY TRAFFIC VOLUMES WITHOUT 44TH STREET INTERCHANGE

FIGURE **3-5**



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 3
RAMP SPACING AND DAILY TRAFFIC VOLUMES WITH 44TH STREET INTERCHANGE

FIGURE **3-6**

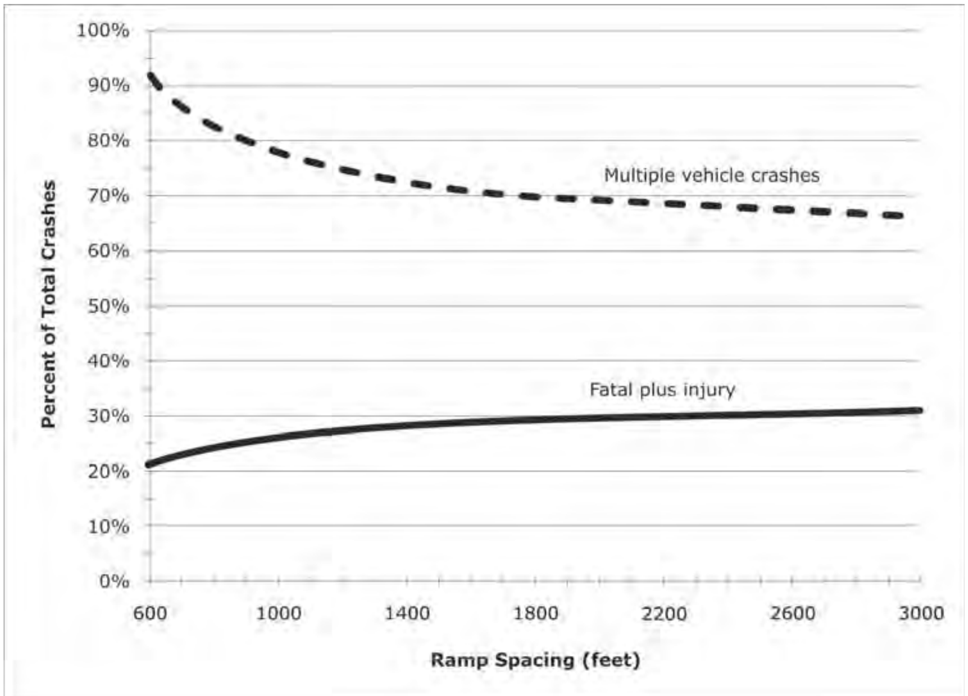


Figure 3-7 Crash Type and Severity Distributions as a Function of Ramp Spacing (Guidelines Exhibit 5-7)

Applying Guidelines Equation 5-1 to Segment 1, the total expected number of crashes on the northbound freeway mainline between 40th street and 44th street is 14 crashes per year without an auxiliary lane, 12 crashes per year with an auxiliary lane.

Approximately 4 crashes per year are expected to be fatal plus injury on the northbound freeway mainline between 40th street and 44th street without an auxiliary lane, approximately 3 crashes per year with an auxiliary lane.

Safety analysis in the northbound direction with the 44th street interchanges requires defining two analysis segments:

Segment 1: From 40th Street to 44th Street, Northbound

'L' = 5400/5280 ≈ 1 mile

'ADT_{EN}' and 'ADT_{EX}' = 4200 and 5850 vehicles per day, respectively

DADT = 67000 – 10200 = 56800 vehicles per day

'S' = 1600 ft (average of expected range of 1400-1800 ft)

AuxLn = 0 if no auxiliary lane; 1 if auxiliary lane present

Figure 3-7 shows about 29% of crashes are expected to be fatal plus injury for a 1600 ft spacing.

Segment 2: From 44th Street to 48th Street, Northbound

'L' = 5300/5280 ≈ 1 mile

'ADT_{EN}' and 'ADT_{EX}' = 2500 and 8350 vehicles per day, respectively

DADT = 61200 – 5850 = 55350 vehicles per day

'S' = 1,450 ft (average of expected range of 1,300-1,600 ft)

AuxLn = 0 if no auxiliary lane; 1 if auxiliary lane present

Figure 3-7 shows about 28% of crashes are expected to be fatal plus injury for a 1,450 ft spacing.

Comparisons of possible scenarios to the current condition are summarized below in Table 3-1.

Table 3-1 Expected Change in Safety Performance with addition of 44th Street Interchange

Scenario	Expected Change in Mainline Safety compared to 'No Build' (i.e., no 44th street interchange)
No Build	---
44th street interchange; no auxiliary lanes	17% increase in total crashes; 14% increase in fatal plus injury crashes
44th street interchange; auxiliary lane between 40th and 44th street ramps only	9% increase in total crashes; no change in fatal plus injury crashes
44th street interchange; auxiliary lane between 44th and 48th street ramps only	9% increase in total crashes; no change in fatal plus injury crashes
44th street interchange; auxiliary lane between both EN-EX combinations	No change in total crashes; 14% reduction in fatal plus injury crashes

STEP 4—Signing:

The I-121 corridor has many interchanges spaced one mile apart due to the design of the arterial network. This interchange spacing results in exit ramps being spaced approximately one mile apart as well. If one-mile advance guide signs were used, they would be located in the vicinity of the gore of the upstream exit, which is discouraged by the MUTCD. Instead, the state has chosen to place many advance guide signs in this corridor at 1 ¼ or ¾ of a mile prior to an exit. Interchange sequence signs are used as well. When a ¾-mile advance guide sign is used, it is generally followed by a ¼-mile advance guide sign instead of a ½-mile advance guide sign. In addition to spreading the signs, this places the second advance guide sign beyond the end of the

Applying Guidelines Equation 5-1 to Segment 2, the total expected number of crashes on the northbound freeway mainline between 44th street and 48th street is 13 crashes per year without an auxiliary lane, 11 crashes per year with an auxiliary lane.

Approximately 4 crashes per year are expected to be fatal plus injury on the northbound freeway mainline between 44th street and 48th street without an auxiliary lane, approximately 3 crashes per year with an auxiliary lane.

upstream entry ramp. This makes the sign visible to drivers entering the freeway on the entry ramp, and in some cases it makes the sign assembly easier to construct by moving it away from the gore.

These same principles have been applied to the segment of the I-121 corridor near the 44th Street interchange, and the signing plan shown in Figure 3-8 was developed. The signing plan includes signs for SR 63 (52nd Street), which is 1 mile north of 48th Street, as well as signs for 32nd and 28th Streets, which are 2 and 3 miles south of 40th Street, respectively.

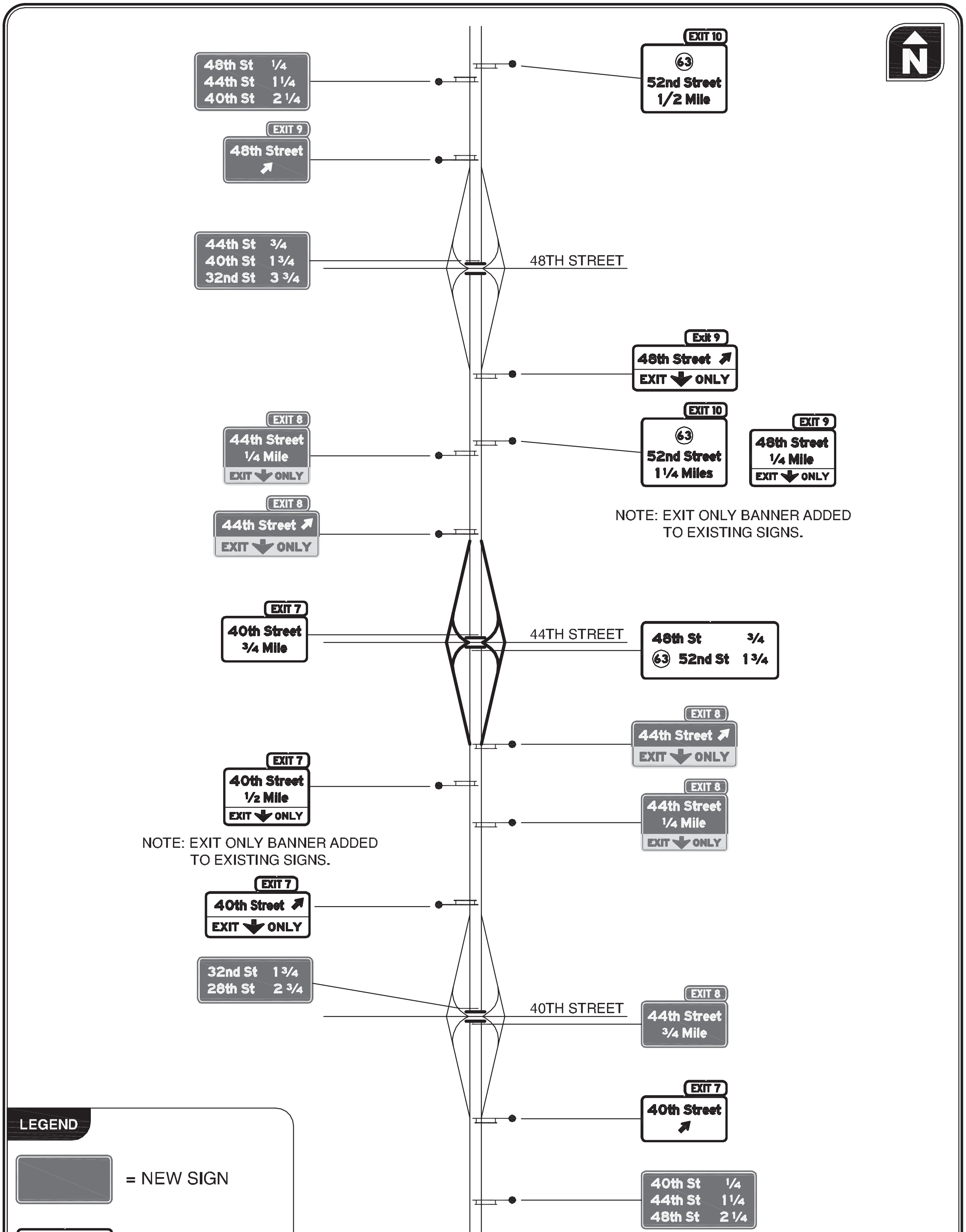
All signs are overhead because of the number of lanes on the freeway and the potential for congestion. The signing plan was developed assuming auxiliary lanes between ramps and single-lane exit ramps. Double-lane exit ramps that maintain lane balance will be more complex to sign as they will need to indicate that two lanes go to an exit. If the double-lane exit ramp option is further considered, a signing plan should be developed for it. However, the signing plan for the single-lane exit ramp option indicates that the basic concept of an interchange at 44 Street is feasible from a signing perspective.

Other Considerations:

The proposed interchange will be on the Interstate Highway System and therefore must be approved by FHWA, which considers eight points before granting or denying access. The state has already entered into discussions with FHWA regarding the 44th Street interchange, and FHWA has indicated they will approve the interchange if the eight points are satisfied.

FINDINGS

Based on the conceptual level of ramp spacing analysis conducted, plans for the 44th Street interchange do not have any fatal flaws. All four of the new ramps will be close enough to existing ramps that auxiliary lanes are recommended and weaving sections will be created. A complete HCM analysis for these segments should be conducted to see if they will be below capacity and to see if they will meet the state's operating guideline of LOS E. No major decrease in freeway mainline safety is expected if auxiliary lanes are provided between all ramp pairs. No increase in crashes on the freeway mainline is expected if auxiliary lanes are provided between all EN-EX ramp combinations. All spacing considerations should be reevaluated during the project's preliminary design phase.



CASE STUDY 3
SIGN LAYOUT FOR NEW 44TH STREET INTERCHANGE

FIGURE
3-8

Case Study 4

Case Study 4 illustrates the modernization of a 1950's vintage freeway. The study is being conducted because of basic capacity constraints on the highway mainline, and also to address traffic operational and safety conditions that result from relatively short ramps at the Stone Road/Plant Drive interchange. The basis of the previous three case studies has been the addition of access to a freeway. In this case study, existing accesses are evaluated in light of capacity and safety concerns. The range of possible solutions would include assessing whether the highway interchanges should be maintained and, if so, how they should be modified to address documented operations and safety conditions while serving forecast traffic.

BACKGROUND

General

A state transportation agency is rebuilding a highway (SR 53) that was constructed in the 1950s with a design speed of 50 mph. The agency has identified operational and safety deficiencies associated with the Stone Road/Plant Drive and SR 71 interchanges. The Stone Road/Plant Drive interchange has short, low-speed hook ramps, and the state agency is investigating replacement options including the following:

> The Stone Road/Plant Drive interchange will be reconfigured to a diamond form and the SR 71 interchange ramps will be reconfigured to a partial cloverleaf form. The focus of the ramp spacing assessment will be understanding the operational and safety relationships between these reconfigured interchanges.

- Removing highway access at this location;
- Reconstructing the hook ramps to provide a contemporary diamond interchange;
- Providing a diamond interchange with C-D roadway system to SR 71; and,
- Providing a diamond interchange with braided ramps to SR 71.

The state and the local business community would prefer to maintain access, and do so with a contemporary diamond form as it will be less expensive than braided ramps or C-D roads. Partial cloverleaf interchange forms are considered infeasible due to the number of properties that would need to be acquired. The C-D or braided-ramp concepts would be considered in detail only if sufficient ramp spacing cannot be achieved without them.

The SR 71 interchange has low-speed curves on its ramps, and it does not provide adequate acceleration and deceleration length along the freeway. Segment speeds are also negatively influenced by a lack of acceleration and deceleration at the ramps at SR 53 to the east. Based on prior studies, the SR 71/SR 53 interchange will likely be reconstructed to a partial cloverleaf form to remove weaving associated with the consecutive loops serving eastbound SR 53 and northbound SR 71 traffic.

Adjacent Interchanges

The Stone Road/Plant Drive interchange and the SR 71 interchange are separated by 3,600 ft, measured from the centerline of SR 71 to the approximate center of the Stone Road ramp area (Stone Road does not cross SR 53 at the interchange). These two interchanges are several miles away from any other interchanges. The project area is shown in Figure 4-1.

Traffic Volumes and Characteristics

SR 53 has three lanes in each direction through the project area, and carries 3,700-4,500 vehicles per hour on the segment between the two interchanges during the peak hour. Ramp volumes at the SR 71 interchange are higher than those at the Stone Road/Plant Drive interchange. Heavy vehicles account for 5% of the volume on the freeway, and terrain in the area is level. While heavy-vehicle traffic is moderate during the peak periods, adjacent aggregate mining results in a consistent stream of trucks on a 24-hour basis. This effect of these heavy vehicles further degrades traffic operations because of the inadequate Stone Road/Plant Drive ramps. Traffic volumes and spacing dimensions are shown in Figure 4-2.

AGENCY REQUIREMENTS

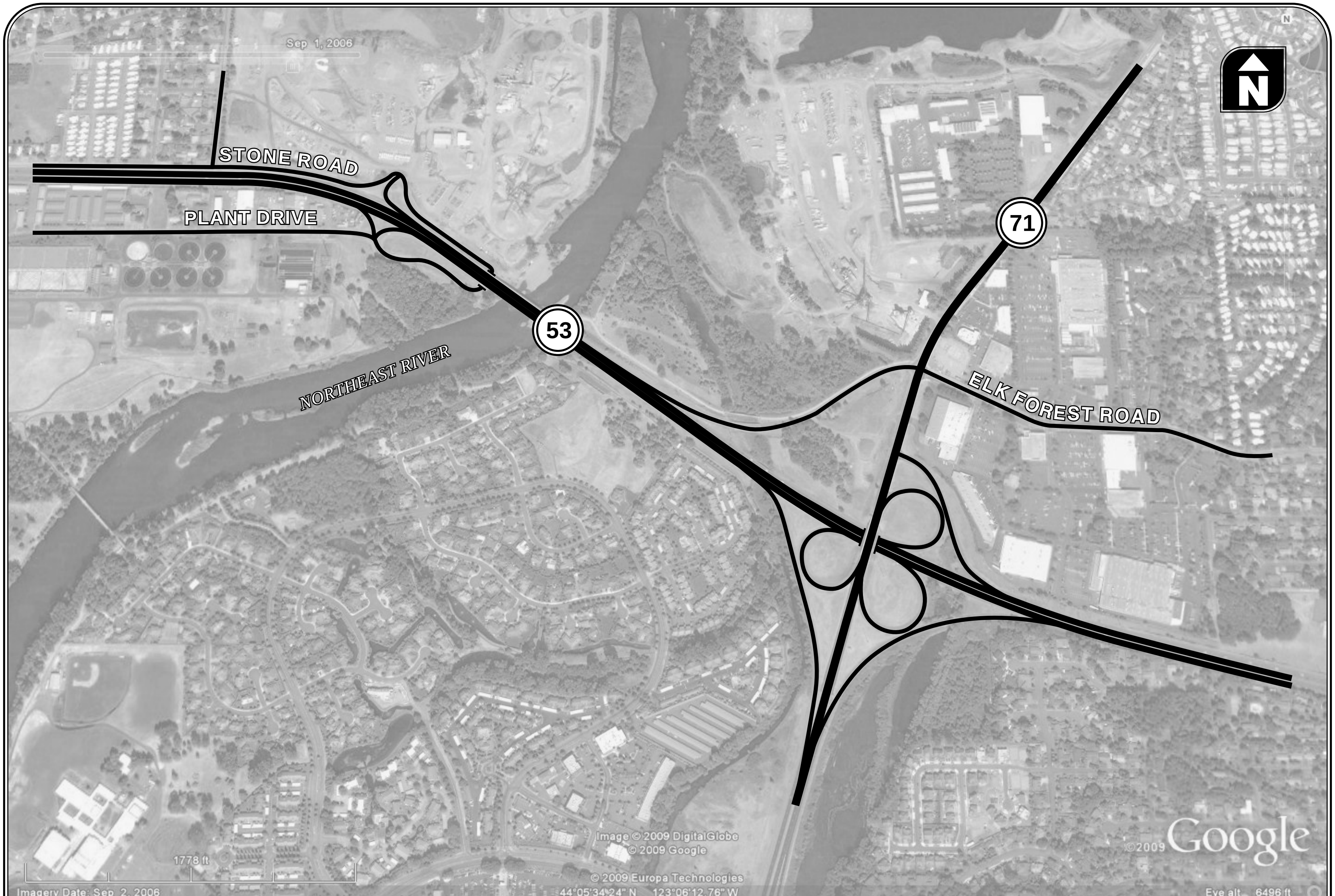
The state in which this project is located has an operating guideline of LOS D for urban freeways. Additionally, the state has a minimum interchange spacing guideline of one-mile urban areas. This spacing guideline was adopted many years after the SR 53 highway was constructed. The state has indicated they will accept spacing shorter than the one-mile guideline for this project if both of the following criteria are met:

- Existing access to adjacent land uses can be preserved (i.e., there is an existing interchange in place, even though it may be entirely rebuilt as part of this project).
- A traffic study demonstrates there will be no adverse impacts to SR 53 traffic operations.

RAMP SPACING CONSIDERATIONS

The following ramp spacing assessment follows the sequence outlined in Section 5.3:

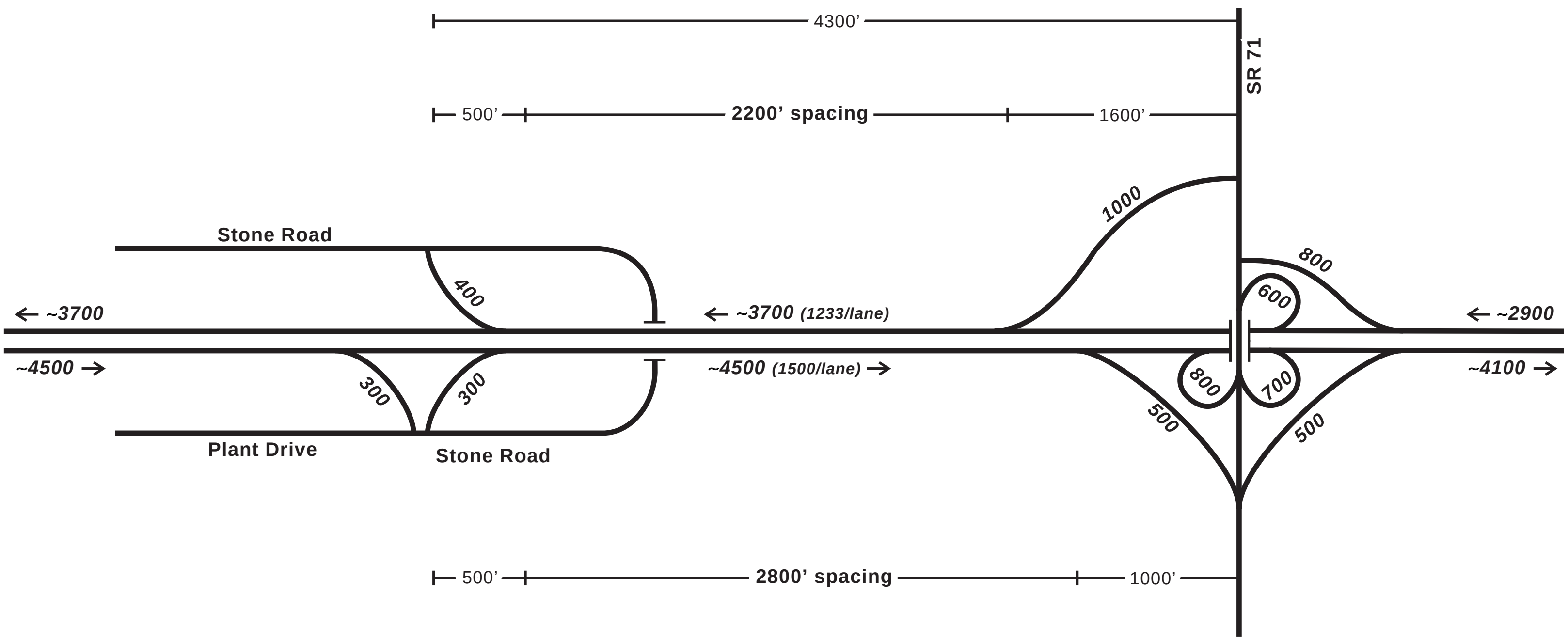
- Geometry considerations,
- Traffic operations,
- Safety, and
- Signing.



Source: Digital Globe

CASE STUDY 4
SITE MAP – EXISTING

FIGURE **4-1**



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 4
EXISTING RAMP SPACING AND DAILY TRAFFIC VOLUMES

FIGURE **4-2**

A number of options exist for the rebuilding of the Stone Road/Plant Drive interchange. For cost, impact, and community input reasons, the concept shown in Figure 4-3 is preferable and is the focus of the analysis presented here. However, other options should be considered until a more detailed analysis is able to determine if the concept in Figure 4-3 is feasible from the perspective of geometry, traffic operations, signing, and safety.

STEP 1—Geometric considerations:

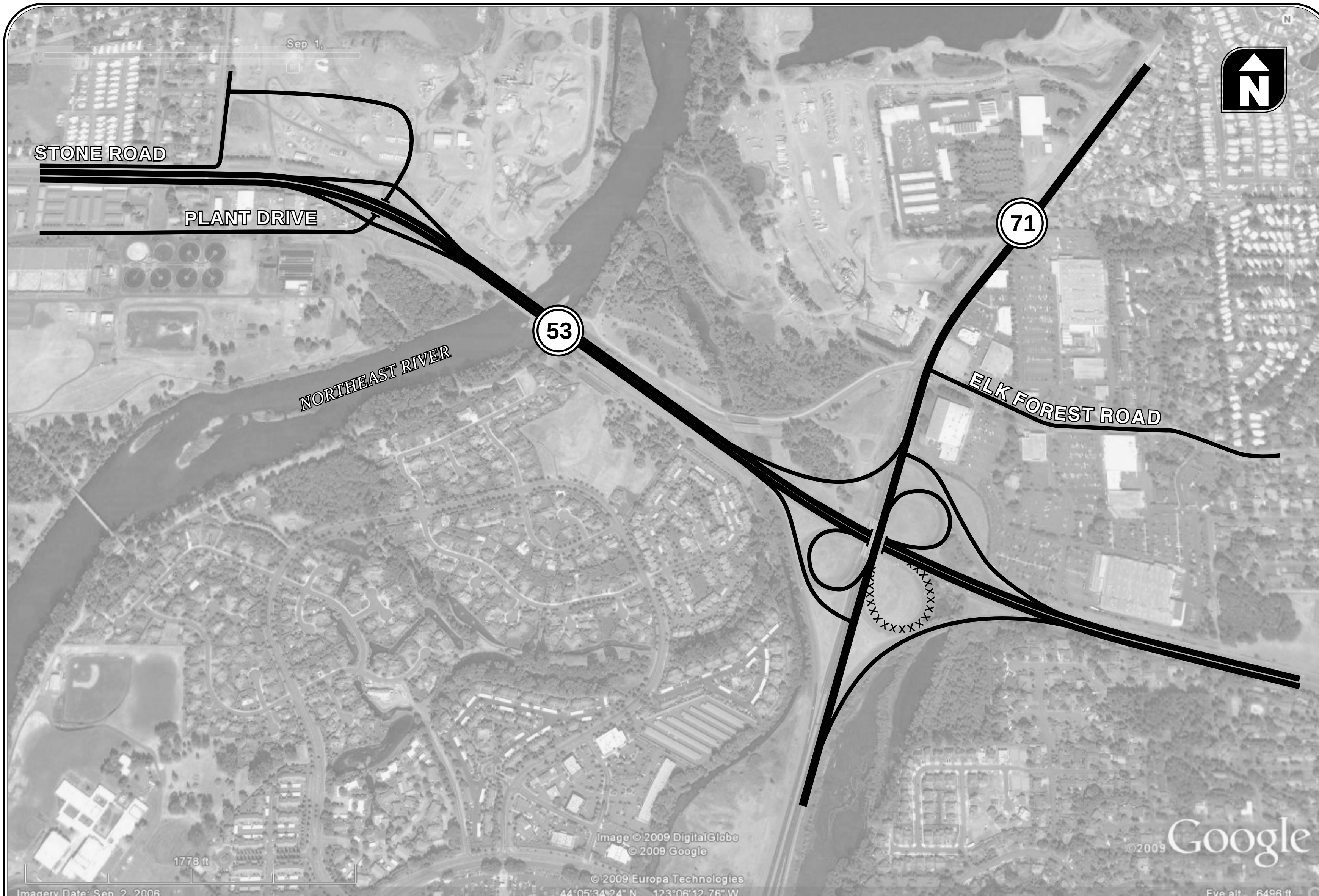
The first step is to conceptually determine the form of the rebuilt interchanges. For Stone Road/Plant Drive, a diamond form will be considered initially. This will minimize cost and right-of-way impacts and create a full interchange (currently there is no ramp from Stone Road to SR 53 westbound). As part of the interchange reconstruction, the Stone Road underpass will be removed, and Plant Drive will be realigned to pass under SR 53 between the entry and exit ramps. Improvements will be made to the SR 71 interchange as well. A conceptual plan for the proposed interchanges is shown in Figure 4-3.

As shown in Figure 4-4, options for the Stone Road/Plant Drive interchange to be reconstructed near its existing location will require collector-distributor roads or braided ramps. These will require at least two additional structures across the Northeast River. This will greatly increase the project's cost and environmental impact, potentially delaying improvements to the SR 53 corridor for many years. In addition, community outreach has resulted in stakeholder preferences to minimize construction in and around the river. Using a typical diamond form but placing the interchange further to the east will impact a number of properties and buildings, which the state also wishes to avoid if possible.

Stone Road Interchange

The eastern ramps of the Stone Road/Plant Drive interchange (SR 53 westbound offramp and SR 53 eastbound onramp) were initially constructed to avoid widening the SR 53 bridge over the Northeast River. At the time the highway was built in the early 1950s, the area was virtually undeveloped and traffic volumes where extremely low. A contemporary, reconstructed interchange at this location will result in ramps that extend to the bridge over the Northeast River.

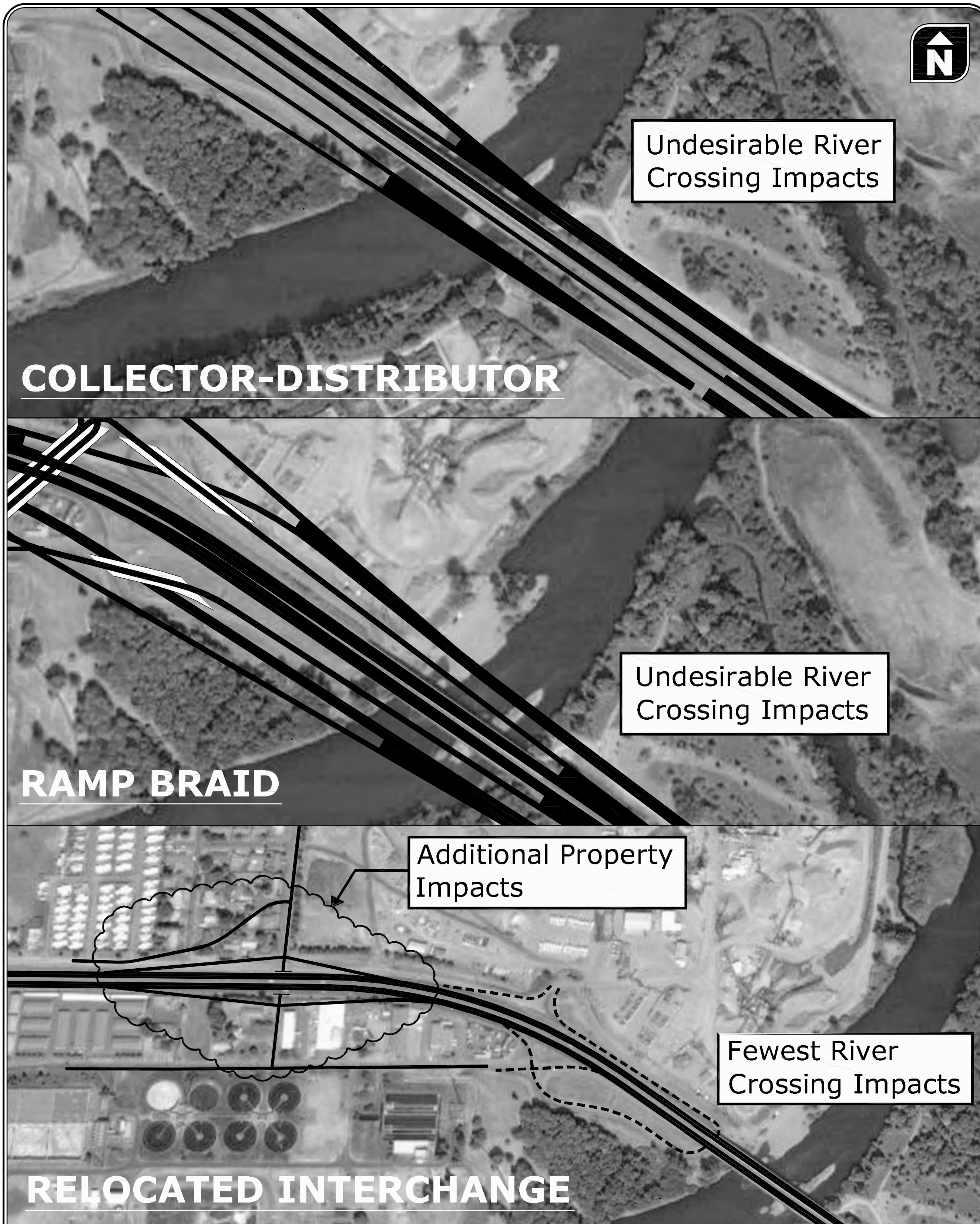
At a conceptual level and starting point in laying out diamond interchange ramps, physical entry and exit ramp gores are approximately 1,000 ft from the crossroad. This distance generally meets vertical alignment needs for making appropriate grade changes and incorporating desired ramp geometry. The distance from a painted diverging tip to the crossroad generally ranges from 1,300-1,500 ft, and the distance from the crossroad to the painted merging tip generally ranges from 1,400-1,800 ft. This is based on an entrance ramp having a distance between the physical gore and the painted merging tip typically in the range of 400-800 ft, based upon the horizontal curvature of the ramp and whether a taper or parallel entrance is used. On an exit ramp, the distance from the painted diverging tip to the physical gore typically varies from 300-500 ft for similar reasons.



Source: Digital Globe

CASE STUDY 4
SITE MAP – PROPOSED

FIGURE
4-3



Source: Digital Globe

CASE STUDY 4
ALTERNATE INTERCHANGE FORMS

FIGURE 4-4

Based on the ramp dimensions noted previously (1,300-1,500 ft and 1,400-1,800 ft), and the 3,500-foot distance between the exiting Stone Road/Plant Drive interchange location, the reconstructed Stone Road interchange will need to be shifted to the west to maximize ramp spacing dimensions to SR 71. In addition, ramp lengths will need to be minimized in such a way as to serve forecast volumes while maximizing the ramp spacing dimensions. Attaining a design that optimizes the ramp geometry and maximizes ramp spacing values appears potentially feasible given the relatively low ramp volumes and estimated queues at the ramp-terminal intersections.

Lengthening the Stone Road/Plant Drive ramps to provide adequate acceleration and deceleration lengths shortens the spacing to the SR 71 ramps. In the westbound direction, the approximate ramp spacing dimension will be at the recommended AASHTO minimum (per Exhibit 10-68) of 1,600 feet for an entry-exit combination on a full freeway. In the eastbound direction, the approximate ramp spacing dimension will be 300 feet greater than the recommended AASHTO minimum. A detailed traffic operations analysis should be conducted to determine if these spacings are feasible, and preliminary design will later determine if the approximate dimensions used in this initial analysis are appropriate.

Based upon the ramp lengths, it appears infeasible to locate the reconstructed Stone Road interchange in such a way as to avoid ramp entrance and exit ramp tapers prior to the Northeast River bridges. Therefore, these mainline bridges will need to be widened or reconstructed to accommodate the exit and entry gore areas. While not desirable based on community input, this configuration would provide a reduced footprint and area of impact in this sensitive area compared to the C-D and braided-ramp concepts.

<u>SR 71 interchange</u>

A partial cloverleaf "A" form will be provided at the SR 71 interchange, based on prior studies. The eastbound-to-northbound loop ramp will be eliminated and the remaining ramps reconfigured to serve all movements to and from SR 53 eastbound. This would eliminate the weaving sections on SR 53 eastbound and SR 71 northbound between the loop ramps. The existing diagonal ramps will be modified to remove low-speed curves to the extent feasible within the available right-of-way.

<u>Resultant Spacing</u>

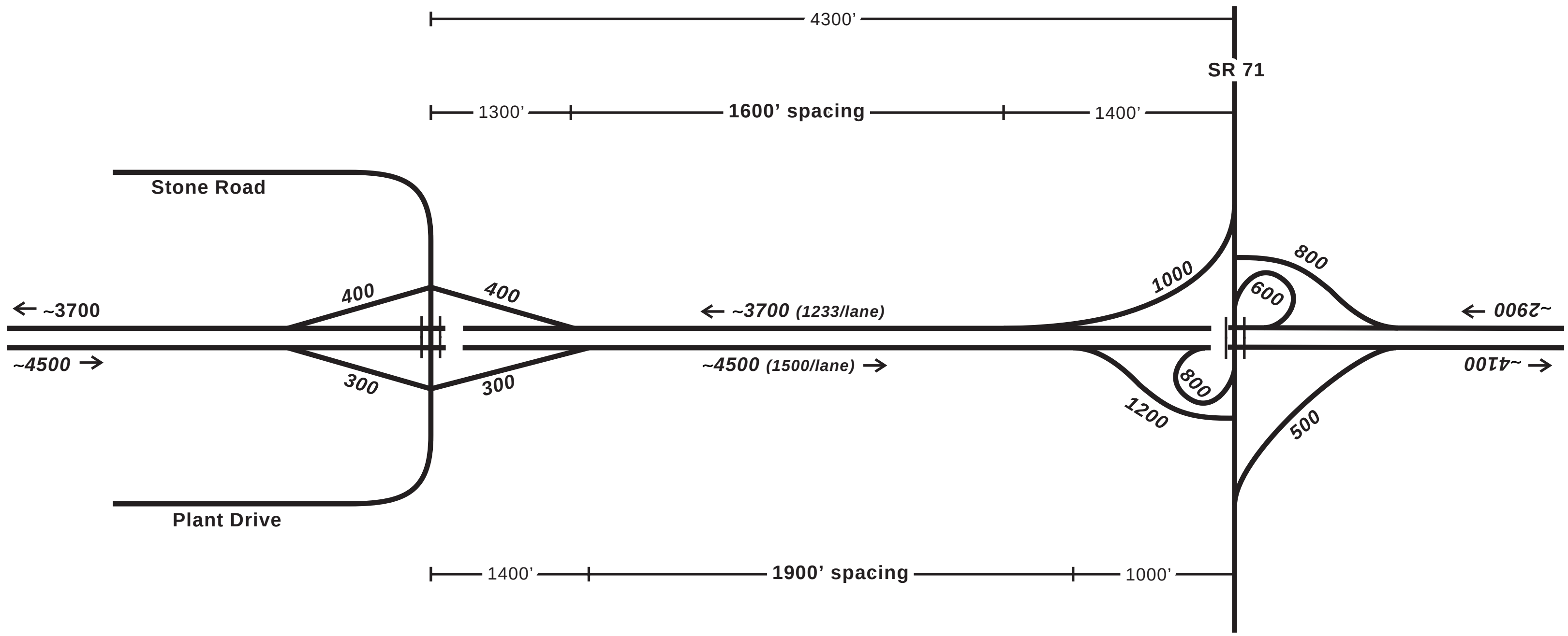
The changes to the Stone Road/Plant Drive and SR 71 interchanges noted above will result in the following ramp spacing dimensions:

- Approximately 1,900 ft between the Stone Road/Plant Drive onramp and the SR 71 offramp on SR 53 eastbound.
- Approximately 1,600 ft between the SR 71 southbound onramp and the Stone Road/Plant Drive offramp on SR 53 westbound.

These spacings, as well as traffic volumes, are shown in Figure 4-5.

STEP 2—Traffic Operations:

The ramp spacing on SR 53 between the two rebuilt interchanges will be between 1,500-2,000 ft. AASHTO policy recommends the consideration of an auxiliary lane when the spacing between an entry ramp and an exit ramp is



Note:
Spacing defined from approximate location of merging and diverging painted tip

CASE STUDY 4
PROPOSED RAMP SPACING AND TRAFFIC VOLUMES

FIGURE **4-5**

1,500 ft or less. Ramp spacing dimensions here are not greatly in excess of 1,500 ft and an auxiliary lane could be used. However, adding a full lane on both of the Northeast River bridges could greatly increase the cost of this project, so auxiliary lanes will only be used if they are needed to fulfill the state's LOS guideline. If the river bridges must be completely reconstructed because of their condition or inability to be modified to serve the entrance and exit ramp tapers, the auxiliary lane should be included. If auxiliary lanes are to be used, designers should consider providing lane balance at the reconstructed exit ramp terminals to reduce the effects of weaving.

To consider worst-case conditions, this initial operational analysis should be conducted under the assumption that no auxiliary lane is present. If an auxiliary lane is added to the design, operations will be improved. Since this is a three-lane freeway, the planning-level HCM merge and diverge analysis charts developed by the project team and discussed in Chapter 4 of the Guidelines may be used.

Eastbound—Analysis

Dashed lines on Figure 4-6 indicate the proposed ramp spacing of 1,900 ft (horizontal line) and the freeway volume of 4,500 vph (vertical line). In order for acceptable operation (LOS D or better) to occur, the blue lines must intersect above and to the left of the curve that corresponds with the ramp volumes that are present. On SR 53 eastbound, the entrance ramp volume is 300 vph. A set of entrance ramp volume curves for 500 vph exits on the chart, and these may be used to conduct a more conservative analysis (a user of the chart could also extrapolate a set of curves for 300 vph entrance ramps). The exit ramp volume on SR 53 eastbound is 1,200 vph, so the 1,200 vph exit ramp curve (dashed curve) within the 500 vph entrance ramp set of curves should be used as the LOS D threshold in this case.

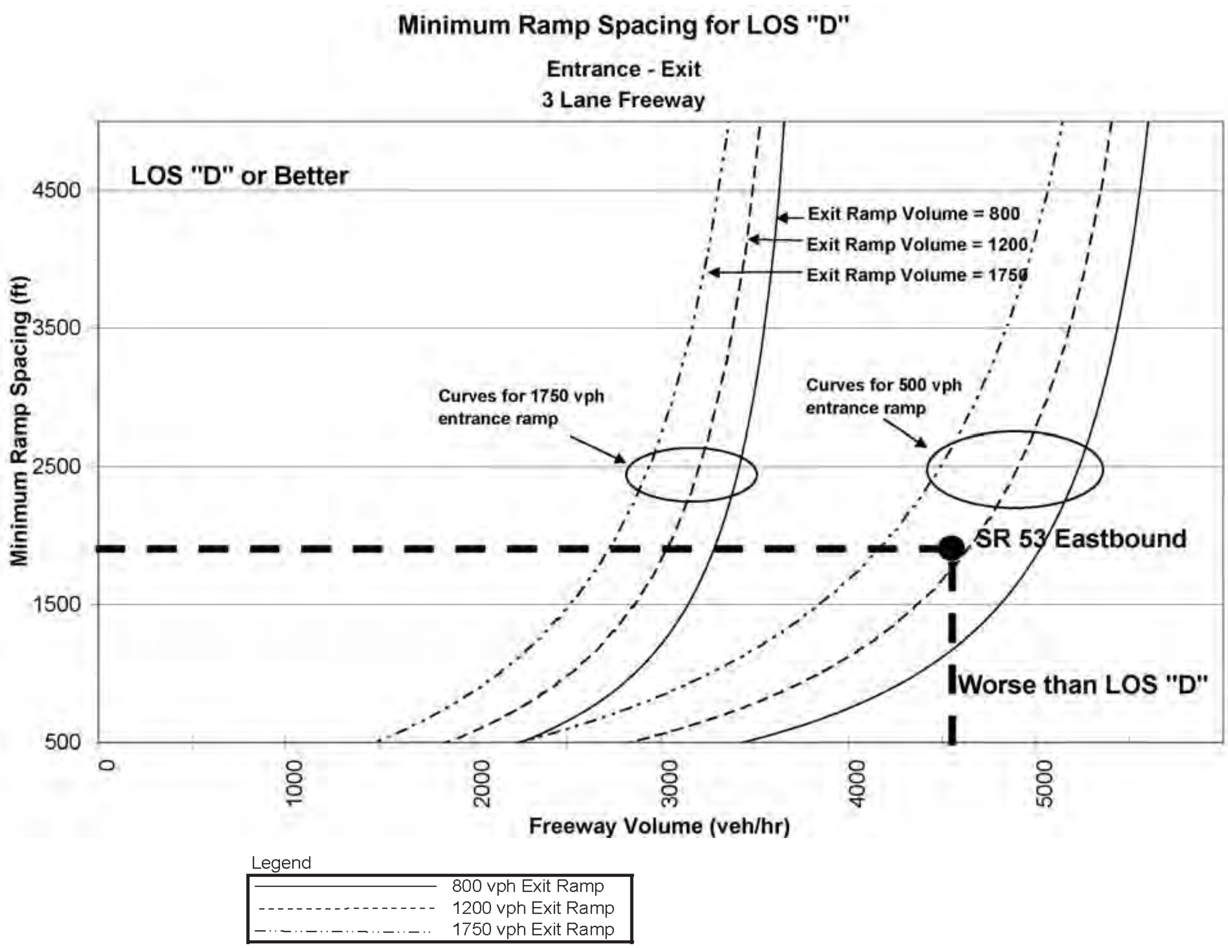


Figure 4-6 Operational Evaluation of SR 53 Eastbound Between Stone Road and SR 71

Eastbound—Findings

Under the expected conditions on SR 53 eastbound, Figure 4-6 indicates that LOS D will be achieved if the volume on the entrance ramp is 500 vph and the volume on the exit ramp is not much over 1,200 vph. These volume thresholds are slightly higher than the volumes projected for the Stone Road/Plant Drive entry ramp (300 vph) and the SR 71 exit ramp (1,200 vph). This indicates that the proposed ramp spacing may meet the state's LOS guideline. A complete HCM analysis should be conducted to determine this with certainty because this specific case is very near the chart's threshold and a number of assumptions have been built into the chart (vehicle mix, peak-hour factor, etc.)

Westbound

A similar analysis, conducted for the westbound direction, is shown in Figure 4-7. In this case, a set of entrance ramp curves was interpolated because the actual entry-ramp volume (1,000 vph) was not depicted on the chart. The actual exit-ramp volume (400 vph) is not shown as well, so the 800 vph was used instead and will result in a more conservative analysis. A portion of the interpolated curve for a 1,000-vph entry ramp and 800-vph exit ramp is shown on the chart. Figure 4-7 indicates that the proposed spacing should result in acceptable operation on SR 53 westbound.

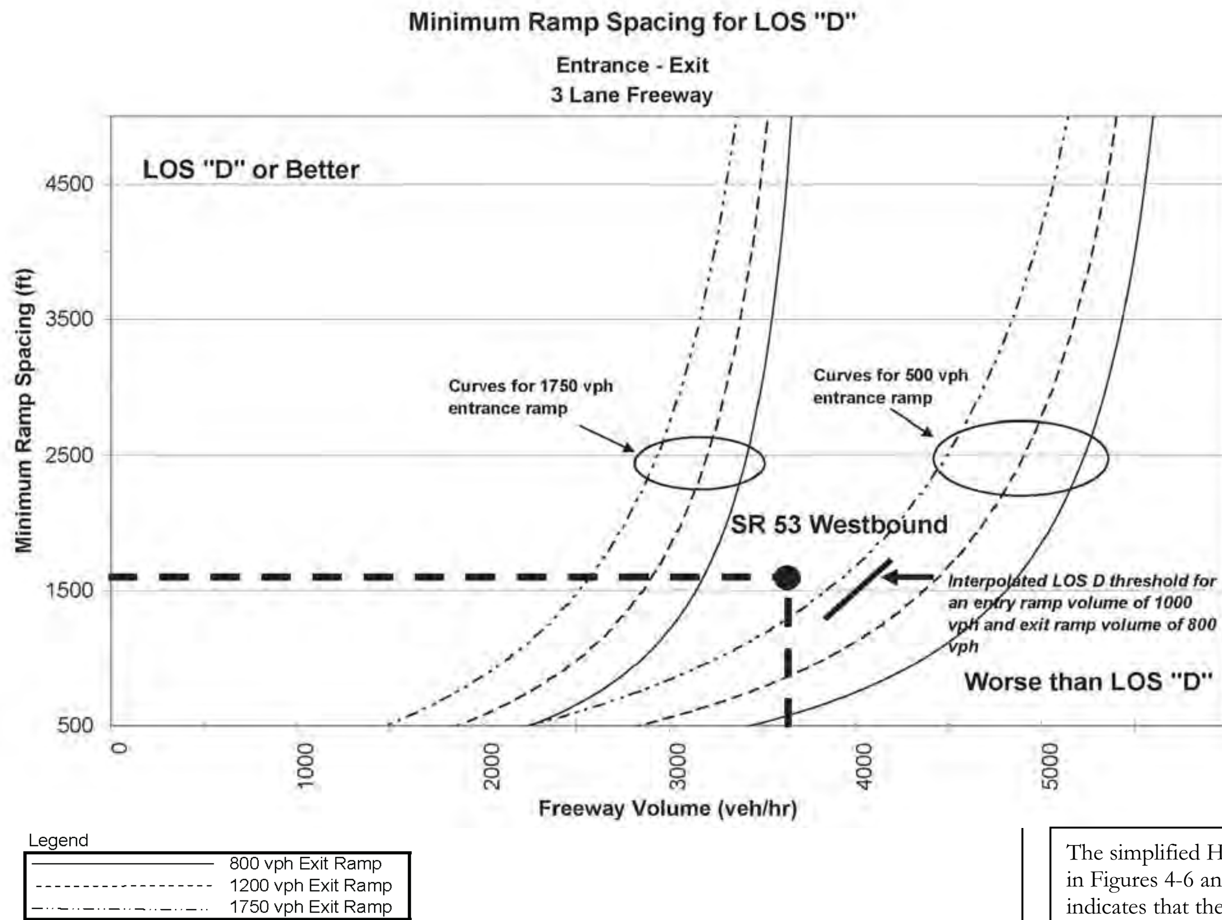


Figure 4-7 Operational Evaluation of SR 53 Westbound Between Stone Road and SR 71

The simplified HCM analysis in Figures 4-6 and 4-7 indicates that the interchange concept shown in Figure 4-3 may be feasible and should be further investigated. It may be possible to construct a diamond interchange on SR 53 at Stone Road/Plant Drive without using braided ramps or collector-distributor roadways or moving the interchange further to the east.

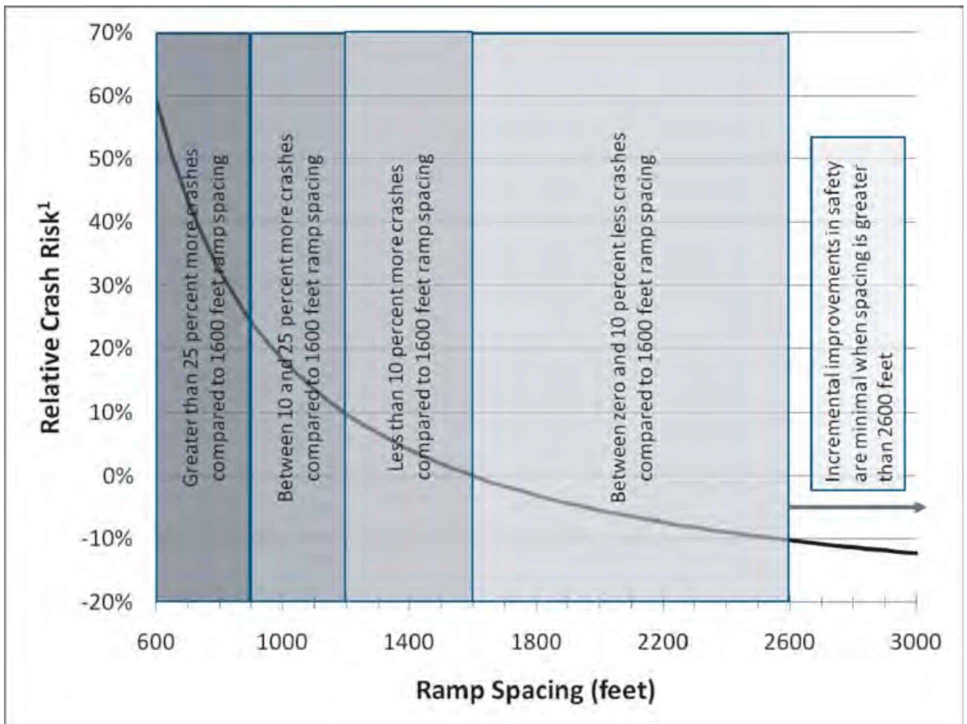
STEP 3—Safety:

The focus of the safety analysis for this case study is the entrance-exit ramp combinations between Plant Drive/Stone Road and SR 71 to determine if a conventional diamond interchange without C-D roads or braided ramps is feasible at Stone Road/Plant Drive. The safety assessment should consider tradeoffs between increasing speed change lane lengths while reducing ramp spacing.

The expected number of crashes on the freeway mainline between Stone Road/Plant Drive and SR 71 is expected to increase by around 7% as a result of a reduction in spacing. This estimate assumes no safety gain as a result of the reconstruction of the Stone Road/Plant Drive interchange and the SR 71 interchange, which is unrealistic.

Ramp spacing values currently are 2,200 (westbound) and 2,800 ft (eastbound). Guidelines Exhibit 5-5 (reproduced below as Figure 4-8) indicates relative crash risks for these spacing values of -7% and -11%, respectively. Reconstructing the Stone Road/Plant Drive interchange to a conventional diamond and the SR 71 interchange to a partial cloverleaf form will result in projected ramp spacing dimensions of 1,600 ft (westbound) and 1,900 ft (eastbound). Relative crash risks for these new spacing values are zero and -4%, respectively.

A significant safety improvement is expected by removing the mainline weaving section at the SR 71 interchange. Research to make a reliable estimate of this safety improvement does not exist, but eliminating the loop ramp greatly reduces the number of vehicle conflicts.



[1] Relative crash risk is measured by the percent difference in crashes, of all types and severities, at some ramp spacing value compared to a ramp spacing of 1,600 ft

Figure 4-8 Preliminary Safety Assessment Tool for Ramp Spacing, Entrance Ramp Followed by Exit Ramp (Guidelines Exhibit 5-5)

Overall, a net improvement in safety is likely by reconstructing the Stone Road/Plant Drive interchange to a conventional diamond and the SR 71 interchange to a partial cloverleaf. Quantitative estimates of the total net improvement cannot be made due to existing gaps in related safety research.

The AASHTO *Highway Safety Manual* includes quantitative safety information associated with lengths of speed change lanes. The manual suggests that for acceleration and deceleration lane lengths less than 690 ft (the condition that existed prior to the Stone Road/Plant Drive interchange improvement), an 11% reduction and a 7% reduction in crashes of all types and severities is expected for every 100 ft increase in the acceleration lane and deceleration lane, respectively. Additional, incremental safety improvements are not expected once the speed change lane reaches 690 ft or longer.

The expected 7% increase in mainline crashes resulting from the spacing reduction assumes the spacing acts in isolation. Models used to create Exhibit 5-4 and make this estimate used data from interchanges with more conventional acceleration and deceleration lanes than the current Stone Road/Plant Drive interchange.

Additional safety gains (approximately 20% reduction in expected crashes along the mainline) are possible by providing auxiliary lanes between the Stone Road/Plant Drive and SR 71 interchanges (see Guidelines Section 4.5.4.1.4). The benefit should be compared to costs of a wider bridge across Northeast River to accommodate the extra lane.

STEP 4—Signing:

On SR 53 westbound, there is presently one location upstream of the SR 71 interchange with two sign panels – a ½ mile advance guide sign for SR 71 and a 1 ½ mile advance guide sign for Plant Drive and Stone Road. This provides adequate advance notice of the Plant Drive/Stone Road exit. In the westbound direction, there is no other location with more than one sign panel.

On SR 53 eastbound, signing will be simplified by removing the loop ramp to SR 71 northbound. Currently there are two sign panels at the gore for the SR 71 southbound ramp and a ½ mile upstream of the gore. When the loop ramp is removed and replaced with a single-exit design, only one sign panel will be needed at each of the locations that currently have two. This sign panel will also have one less message unit than each of the existing panels because it will not be necessary to indicate which direction of SR 71 the ramp will serve (it will serve both directions). A ½ mile before the Plant Drive/Stone Road exit ramp, there is one additional location with two sign panels (one advance guide sign for Plant Drive/Stone Road and one advance guide sign for SR 71). This is not problematic and can remain after improvements are implemented.

No additional ramps are being added. Each direction of the highway will have only two exits, so there will not be a need for more than two sign panels at any location.

No additional exit ramps are being added on SR 53 as part of this project. In the westbound direction, the number of ramps will remain the same. In the eastbound direction, one of the two exit ramps at SR 71 will be eliminated. All exits currently have at least two advance guide signs which are placed in a manner that adheres to the current MUTCD. At no location are there more than two sign panels. No signing issues are anticipated.

FINDINGS

At the first stage of conceptual development, the proposed rebuilding of the Stone Road/Plant Drive and SR 71 interchanges shown in Figure 4-3 appears feasible from a ramp and interchange spacing perspective. Based on forecast ramp and freeway volumes and anticipated ramp spacing dimensions, it appears that the state's LOS D guideline will be satisfied. No ramps are added, and signing needs can easily be accommodated in a manner that is consistent with the MUTCD. The safety analysis suggests an overall

The simplified analysis conducted thus far indicates that it may be possible to achieve adequate ramp spacing between the SR 71 interchange and the Plant Drive/Stone Road interchange without using collector-distributor roadways or braided ramps.

net improvement in safety following the reconstruction of the Stone Road/Plant Drive interchange to a conventional diamond and the SR 71 interchange to a partial cloverleaf. These conclusions are highly dependent upon the assumed ramp lengths and should be reevaluated as the design is further developed. If ramps need to be lengthened, auxiliary lanes or alternate interchange forms may be needed.

Case Study 5

Case Study 5 illustrates ramp spacing considerations for adding new freeway connections in a complex environment where many ramps already exist. This case study evaluates a ramp braid and other relatively complex ramp solutions and highlights the role that signing plays in ramp spacing considerations.

BACKGROUND

General

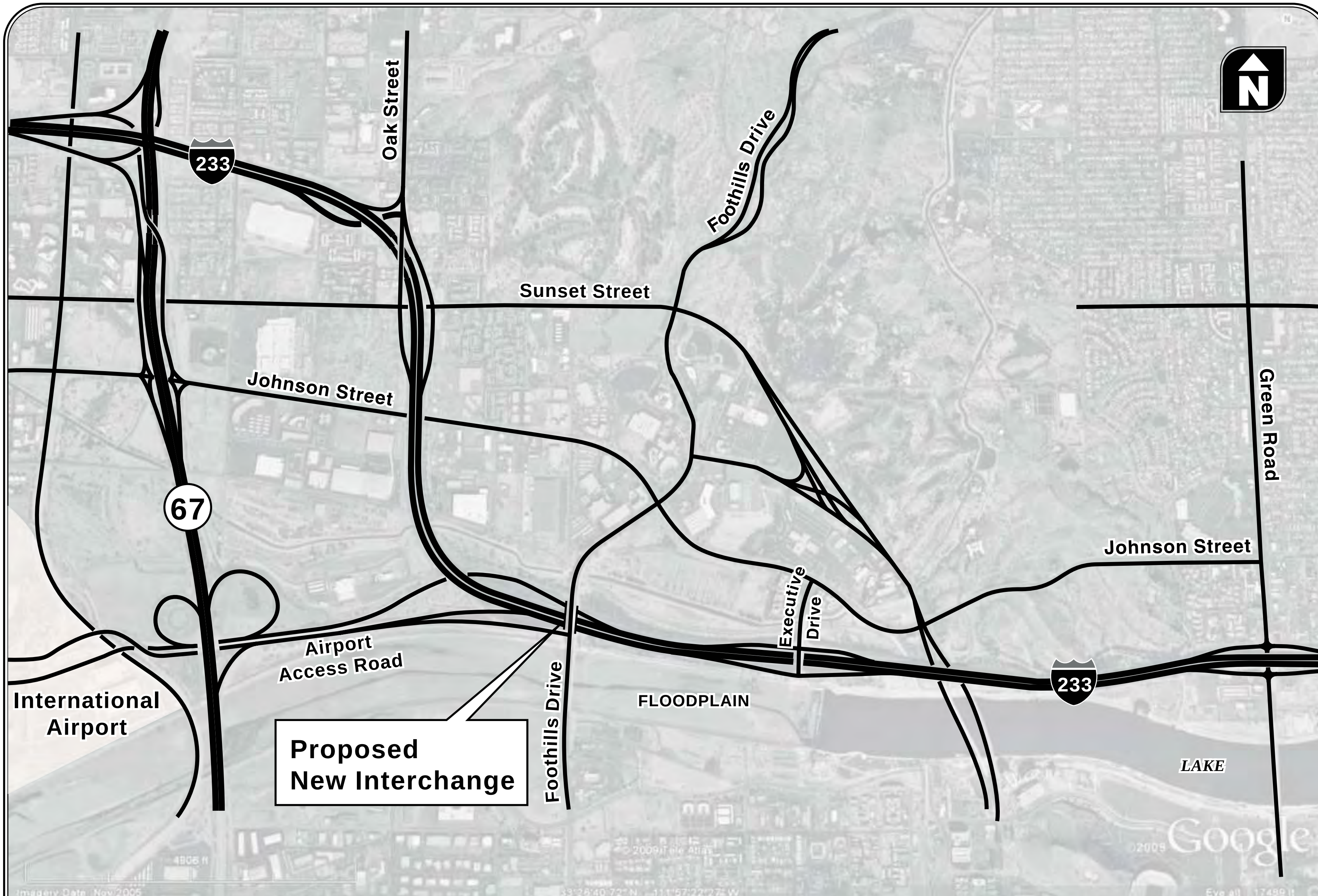
A circumferential interstate (I-233) passes through a heavily developed urban area with several complex interchanges. This portion of the I-233 loop is signed as an east-west route. The state transportation agency is proposing new connections to I-233 to improve access to Foothills Drive and enhance area circulation. The design of these new connections is complicated by existing interchange ramps that are in close proximity to Foothills Drive. These existing ramps serve an existing service interchange to Executive Drive and a connection to the international airport access road. The ramp configuration in the eastbound direction of I-233 was recently established and is not included in this current evaluation. Similarly, the on-ramp from Foothills Drive to I-233 eastbound will be a diagonal ramp that, although it will be close to the Sunset Street offramp, will not create any operational issues. Therefore, the focus of this exercise is to establish the configuration of the westbound exit ramp to Foothills Drive while considering the existing westbound exit ramps at Executive Drive and the airport access road. The planning considerations of the westbound ramp configuration, with a focus on spacing considerations related to the Foothills Drive exit ramp, are presented in the following sections.

Adjacent Interchanges

The footprint of the partial, directional interchange between I-233 and the airport access road includes the Foothills Drive overpass at I-233. Other than this, the nearest interchange to the west is a single-point diamond at Sunset Street that is 6,200 ft away from Foothills Drive (centerline-to-centerline of each crossroad). To the east, the nearest interchange is a diamond at Executive Drive that is 3,500 ft away from Foothills Drive (centerline-to-centerline). These roads and interchanges are shown on the site map in Figure 5-1.

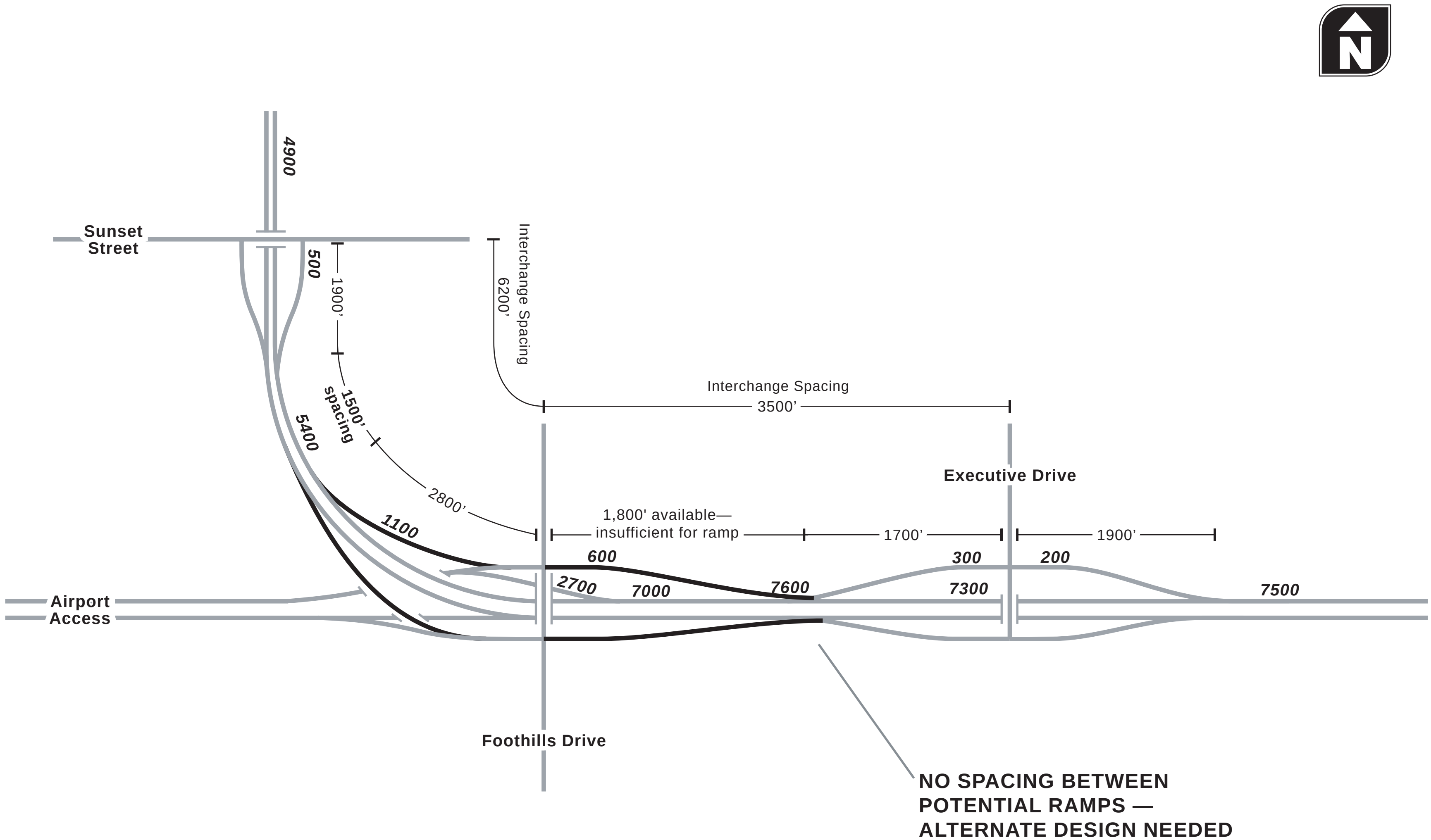
Traffic Volumes and Characteristics

Figure 5-2 depicts traffic volumes and existing interchange and ramp spacing along I-233. In addition, the figure schematically shows the approximate configuration of traditional diagonal ramps. The number of westbound basic lanes on the interstate decreases through this area. There are four basic lanes upstream of the diverge to the airport and three basic lanes downstream. As



CASE STUDY 5
SITE MAP

FIGURE
5-1



Notes:

1. Spacing defined from approximate location of merging and diverging painted tip
2. Movement to be served between I-233 and Foothills Drive shown in black

CASE STUDY 5
EXISTING RAMP SPACING, NEW MOVEMENTS TO BE SERVED, AND TRAFFIC VOLUMES

FIGURE **5-2**

Figure 5-2 shows, there is insufficient ramp spacing for conventional diagonal ramps between Foothills Drive and the existing interchange ramps at Executive Drive. Presently, there are only 1,800 ft of spacing between the merging tip of the Executive Drive onramp and the centerline of Foothills Drive. If the diverging tip of a ramp to Foothills Drive were to be placed at the same location as the merging tip of the ramp from Executive Parkway (which in itself is not a feasible design), the resulting exit ramp would still be shorter than the other exit ramps in the corridor.

Westbound volumes are highest during the p.m. peak period, with heavy vehicles accounting for approximately 10% of the volume on the interstate and less than 5% of the volume on the arterials. Terrain in the area is rolling. Due to the proximity to the airport and a high percentage of tourists, a significant number of drivers on I-233 will be unfamiliar with the area. Since there is no room for typical diagonal exit ramps at Foothills Drive, alternate ramp and interchange forms will be required. These are discussed in the Ramp Spacing Considerations section.

AGENCY REQUIREMENTS

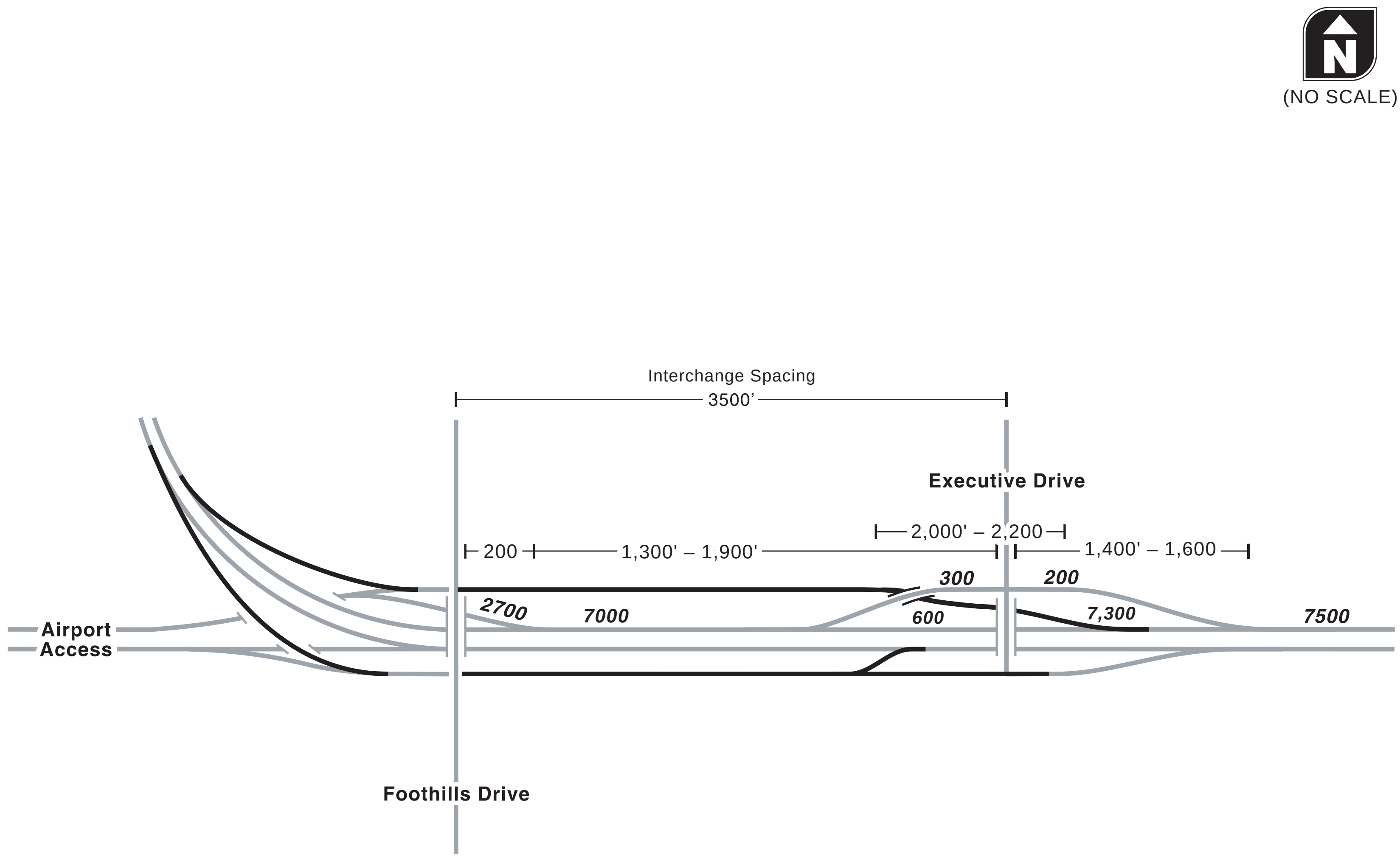
The state in which this project is located has an operating guideline of LOS D for urban interstates. The new interchange should not result in any components of the freeway operating below LOS D.

ALTERNATIVES UNDER CONSIDERATION

This section provides an overview of other alternatives that might be investigated beyond traditional diamond ramps.

Due to the complexity of existing ramps in this area, the most desirable form of ramps for a connection to Foothills Drive is not immediately clear. Three alternatives have been proposed and are depicted schematically in Figures 5-3 A, B, and C:

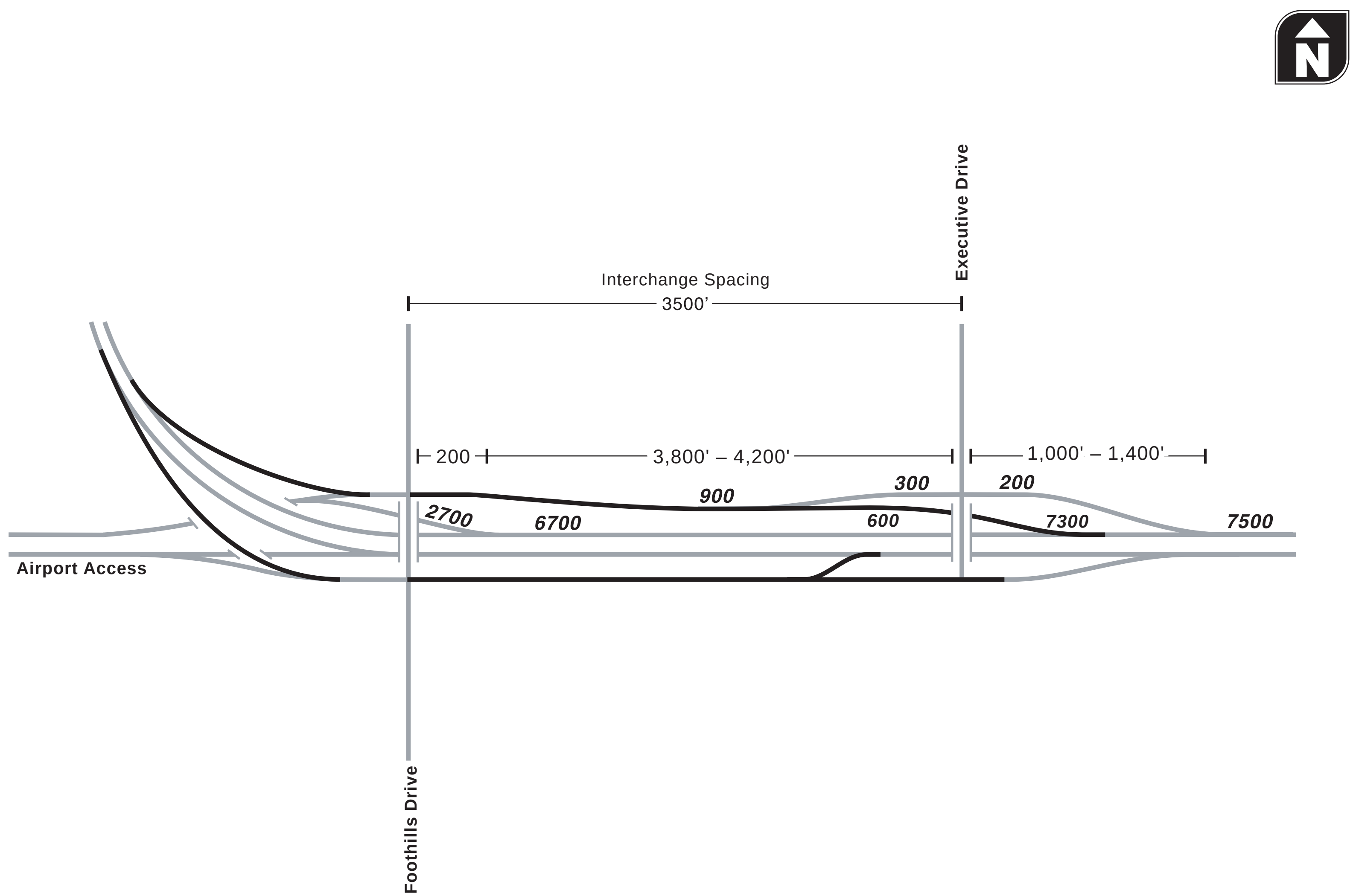
- Braided ramps—The Executive Drive entry ramp and Foothills Drive exit ramp would be braided (grade separated).
- Double exit with frontage road—There would be two separate exits from I-233 to Executive Drive and Foothills Drive. The existing westbound onramp from Executive Drive would be removed, and this traffic would connect to the frontage road and pass through the ramp-terminal intersection at Foothills Drive
- Single exit with frontage road—There would be a single exit from I-233 for Executive Drive and Foothills Drive, and the connection to Executive Drive would depart the single ramp as a "turning roadway." The existing westbound entrance ramp from Executive Drive to I-233 would be removed, and this traffic would connect to the frontage road and pass through the ramp-terminal intersection at Foothills Drive.



Notes:
1. Spacing defined from approximate location of merging and diverging painted tip
2. New ramps shown in black

CASE STUDY 5 — PROPOSED RAMP SPACINGS AND TRAFFIC VOLUMES (BRAIDED RAMPS ALTERNATIVE)

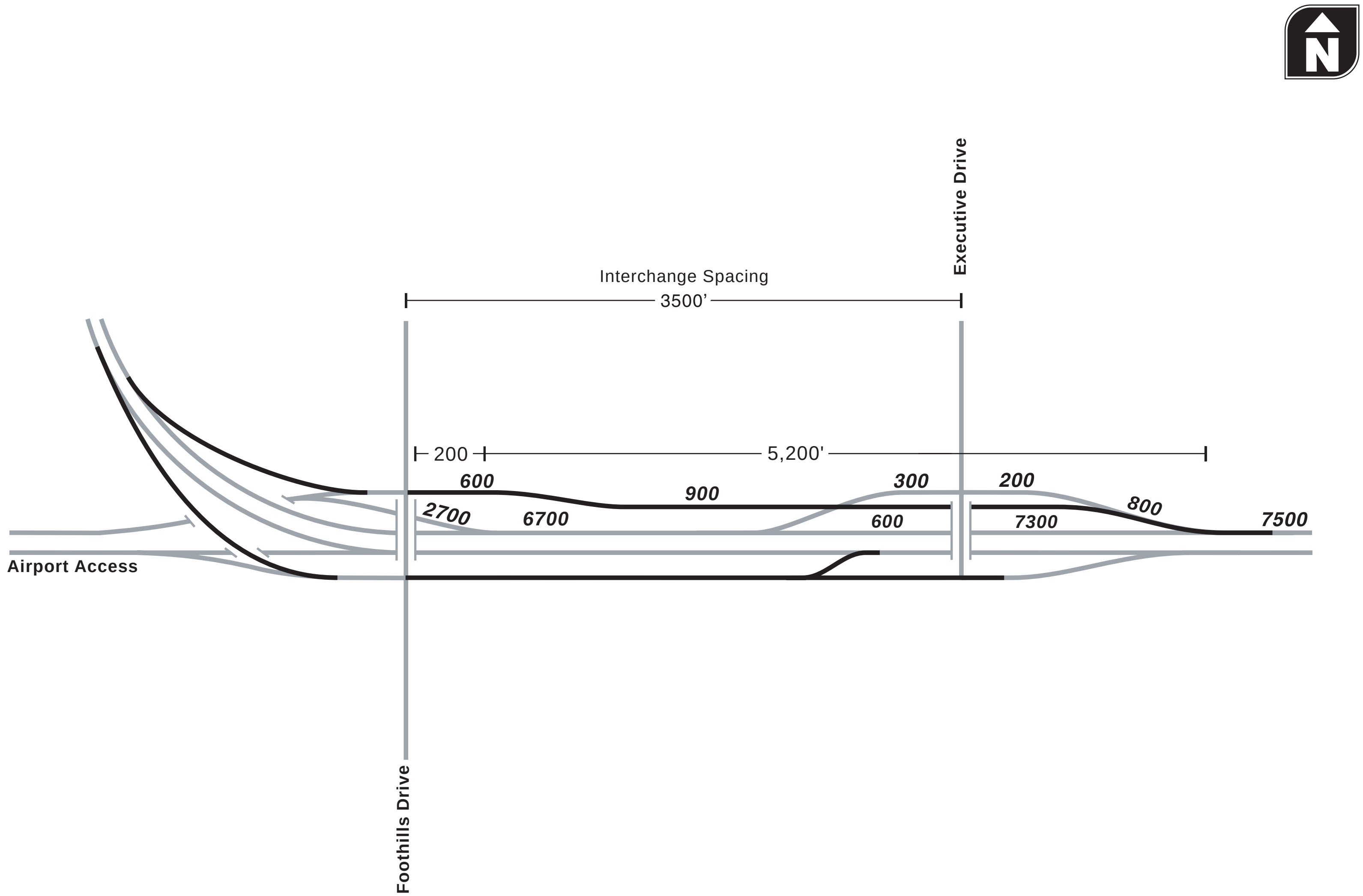
FIGURE **5-3A**



Notes:
1. Spacing defined from approximate location of merging and diverging painted tip
2. Movement to be served between I-233 and Foothills Drive shown in black

CASE STUDY 5
PROPOSED RAMP SPACING, AND TRAFFIC VOLUMES
(DOUBLE EXIT ALTERNATIVE)

FIGURE
5-3B



Notes:

1. Spacing defined from approximate location of merging and diverging painted tip
2. Movement to be served between I-233 and Foothills Drive shown in black

CASE STUDY 5
PROPOSED RAMP SPACING, AND TRAFFIC VOLUMES
(SINGLE EXIT ALTERNATIVE)

FIGURE
5-3C

RAMP SPACING CONSIDERATIONS

A planning-level analysis will now be conducted for each of the alternatives to determine if they are viable from a ramp spacing perspective. The following topics that influence ramp spacing will be considered:

- Geometric considerations,
- Traffic operations,
- Safety,
- Signing, and
- Other considerations.

STEP 1—Geometric considerations:

Braided Ramps (See Figure 5-3A)

When considering this alternative, the first step is to locate the new ramp braid while attempting to maintain or minimally impact existing ramp spacing between the ramps at Executive Drive and the airport access road. The second step is to consider the three-dimensional roadway design needs to attain the grade separation between the new Foothills Drive ramp and the reconstructed Executive Drive ramp.

The design of braided ramps for these interchanges should attempt to keep the painted tip of the reconstructed Executive Drive onramp at its current location to avoid reducing the ramp spacing dimension to the exit to the airport access road. This requires locating the diverging tip of the new Foothills Drive offramp as far upstream as necessary to achieve vertical clearances between ramps. The ramps would be braided with the Executive Drive onramp passing over the new Foothills Drive offramp since the Executive Drive onramp is already elevated.

The distance required to achieve adequate grade separation between the two ramps will influence the location of the diverging tip of the new Foothills Drive offramp. The first step is to determine the approximate location of the ramp crossing location. Given that Executive Drive passes over I-233, the existing ramp-terminal intersection is already approximately one level above the interstate. The crossing angle of the two roadways should not be too flat in order to avoid complex bridge designs (extra long bridges or straddle bent supports). It also should be located as near the ramp terminal intersection as possible so that the reconstructed Executive Drive onramp can reach grade on I-233 without appreciably shortening the ramp spacing dimension to the airport access Road exit. Therefore, the crossing location might be targeted 200-300 ft downstream of the ramp-terminal intersection.

The new Foothills Drive exit ramp should be located so that it is not hidden by the Executive Drive overcrossing. Ideally, the physical gore would be located 100-200 ft in advance of the overcrossing for maximum visibility by drivers on westbound I-233. This is sometimes unattainable depending on the lateral clearance of the existing overcrossing bridge abutment, and adjustments must sometimes be made to avoid reconstructing existing overpasses. This places the painted tip of the exit ramp approximately 300-500 ft in advance of the Executive Drive overcrossing and approximately 2,000-2,200 ft from the reconstructed Executive Drive westbound onramp.

This provides approximately 1,400-1,600 ft to the upstream exit to Executive Drive.

As designers advance the ramp-braid concept, the focus will be on optimizing the spacing between the proposed exit ramp and the up- and downstream ramps to and from Executive Drive. Designers must balance the tradeoffs in ideally locating the new exit ramp, attaining adequate vertical and horizontal alignments for the new and reconstructed ramps, and maximizing ramp spacing values between the series of entrance and exit ramps along this segment of I-233.

<u>Double Exit with Frontage Road (Figure 5-3B)</u>

This alternative would eliminate the Executive Drive onramp connection to westbound I-233 and combine it with a new exit ramp for Foothills Drive. Many issues will influence where the diverging tip for the Foothills Drive offramp should be placed. These include the following:

> The number of ramps associated with this alternative will be difficult to accommodate and will result in minimal spacing.

- The exit to the airport is a major fork with a two-lane exit ramp and a reduction in the number of basic lanes on the freeway. It would be desirable to place the new exit ramp as far upstream (and away from the airport exit) as possible. However, at this project location, this upstream distance must be balanced by considering the location of the existing Executive Drive overcrossing.
- The new exit should be placed as far as reasonably possible from the existing westbound I-233 exit to Executive Drive. This places the proposed exit in the vicinity of the Executive Drive overcrossing. Exits immediately beyond or directly under an overpass are undesirable because they frequently can not be seen. Placing the diverging tip for the proposed Foothills Drive exit prior to the Executive Drive overpass would eliminate this issue, although it would bring the Foothills Drive exit ramp and the Executive Drive exit ramp closer together.
- The westbound traffic from Executive Drive would now use the frontage road and pass through the ramp-terminal intersection at Foothills Drive. The Foothills Drive exit should be placed far enough upstream to accommodate this merge on the frontage road, and provide a section of the frontage road downstream of the merge long enough to accommodate lane changing and queuing associated with the ramp-terminal intersection.
- The merge location on the frontage road will be influenced by the need to bring the new ramp and the Executive Drive connection to the same grade. The current Executive Drive ramp-terminal intersection is approximately one level above I-233. The proposed ramp will be raised to meet a falling reconstructed connection

between Executive Drive and the new frontage road. The frontage road would then connect to Foothills Drive.

Considering these issues, the most feasible location for the ramp-freeway junction of the new Foothills Drive exit ramp appears to be between the existing Executive Drive exit ramp and the Executive Drive overpass. The 2004 AASHTO Policy (Exhibit 10-68) recommends a 1,000-foot minimum spacing between successive exit ramps. Using this dimension as a starting point, the diverging tip of the proposed Foothills Drive exit ramp would be located approximately 900 ft upstream of the Executive Drive overpass, and the physical gore would be nearly underneath the overpass, an undesirable condition. This design could be improved by moving the proposed Foothills Drive exit ramp several hundred feet upstream and locating the gore and exit ramp taper further in advance of the Executive Drive overpass. This design would create a spacing of less than 1,000 ft between successive exit ramps from westbound I-233 to Executive Drive and the proposed Foothills Drive ramp.

The double-exit design eliminates the weaving section prior to the airport exit, but like the braided ramp alternative, it places the diverge for the Foothills Drive ramp near the Executive Drive overpass and close to the Executive Drive exit ramp. Executive Drive traffic must pass through the Foothills Drive ramp-terminal intersection. This complex environment reinforces the need to more closely evaluate traffic operations analyses and consider design adjustments as the evaluations move forward.

The existing Executive Drive exit gore could be shifted upstream to create a 1,000-foot spacing. Modifications to the Executive Drive exit gore will be difficult and expensive because I-233 is on an elevated section upstream of the gore. The more feasible design option may be to not modify the Executive Drive exit gore and create an entry-entry ramp spacing of less than 1,000 ft. The 1,000-foot dimension is recommended but not a standard, and in complex environments such as this location, it will not always be possible to achieve recommended spacing values.

Single Exit with Frontage Road (Figure 5-3C)

By having fewer ramps, the single-exit design increases the spacing of remaining ramps compared to the other scenarios. However, this configuration concentrates traffic to the single-exit and requires Executive Drive traffic to pass through the Foothills Drive ramp-terminal intersection.

This alternative would also replace the existing Executive Drive entry ramp, combining this movement to the new frontage road, and allowing traffic to pass through the ramp-terminal intersection at Foothills Drive. The current Executive Drive exit from I-233 would be modified to a single-exit configuration that serves Executive Drive and Foothills Drive, with the Executive Drive movement diverging from the single exit as a turning roadway. This configuration, like the previous configuration, eliminates the weaving section on I-233 prior to the airport exit.

STEP 2—Traffic Operations:

The three alternatives described above will result in the ramp spacings that are listed below in Tables 5-1 through 5-3 and shown in Figures 5-3A through 5-3C.

Table 5-1 Ramps in project area on I-233 Westbound—braided ramps alternative.

Ramp	Resultant Spacing
Offramp to Executive Drive	
	Exit-exit with 1,400 ft to 1,600 ft spacing
Offramp (braided) to Foothills Drive	
	Exit-entry with 2,000 ft to 2,200 ft spacing
Onramp (braided) from Executive Drive, with lane from ramp continuing as auxiliary lane	
	Entry-exit weaving section with 1,300 ft to 1,900 ft spacing
Offramp (double lane) to the airport. One auxiliary lane and one freeway lane dropped	

Table 5-2 Ramps in project area on I-233 Westbound – double exit with frontage road alternative.

Ramp	Resultant Spacing
Offramp to Executive Drive	
	Exit-exit with 1,000 ft to 1,400 ft spacing
Offramp to Foothills Drive	
	Exit-exit with 3,800 ft to 4,200 ft spacing
Offramp (double lane) to the airport. One auxiliary lane and one freeway lane dropped	

Table 5-3 Ramps in project area on I-233 Westbound – single exit with frontage road alternative.

Ramp	Resultant Spacing
Offramp to Executive Drive	
	Exit-exit with 5,200 ft spacing
Offramp (double lane) to the airport. One auxiliary lane and one freeway lane dropped	

The three alternatives, with ramp spacings detailed in Tables 5-1 to 5-3, will result in one or more closely spaced ramp combinations. In the next phase of ramp sequencing investigations, a complete operational analysis of each alternative still under consideration should be performed. The HCM procedures are best suited for analyzing individual ramp-highway junctions and weaving sections. Complex environments may benefit from applying other analysis tools. Simulation models may need to be employed to address the complex interrelationships of the ramp configurations. At this planning stage, the qualitative traffic operations analyses can be used to compare each alternative ramp combination.

> In addition to operation of the freeway, operation of individual ramp-terminal intersections should also be considered when comparing the alternatives. Complex configurations may sometimes preclude applying planning-level operations tools. Complex configurations, such as this, require a special emphasis on traffic operations at the earliest stage of the project's development.

Figure 5.4 provides schematic diagrams of the lane numbers and arrangements for each of the alternative concepts. Traffic operational considerations for each of the concepts are described in the following sections:

Braided Ramps

The braided-ramp alternative creates the greatest number of ramps on I-233. The first ramp combination encountered by drivers on I-233 will be the offramp to Executive Drive and the offramp to Foothills Drive. Although exit-exit ramp combinations generally have a minimal impact on traffic operations, the close spacing dimension may result in unacceptable traffic flow. The weaving section between the Executive Drive entrance and the airport exit is of greater concern. This section already exists and experiences poor operation. Traffic entering the freeway from Executive Drive must make two lane changes to remain on I-233 instead of exiting to the airport. This may be a fatal flaw for this configuration. This maneuver will be difficult when volume on the airport exit is high. The freeway will have five lanes upstream of the major fork to the airport access road, and downstream of the fork there will be five lanes as well (three on I-233 and two on the airport access road ramp). Such a design will violate the principles of lane balance as discussed in Chapter 3 of the Guidelines. This design is undesirable from a traffic operations perspective and because it retains the weaving section that currently experiences poor operation.

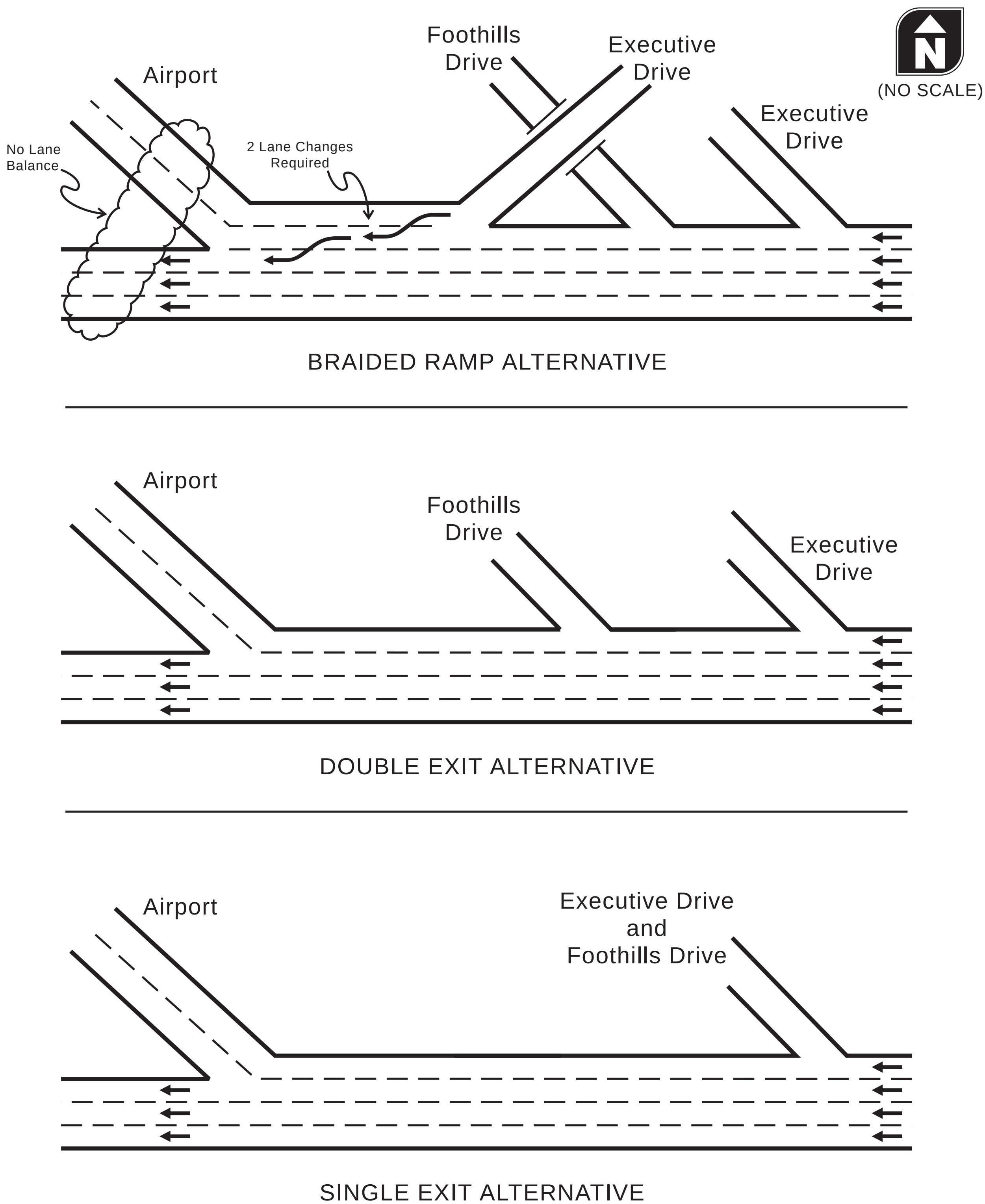
Double Exit with Frontage Road

By introducing a frontage road, this alternative eliminates the Executive Drive onramp and the resulting weaving section between it and the airport exit. From this perspective, this alternative is superior to the braided ramp alternative in terms of traffic operations. This alternative provides lane balance. Other ramp spacing values are similar to the braided-ramp alternative.

Both frontage road alternatives, while seemingly less disruptive to the freeway than the braided-ramp alternative, will increase volumes at the Foothills Drive ramp-terminal intersection. Traffic operations and queuing should be evaluated to assess queue length on the frontage road and to determine lane configuration needs.

Single Exit with Frontage Road

Compared to the other alternatives, this alternative eliminates the weaving section prior to the airport exit. In addition, it removes the design challenges of locating the new Foothills Drive exit ramp in the vicinity of the Executive Drive overpass and near the Executive Drive exit. The new combined Executive Drive and Foothills Drive exit would have a higher volume than the existing Executive Drive exit. However, the proposed combined exit is well-spaced from up- and downstream ramps, and this may mitigate the increased volume on this revised ramp.



CASE STUDY 5 — PROPOSED RAMP SEQUENCE ON I-233 WESTBOUND

FIGURE 5-4

Basic Capacity Considerations—All Scenarios

Basic Capacity Thresholds from the HCM are presented in Table 4-1 of the Guidelines.

None of the scenarios appear to have volumes that are high enough to result in failing operation regardless of ramp spacing. The highest freeway volume on I-233 in all scenarios will be 7,500 vehicles per hour, or 1,875 vehicles per hour per lane (veh/hr/ln) upstream of Green Road. The capacity of a basic freeway segment under ideal conditions is 2,250 to 2,400 veh/hr/ln. I-233 does not have ideal conditions—total ramp density is greater than one ramp per mile, the free-flow speed is unknown, the driver population is less than 1.00, and the heavy vehicles account for 10% of the traffic volume. The basic segment of I-233 upstream of Green Road may be under capacity, although a complete HCM analysis is needed to determine this with certainty due to the non-ideal conditions that exist.

The highest volume ramp in any scenario is the frontage road ramp in the latter two alternatives, with 900 vehicles per hour. This value is less than half the capacity of a ramp roadway. Of greater concern operationally than ramp roadways are ramp-freeway junctions. The maximum desirable flow rate entering a merge influence area is 4,600 passenger cars per hour, and the maximum flow rate entering a diverge influence area is 4,400 passenger cars per hour. However, determining the number of vehicles in an influence area (the right two lanes of the freeway and the ramp itself) requires a complete HCM analysis.

Summary

The ramp-braid concept could possibly be dropped at this point in the evaluation. However, for the purpose of this case study, it will be carried forward.

The complexity of all three alternatives diminishes the value of applying planning-level operational analysis tools. However, it appears that the braided-ramp alternative will have the most operational impact on the freeway due to the weaving section requiring two lane changes, which is preceded by several other closely spaced ramps. The double-exit-with-frontage-road alternative eliminates the weaving section, and the single-exit-with-frontage-road alternative eliminates the weaving section and another closely spaced ramp combination.

STEP 3—Safety:

The EX-EN ramp combination spaced at 2,000-2,200 feet as part of the braided ramp alternative is not expected to cause a freeway mainline safety issue. Research used to draw this conclusion is limited. The geometric analysis discussed in Guidelines Section 5.3.1.4 should be a primary factor in the spacing assessment until additional safety information becomes available.

Table 5-1 summarizes the ramp combinations of interest for the three alternatives in this case study. Research conducted to develop these Guidelines did not show an increase in crashes associated with a decrease in ramp spacing for the EX-EN ramp combination. Limitations of these findings are identified in Guidelines Section 4.5.4.3.

The EX-EX combination was not studied from a safety perspective (in research conducted for the Guidelines), but results are expected to be consistent with the EX-EN results (i.e., no relationship between ramp spacing and safety).

Quantitative safety conclusions for the EX-EX ramp combinations spaced between 1,400-1,600 ft for the braided ramp alternative and 1,000-1,400 ft for the double exit/frontage road alternative cannot be drawn using existing safety research. Again, freeway mainline safety issues are not expected as a result of the tighter spaced EX-EX combinations if limited findings for the EX-EN can be generalized to the EX-EX. However, future research to explore the EX-EX combination is needed.

Guidelines Exhibit 5-5 indicates that the 1,300-1,900 ft EN-EX combination that is part of the braided ramp alterative may result in 8 to 19% more mainline crashes than a basic freeway segment of the same length. This result is found by subtracting the relative crash risk for a long spacing (which approaches -12% for spacing dimensions greater than 3,000 ft) from the relative crash risk for the 1,300-1,900 ft range (7 to -4%).

The EX-EX spacing values of 3,800-4,200 feet for the double exit/frontage road alternative and 5,200 feet for the single exit/frontage road alternative are not expected to reduce freeway mainline safety. For EN-EX and EN-EN ramp combinations, mainline safety approached that of a basic freeway segment when ramp spacing values were greater than 3,000 feet. The conclusion is generalized to the EX-EX alternative until additional research is available.

STEP 4—Signing:

Signing should be considered at the earliest stages of concept development to assess the types and amount of information that will need to be presented and to consider the advance placement of signs. This is especially true for complex highway and interchange configurations such as those presented here. The Executive Drive/Foothills Drive/airport interchange area is near the Green Road and Sunset Street/Oak Street interchanges. Signing needs for these interchanges should be incorporated into the signing assessment for each of the concept alternatives for the new Foothills Drive ramps.

Without quantitative safety findings, the geometric analysis (Section 5.3.1.3) and signing considerations (Section 5.3.4) are the primary factors for the EX-EX spacing assessment.

Existing signing on this portion of I-233 westbound is shown in Figure 5-5. All signs are overhead due to the number of lanes on the freeway, and future signs should be overhead as well. The advance guide sign sequence for most exits begins more than one mile before the exit due to the high number of drivers on I-233 who are unfamiliar with the area and the importance of some of the interchanges. It is desirable to maintain this advance signing.

At one location along I-233 between Green Road and Executive Drive, three advance guide signs currently exist. This is the maximum number recommended by the MUTCD, and collectively they contain the maximum number of message units recommended by the ITE Handbook. This is computed in Table 5-4. Adding new exit ramps could potentially necessitate a fourth guide sign at this location or other locations that could present drivers with more information than they are able to process.

The expected difference between freeway mainline crashes for the 1,300 to 1,900 foot EN-EX combination that is part of the braided ramp alternative and a basic freeway segment can be reduced or eliminated if an auxiliary lane is provided.

Table 5-4 Computation of message units at existing sign assembly on I-233 westbound between Green Road and Executive Drive

4 message units • Exit number • Road Name • Second Road Name • Distance	4 message units • Exit number • Destination • Connecting Route • Distance	3 message units • Exit number • Road Name • Distance
3 sign panels – maximum recommended 11 total message units – maximum recommendation		

Braided Ramps

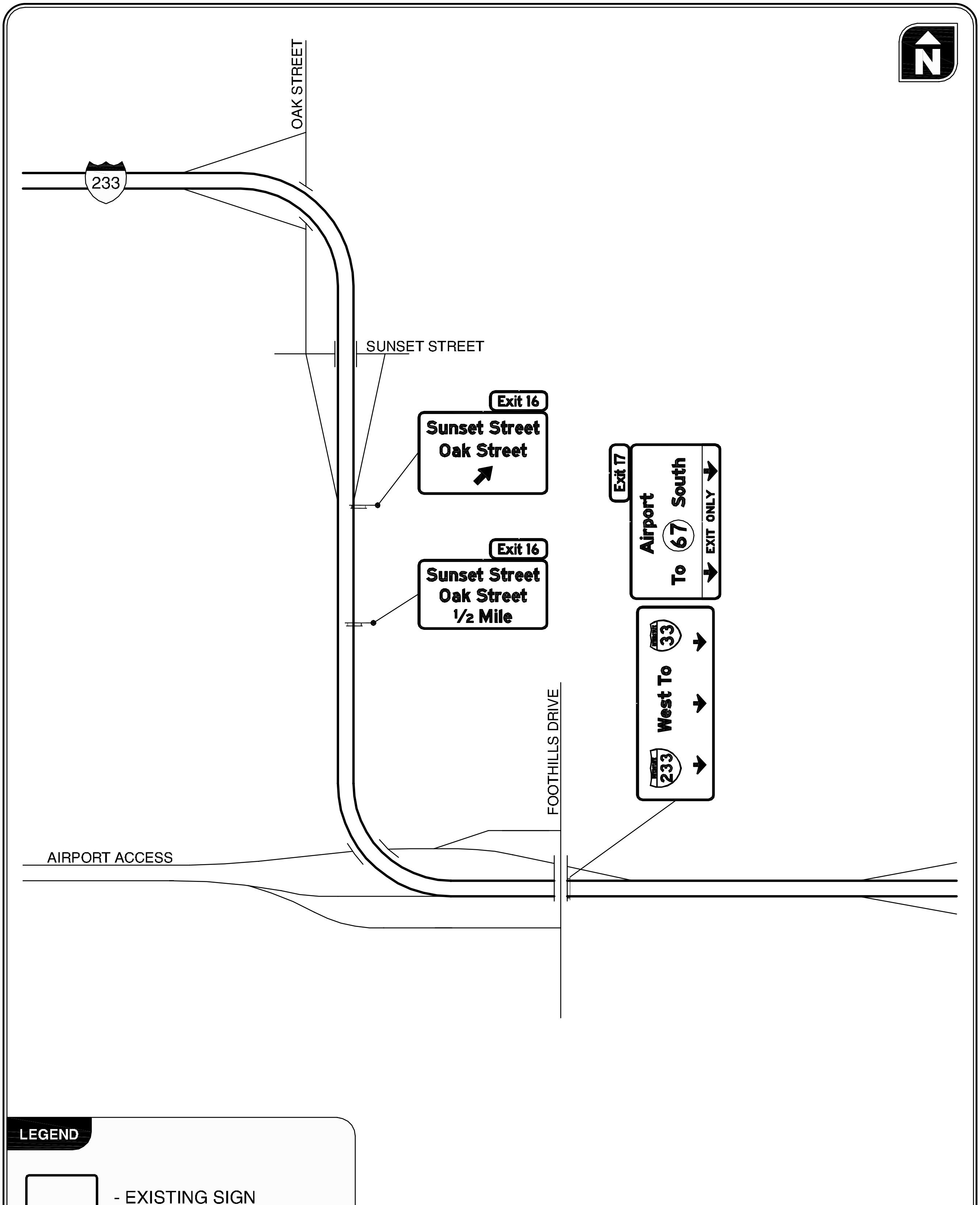
The braided-ramp scenario adds an exit ramp for Foothills Drive to I-233. The gore will be located near the Executive Drive overpass where a sign for the airport exit and a pull-through sign for I-233 are currently located. The MUTCD discourages placing signs other than an exit direction sign near the gore, so the existing signs should be moved downstream. Ideally, the signs will be located in the following places:

- At least 800 ft beyond the Foothills Drive exit direction sign (recommended by the MUTCD);
- At least 800 ft beyond the Executive Drive overpass so that the bridge structure does not obscure drivers' view of the sign (recommended by the MUTCD);
- At least a quarter of a mile upstream of the airport exit/pull though sign assembly that is at the gore of the airport exit; and,
- At a location that will minimize the attentive demands on the driver.

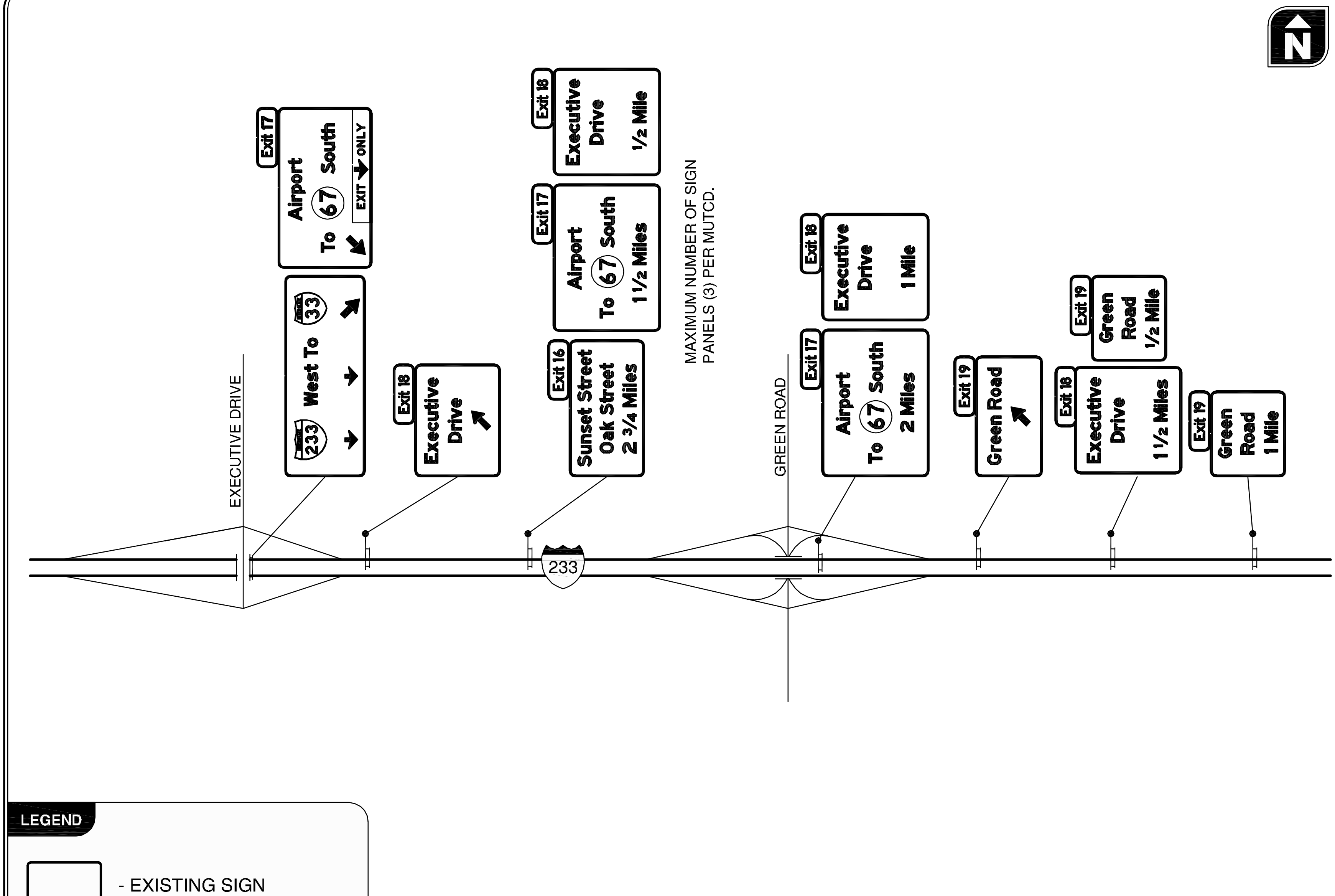
A sign placement concept developed with these considerations in mind is shown in Figure 5-6. Its development is discussed in detail below.

Moving existing signs and eliminating unnecessary information will help to accommodate new signs for the new interchange. Exiting numbers must also be changed to serve the proposed new exit.

Before beginning to place signs for Foothills Drive, existing signs that will be in the vicinity of the exit gore should be moved and modified if necessary. Based upon MUTCD recommendations, the airport exit and pull-though sign assembly can be moved from their current location to a position that is 800 ft or more downstream of the Foothills Drive exit direction sign, but still upstream of the weaving segment between the Executive Drive onramp and the airport exit. To reduce the number of message units in an area with many signs, "west to I-33" can be removed from the I-233 pull-though sign. This information can be conveyed to drivers elsewhere in the corridor. The number of the airport exit will need to be changed from 17 to 17B. The new Foothills Drive exit will be located between exits 17 and 18. Since it will be closer to mile marker 17 than mile marker 18, it will be numbered as exit 17A.



CASE STUDY 5
EXISTING WESTBOUND SIGN LAYOUT
FIGURE 5-5A



CASE STUDY 5
EXISTING WESTBOUND SIGN LAYOUT

FIGURE
5-5B

Now that existing signs have been moved based upon the location of the new ramp, placement of advance guide signs for Foothills Drive may occur. Three-quarters of a mile upstream of the new Foothills Drive exit gore is an overhead sign assembly with panels for the airport exit, the Executive Drive exit, and the Sunset Street/Oak Street exit. This assembly is the natural location for an advance guide sign for Foothills Drive. It is not too far from the Foothills Drive exit, nor is it in the vicinity of the exit direction sign for Executive Drive. Since the assembly already has three sign panels, the one for the furthest exit (Sunset Street/Oak Street) should be removed when the Foothills Drive advance guide sign is added. An interchange sequence sign is not appropriate here because such a sign would not be able to indicate that the airport exit goes to SR 67 south and, per MUTCD recommendations, could not contain more than three exit names and distances (i.e., Sunset Street/Oak Street could not be included anyway).

Advance guide signs for Foothills Drive will need to be placed upstream of the exit. Existing sign assemblies will be the logical locations to add these signs.

The location of additional advance guide signs can be determined in the same manner as the ¾-mile sign.

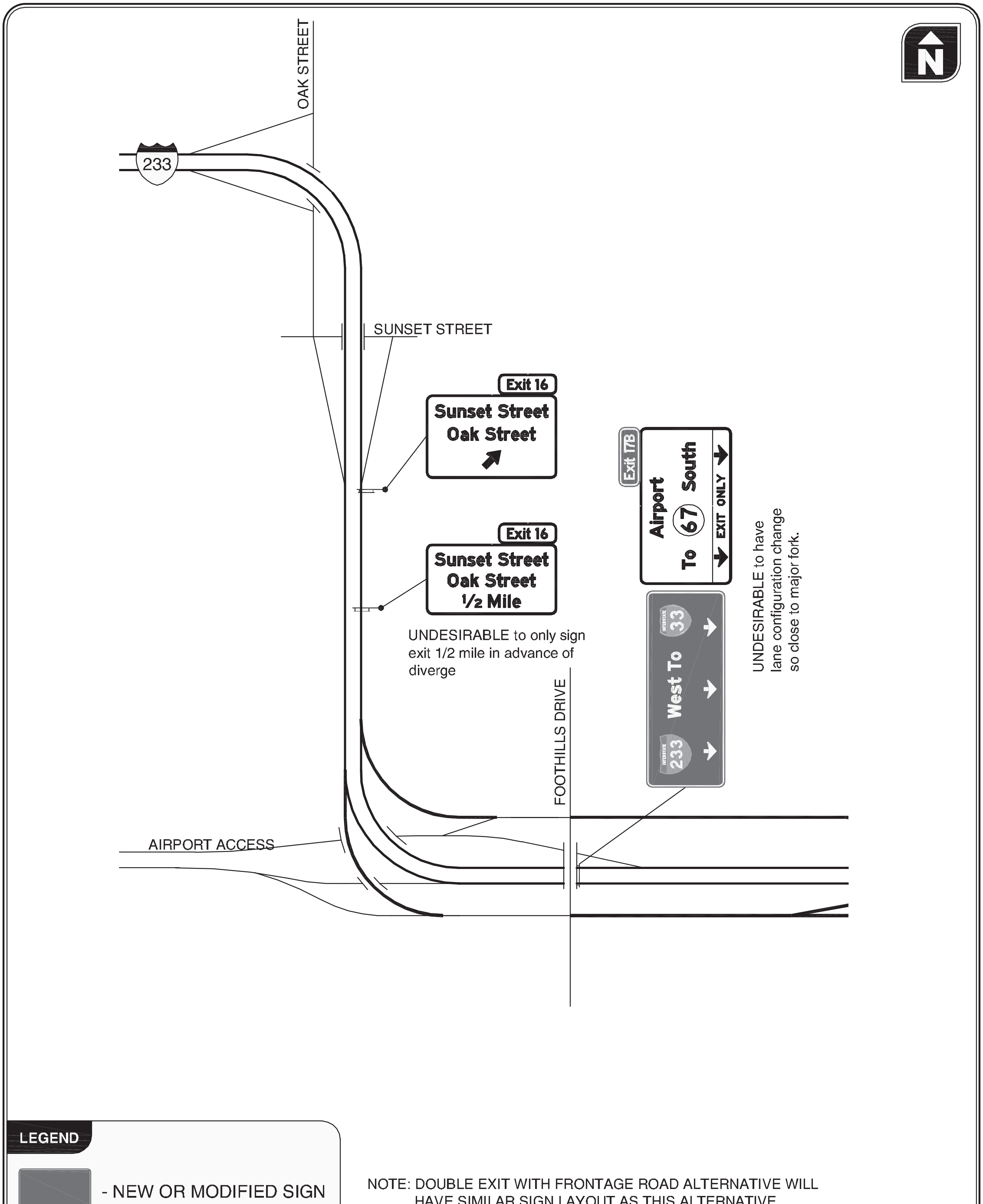
A 1¼-mile advance guide sign for Foothills Drive can be added to the sign assembly mounted on the Green Road overpass, and a two-mile advance guide sign for Foothills Drive can be added to the sign assembly that is one-half mile upstream of the Green Road exit. These additions would place three sign panels at each location. Under such a circumstance, interchange sequence signs could also be used. However, the MUTCD recommends that interchange sequence signs be used over the entire length of a route in an urban area, and on I-233 they would only be needed in these two locations. All sign placements associated with the braided-ramp alternative are shown in Figure 5-6.

The braided-ramp alternative will require signing that begins to exceed the number of message units that drivers are able to comprehend and process. Three sign assemblies in the corridor will display three guide signs each. The Sunset Street/Oak Street interchange will not be signed until one-half mile in advance of the exit, since sign assemblies for several miles upstream cannot accommodate additional sign panels. There may also be challenges locating the exit direction sign for Foothills Drive since it will be near an overpass. Based on the signing alone, the braided-ramp alternative is not recommended.

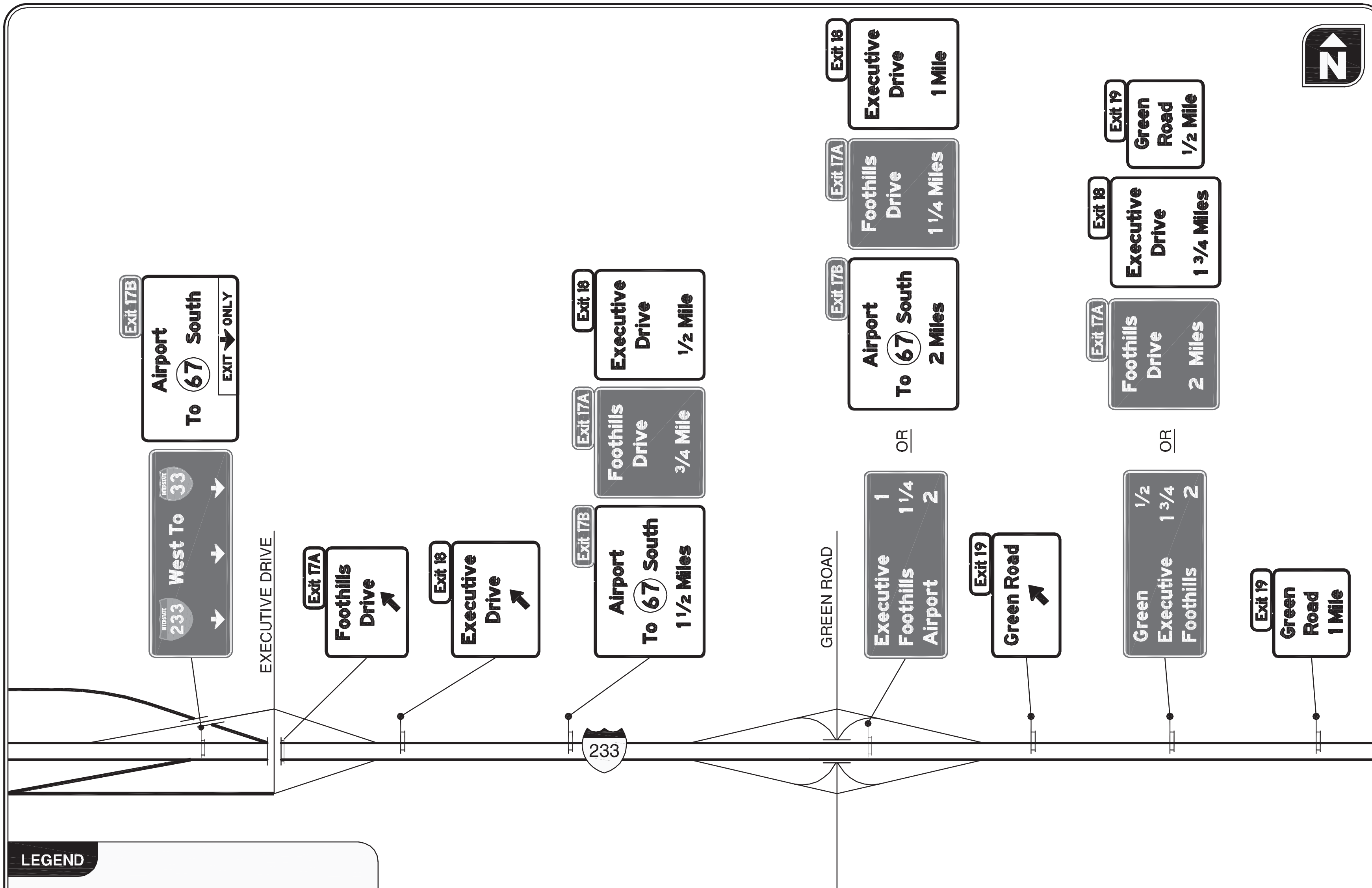
It does not appear that the braided-ramp alternative can be adequately signed. The configuration requires signing that exceeds the number of message units that drivers are able to comprehend and process. There may also be challenges locating the exit direction sign for Foothills Drive since it will be near an overpass. Based on the signing challenges, the issues with lane balance and weaving on the mainline, and the previously identified operational issues, this alternative is a strong candidate for elimination from further consideration.

<u>Double Exit with Frontage Road</u>

This alternative has signing similar to the braided-ramp alternative. No sign layout is provided for this alternative because of its similarity to the braided-ramp alternative shown in Figure 5-6. The same number of exit ramps will exist at approximately the same locations as under the braided-ramp scenario. Many of the same issues that exist with the braided-ramp alternative, such as a high number of message units, also exist with this alternative. However, from a signing perspective, it is superior to the braided-ramp alternative in two ways:



CASE STUDY 5
WESTBOUND SIGN LAYOUT FOR NEW FOOTHILLS DRIVE INTERCHANGE
(BRAIDED RAMP ALTERNATIVE)
FIGURE 5-6A



LEGEND

- NEW OR MODIFIED SIGN
- EXISTING SIGN

NOTE: DOUBLE EXIT WITH FRONTAGE ROAD ALTERNATIVE WILL HAVE SIMILAR SIGN LAYOUT AS THIS ALTERNATIVE.

CASE STUDY 5
WESTBOUND SIGN LAYOUT FOR NEW FOOTHILLS DRIVE INTERCHANGE (BRAIDED RAMP ALTERNATIVE)

FIGURE **5-6B**

- Without the Executive Drive onramp, there is more flexibility in locating the Foothills Drive exit ramp. This flexibility can be used to minimize the impact of placing the sign for the exit so near the overpass.

- Without the Executive Drive onramp, there will be no auxiliary lane immediately prior to the airport exit. There will not be a change in lane configuration for the airport exit on the two signs prior to it.

Despite the positive signing qualities of this configuration compared to the braided-ramp alternative, the double-exit-with-frontage-road alternative is not recommended because it would require signing that exceeds the number of message units drivers can be expected to comprehend.

<u>Single Exit with Frontage Road</u>

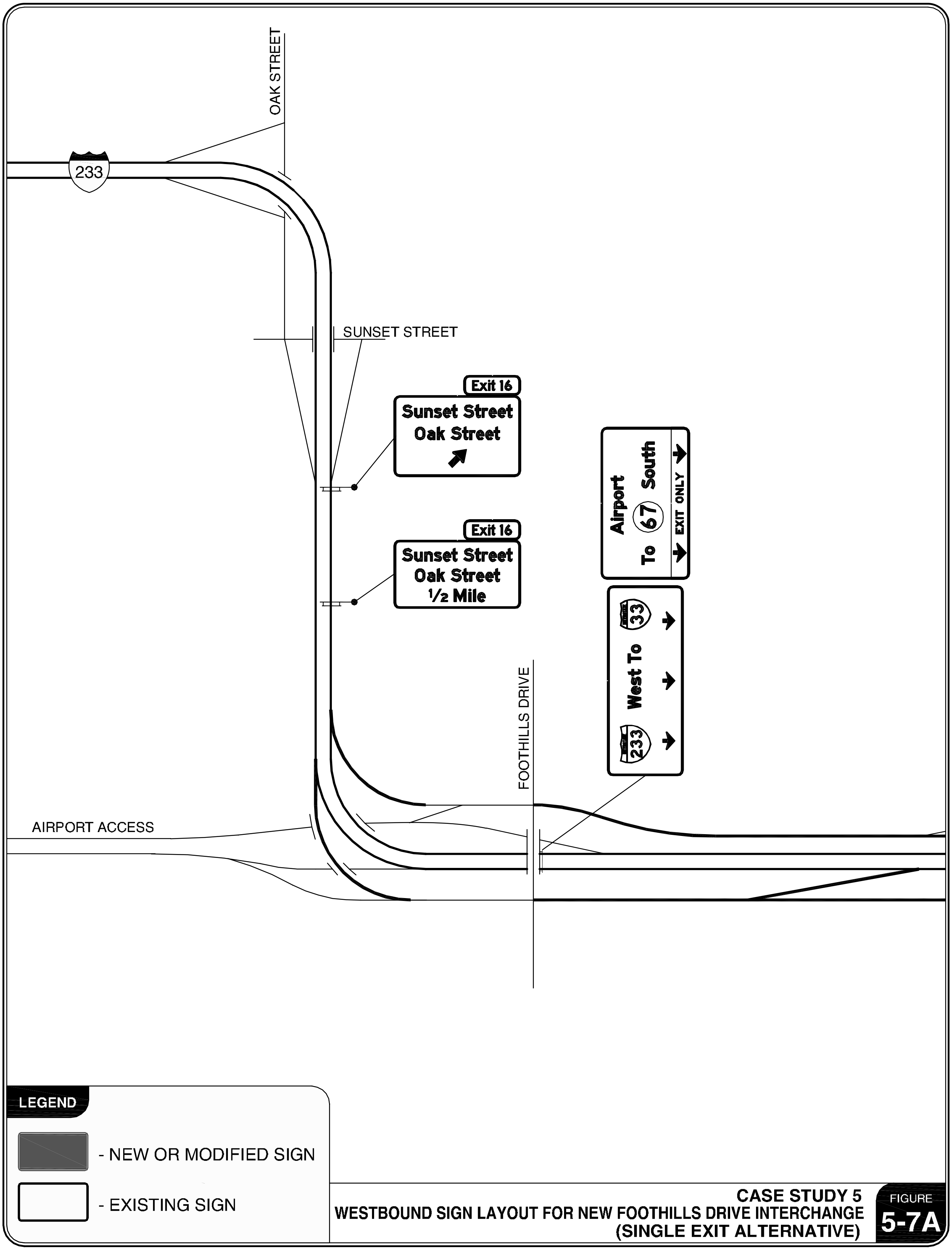
The single exit with frontage road alternative is superior to the other two from a signing perspective.

The single-exit-with-frontage-road alternative has one less exit than the other two alternatives and will be considerably easier to sign as a result. There will be no exit gore near the Executive Drive overpass and, thus, no signing issues relates to this. Signs for the airport exit downstream of Executive Drive do not need to be modified or relocated. The Sunset Street/Oak Street exit, while not signed the typical one or two miles prior to the exit, can be signed 2 ¾ miles prior to the exit. A sign layout for this alternative is shown in Figure 5-7.

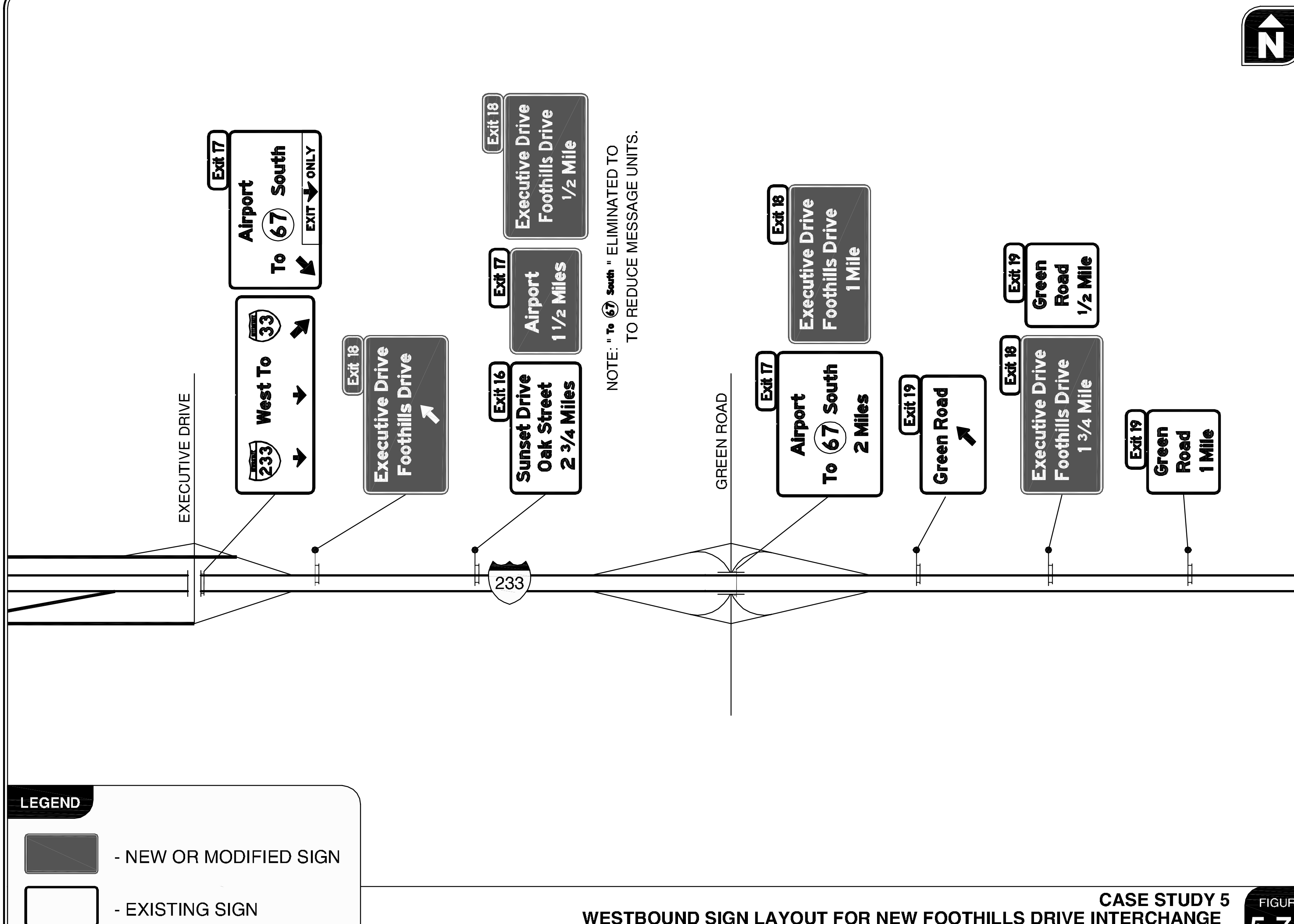
In this alternative there is only one location that requires three sign panels. At this location, which is between Green Road and Executive Drive, each sign will have four message units: an exit number, two street names, and the distance to the exit. To reduce the number of message units, the “To SR 67 South” text on the sign for the airport exit could be eliminated. Other signs for the airport indicate that SR 67 can be accessed from the airport exit. Signing at this assembly will essentially be at but not exceed the limit of what drivers are able to process from a message-unit perspective.

Other Considerations

The proposed interchange will be on the Interstate Highway System, and therefore, changes must be approved by FHWA. Discussions between the state transportation agency and FHWA are underway, and FHWA has indicated it will approve the proposed interchange if a traffic study demonstrates that it meets the requirements of the agency’s access review policies.



CASE STUDY 5
WESTBOUND SIGN LAYOUT FOR NEW FOOTHILLS DRIVE INTERCHANGE
(SINGLE EXIT ALTERNATIVE)
FIGURE
5-7A



CASE STUDY 5
WESTBOUND SIGN LAYOUT FOR NEW FOOTHILLS DRIVE INTERCHANGE
(SINGLE EXIT ALTERNATIVE)

FIGURE
5-7B

FINDINGS

Adding an exit and entrance ramp to serve Foothills Drive from I-233 westbound will be challenging due to ramp spacing issues. The use of braided ramps between Executive Drive and Foothills Drive is not recommended. It will keep the existing weaving section prior to the airport diverge (which violates the principles of lane balance and requires two lane changes for some movements) intact, and sufficiently signing all exits without overloading drivers with too many message units will not be possible. The double-exit-with-frontage-road alternative eliminates the weaving section prior to the airport diverge, but still cannot be adequately signed. The single-exit-with-frontage-road alternative is preferred from a spacing perspective, as it does not have any of the issues noted above. Ramp spacing dimensions are well above the AASHTO policy's recommended minimums, major operational impacts are not anticipated, and signing needs can be satisfied. Significant freeway mainline safety impacts of a new Foothills Drive interchange are unlikely. Research used to draw safety conclusions related to some of the tightly spaced ramp combinations is limited.

The braided-ramp alternative is a candidate for early screening and elimination from further study for the reasons noted above. The double-exit-with-frontage-road alternative is as well, unless it has significant advantages over the single-exit-with-frontage-road alternative for aspects of the project not related to ramp spacing, such as arterial operations, cost, environmental constrains, etc. The single-exit-with-frontage-road alternative should be studied in greater detail.

Appendix B
Traffic Operations Tools

This appendix contains charts summarizing the operational findings of the research conducted for this project.

Impacts of Ramp Spacing on Freeway Speed

Simulation models of entry-entry and entry-exit (without an auxiliary lane) ramp combinations were used to assess the impact of ramp spacing on freeway speeds. For each ramp combination, two models were constructed:

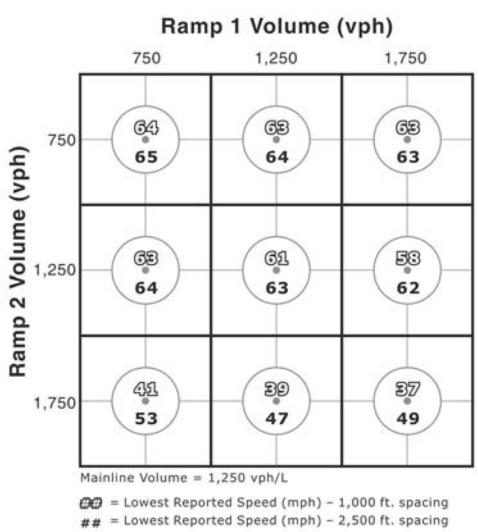
- Short Ramp Spacing (700 ft for the entry-entry ramp combination and 1000' for the entry-exit ramp combination)
- Long Ramp Spacing (2,500 ft for both ramp combinations)

Ramp spacing was measured from painted tip to painted tip, consistent with the ramp spacing definition in Chapter 1 of the Guidelines. The VISSIM software package was used for the simulation modeling.

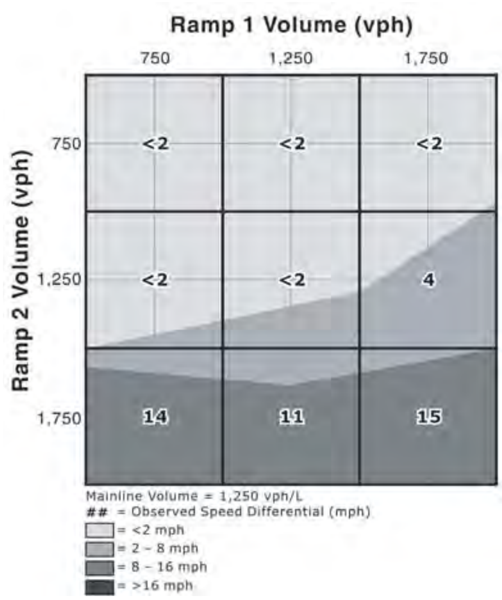
PRESENTATION OF THE RESULTS

Speeds were measured in VISSIM at five locations. One speed collection location was at each painted tip, and the remaining three speed collection locations were equally spaced on the freeway between the painted tips. Speed data was then summarized in two ways:

1. **A comparison of the lowest speeds.** This evaluation simply compares the lowest speeds occurring within each mainline segment, regardless of the location within the segment. The figure below shows an example of this lowest-speed-reported comparison. For example, in the top left cell, the lowest point speed for a 700-ft ramp spacing of 64 mph may be measured at the midpoint between gore points, while the lowest point speed for the 2,500-foot spacing (65 mph) was measured at the downstream ramp gore point. This comparison highlights the effect of ramp spacing on the lowest speed between gore points but also shows absolute speeds which can be used in comparison to free-flow speed.

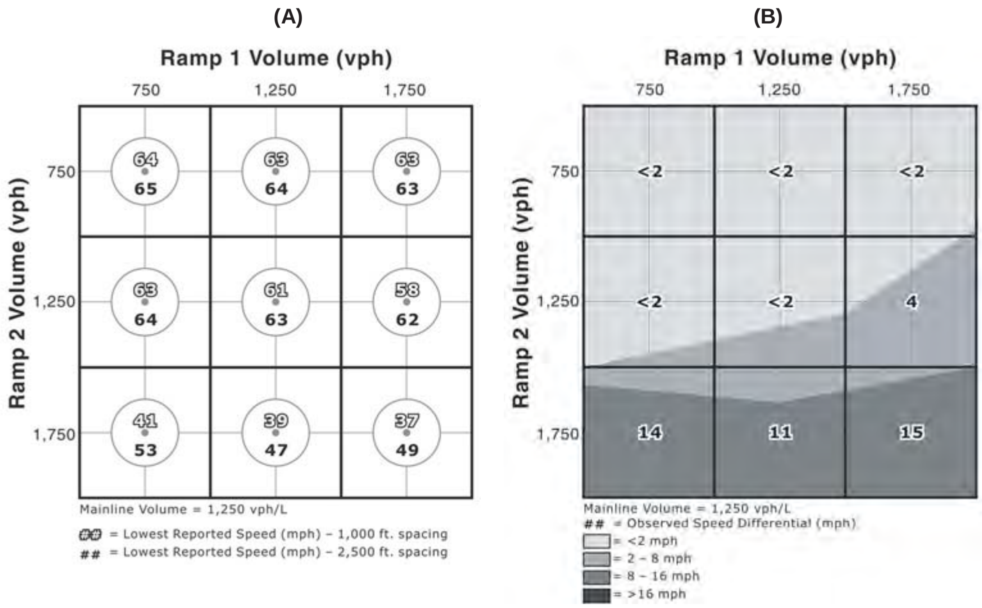


2. **The maximum corresponding point-speed difference**. This evaluation considers the speed difference between the two ramp spacing alternatives at each measurement location. The speed differential at each of the five measurement points was determined, and the maximum speed differential is considered for each ramp-volume combination. The speed measurement points are equivalent in this comparison, regardless of ramp spacing, unlike the comparison of lowest reported speed, which does not necessarily compare measurements at the same point. For example, if the speed occurring at the downstream gore point in the 1,000-foot model is 35 mph, and in the 2,500-foot model is 50 mph, then the corresponding point-speed difference is 15 mph. The figure below shows an example of the maximum corresponding point-speed differentials for each volume scenario. From the nine data points shown in the exhibit, expected trend zones have been inferred showing the anticipated maximum speed differential at corresponding points under different ramp-loading conditions.

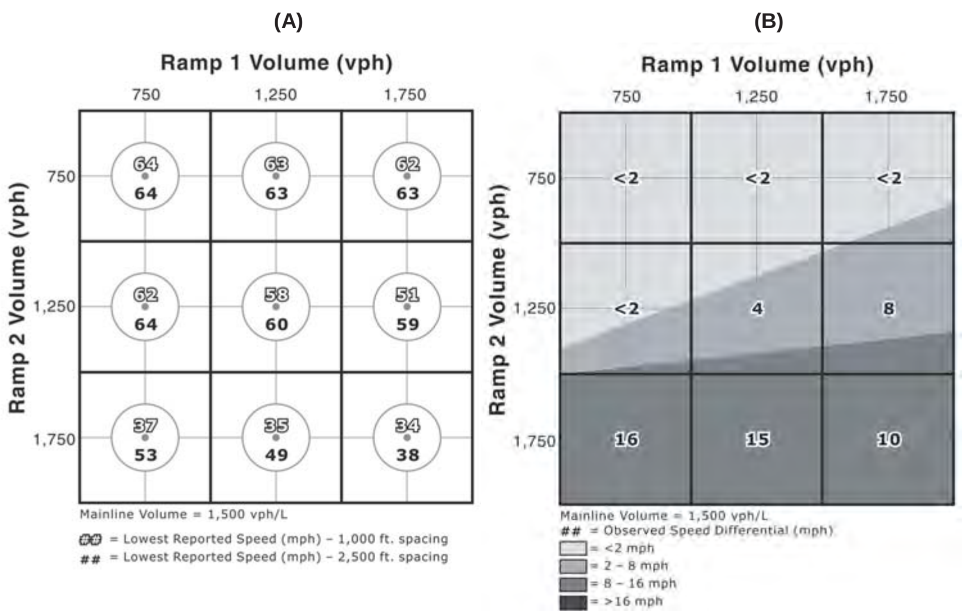


ENTRY-EXIT RAMP COMBINATIONS

The following charts summarize the lowest-reported-speed comparisons and maximum corresponding point-speed differentials for the two entry-exit ramp spacing alternatives, 1,000 ft and 2,500 ft. The average free-flow speed is 66 mph.

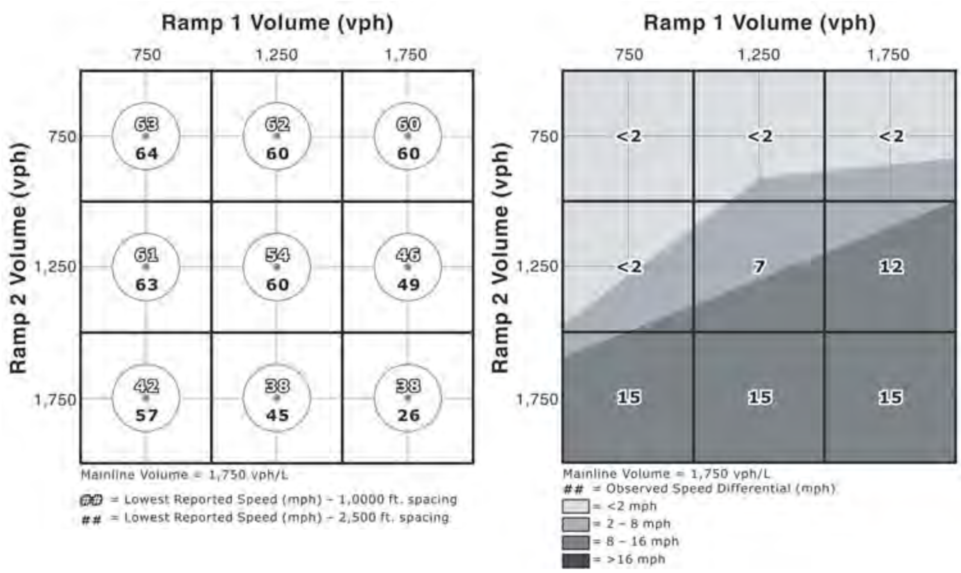


Entry-Exit Mainline Entering Volume 1,250 vphpl, 1,000-ft spacing and 2,500-ft spacing:
(A) Comparison of Lowest Speed Reported,
(B) Maximum Corresponding Point-Speed Difference



Entry-Exit Mainline Entering Volume 1,500 vphpl, 1,000-ft spacing and 2,500-ft spacing:
(A) Comparison of Lowest Speed Reported,
(B) Maximum Corresponding Point-Speed Difference

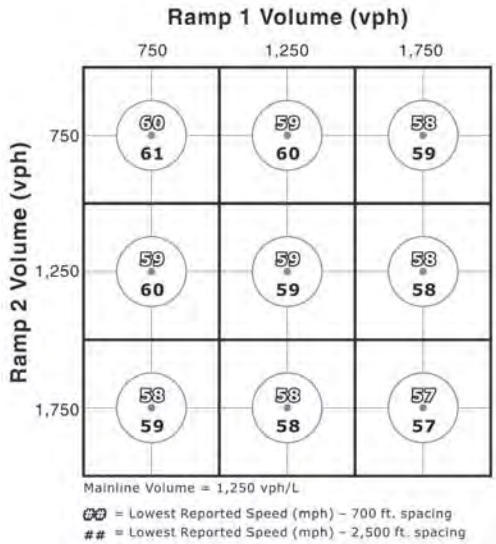
A) B)



Entry-Exit Mainline Entering Volume 1,750 vphpl, 1,000-ft spacing and 2,500-ft spacing:
A) Comparison of Lowest Speed Reported,
B) Maximum Corresponding Point-Speed Difference

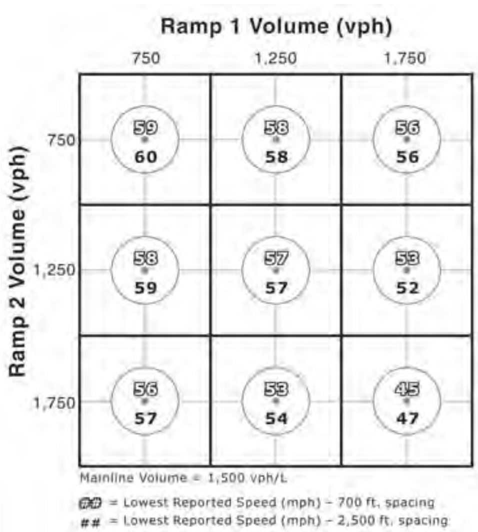
ENTRY-ENTRY RAMP COMBINATIONS

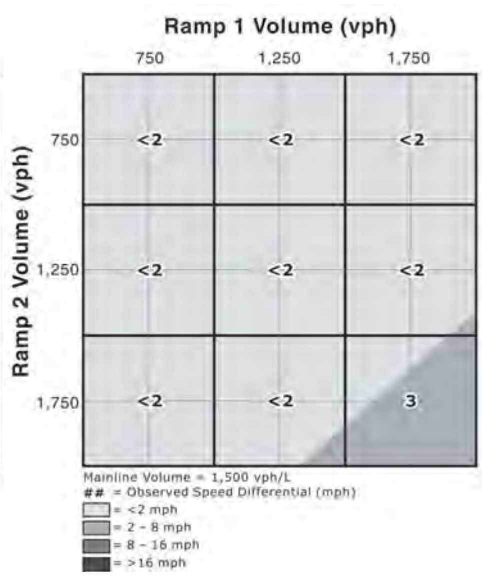
The following charts summarize the lowest-reported-speed comparisons and maximum corresponding point-speed differentials for the two entry-entry ramp spacing alternatives, 700 feet and 2,500 feet. The average free-flow speed is 64 mph.



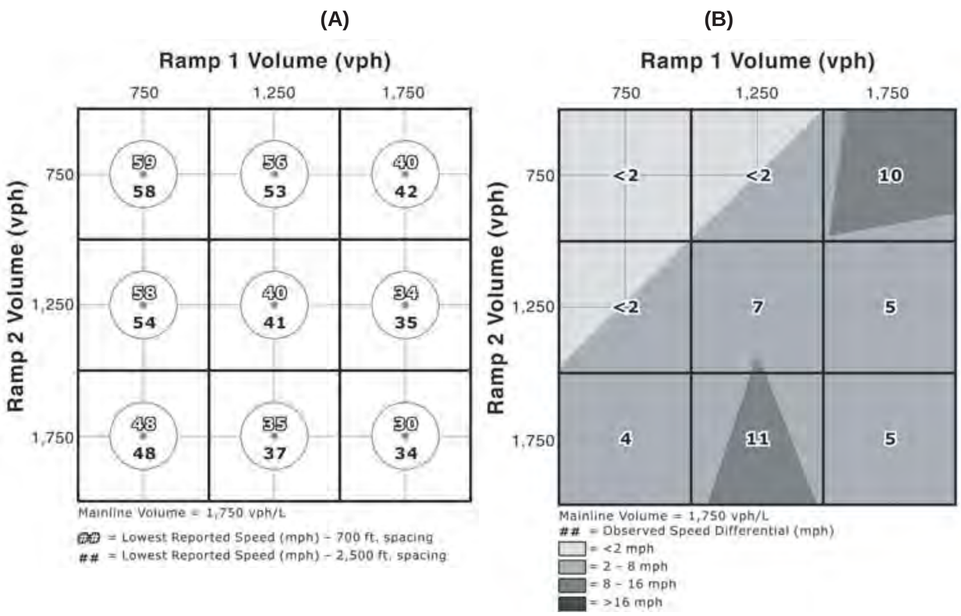
Entry-Entry Mainline Entering Volume 1,250 vphpl, 700-ft spacing and 2,500-ft spacing: Comparison of Lowest Speed Reported

(The graph for corresponding speed differentials was omitted for this mainline volume due to it showing no speed differentials greater then 2 mph.)





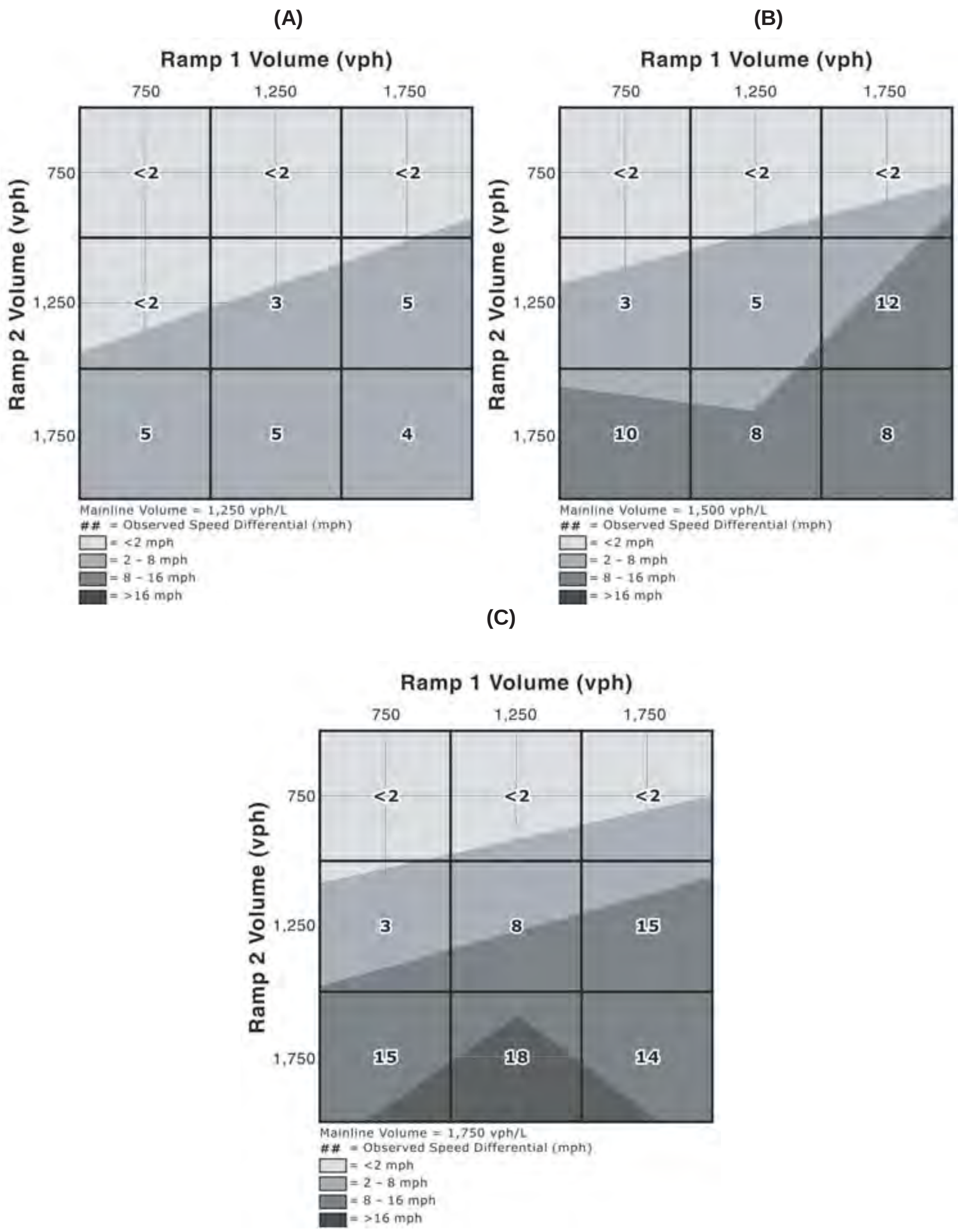
Entry-Entry Mainline Entering Volume 1,500 vphpl, 700-ft spacing and 2,500-ft spacing:
(A) Comparison of Lowest Speed Reported,
(B) Maximum Corresponding Point-Speed Difference



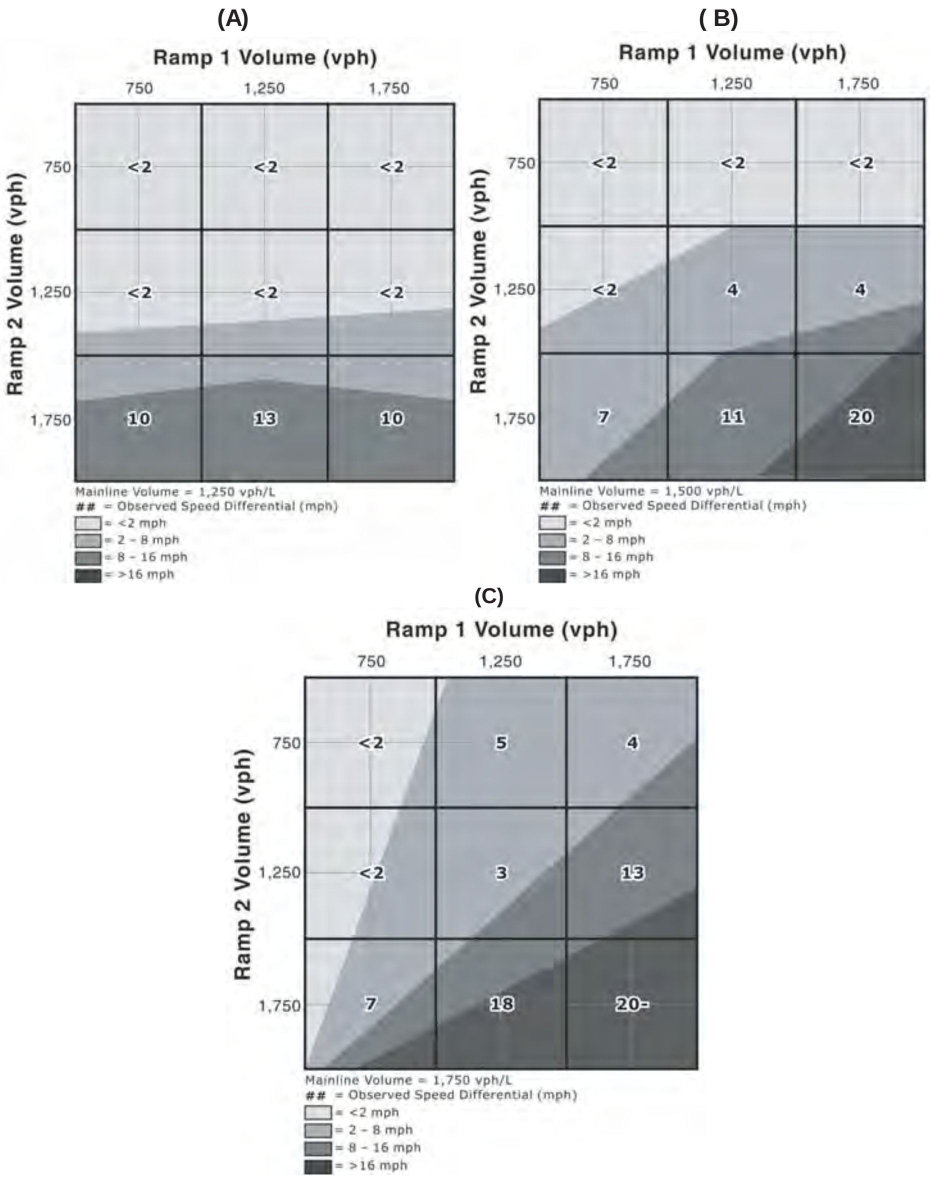
**Entry-Entry Mainline Entering Volume 1,750 vphpl, 700-ft spacing and 2,500-ft spacing:
(A) Comparison of Lowest Speed Reported,
(B) Maximum Corresponding Point-Speed Difference**

Impacts of Auxiliary Lanes on Freeway Speed

Comparisons of the entry-exit ramp configuration with and without an auxiliary lane between the ramps are shown in the following charts. For each entry-exit model an auxiliary lane was added, and the results were compared to entry-exit ramp combinations without auxiliary lane results that were presented in the previous sections.



Effect of Auxiliary Lane on Mainline Speed
(1,000-ft ramp spacing)
(A) Mainline Entering Volume = 1,250 vphpl
(B) Mainline Entering Volume = 1,500 vphpl
(C) Mainline Entering Volume = 1,750 vphpl



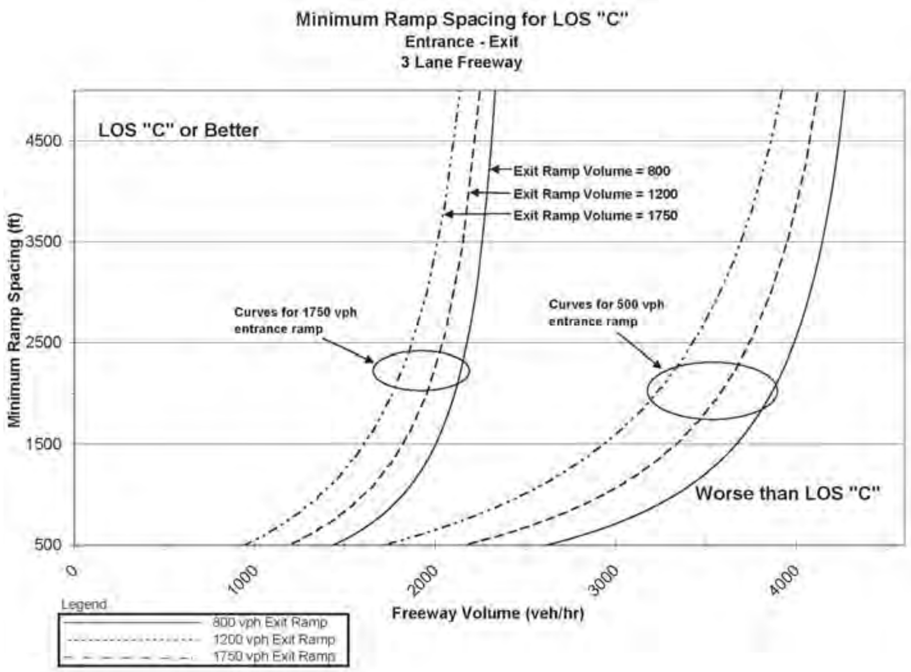
Effect of Auxiliary Lane on Mainline Speed
(2,500-ft ramp spacing)
A) Mainline Entering Volume = 1,250 vphpl
B) Mainline Entering Volume = 1,500 vphpl
C) Mainline Entering Volume = 1,750 vphpl

Impacts of Ramp Spacing on Ramp-Freeway Junction Level of Service (LOS)

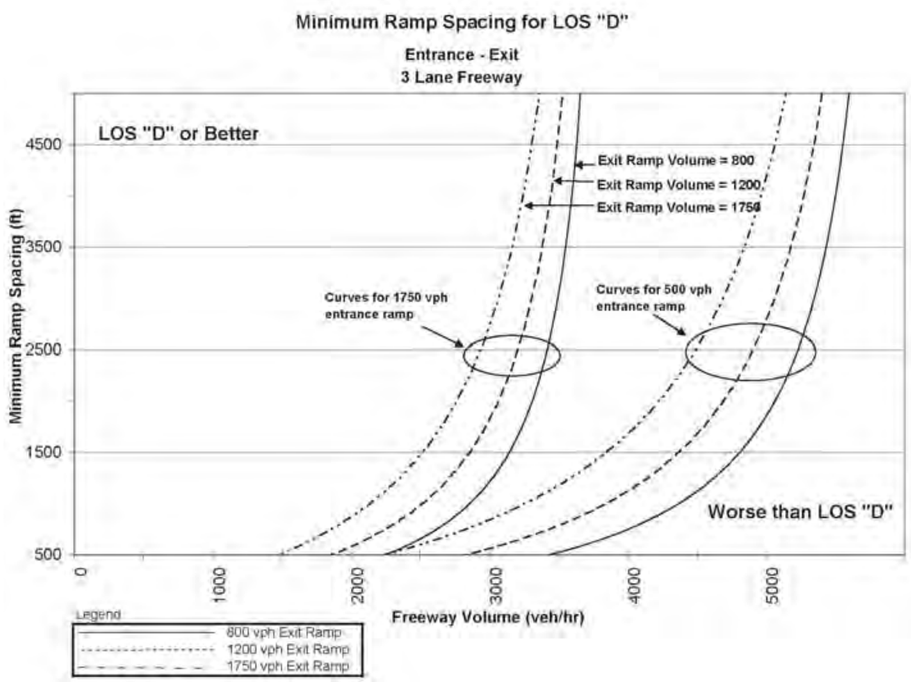
The HCM provides a procedure for analyzing ramp-freeway junctions on two-, three-, and four-lane freeways. The procedure determines the LOS for the right two lanes of the freeway at a single merging or diverging ramp. On three- and four-lane freeways, the procedure includes a step that calculates the volume in the right two lanes given the freeway's directional flow. When analyzing an entry ramp on a three-lane freeway, the calculation of the volume in the freeway's right two lanes (and ultimately the LOS of the ramp-freeway junction) takes into account the distance to the next exit ramp downstream.

If values for some variables are assumed, charts like those shown below can be constructed to identify if a set of volumes will result in a desired LOS or not. For the following charts, the following values were assumed:

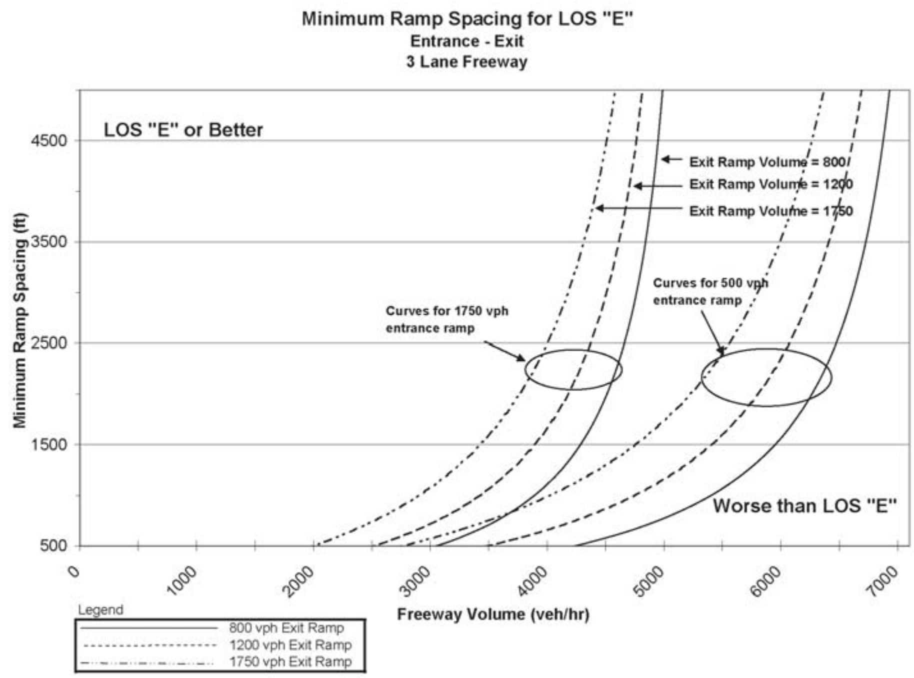
- Peak-hour factor of 0.92
- Passenger-car equivalent for trucks of 1.5
- Driver population factor of 1.0
- Acceleration lane length of 600 feet
- For the freeway:
  - 60 mph free-flow speed
  - 10% trucks
  - 0% RVs
- For the ramps:
  - 5% trucks
  - 0% RVs



Minimum Ramp Spacing to Achieve LOS C on a Three-Lane Freeway



Minimum Ramp Spacing to Achieve LOS D on a Three-Lane Freeway



Minimum Ramp Spacing to Achieve LOS E on a Three-Lane Freeway

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation