Performance-Based Analysis of Geometric Design of Highways and Streets

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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This report was developed through the NCHRP Project 15-34A, "Performance-Based Analysis of Geometric Design of Highways and Streets." The project team consisted of Brian L. Ray (principal investigator), Erin M. Ferguson, and Julia K. Knudsen, Kittelson & Associates, Inc. (prime contractor); Dr. R.J. Porter, University of Utah; and Dr. John Mason. Ralph Bentley and Rowena Ona of Kittelson & Associates, Inc. assisted with exhibits and production.

The project research team benefited greatly from the patience and guidance of the project panel. This group helped assess and prioritize early project work efforts while being open to new ideas and updates as the project advanced under the revised project research team. The project panel was accepting of the project research team's fundamental models and approaches to conveying the principles of performance-based design. The principal investigator found it was a pleasure to work so closely and collaboratively with the project panel and the research team.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

This report presents ways to incorporate performance-based analysis into the project development process. This process framework begins with setting desired project multimodal outcomes and design controls. Geometric design decisions that can influence those outcomes are identified as well as analysis tools that can be used to estimate the impacts of those decisions. The report includes six project examples illustrating how this framework can be applied to actual projects. The report will be useful to geometric designers in making informed decisions about the tradeoffs inherent in design.

Most highway and street design processes rely on standards that set minimum values or ranges of values for design features. These standards are intended to provide operational safety, efficiency, and comfort for the traveler, but it is difficult or impossible for the designer to characterize quantitatively how the facility will perform. For both new construction and reconstruction of highways and streets, stakeholders and decision makers increasingly want reasonable measures of the effect of geometric design decisions on the facility's performance for all of its users.

Each agency has its own process for designing a highway or street. Three critical stages in the process are project initiation (i.e., setting the project's purpose, need, and scope), preliminary design (e.g., analyzing alternative designs and environmental impacts and setting design criteria), and final design (i.e., preparing the construction plans); these stages may have different names in different agencies. Although the expected performance of the facility is only one of the factors that must be considered in designing a highway or street, a better understanding of the expected performance should result in better decisions during these stages. Research was needed to provide the designer with the tools to evaluate the performance of different design alternatives objectively.

NCHRP Project 15-34A completed the work begun under NCHRP Project 15-34. In that project, Pennsylvania State University and Kittelson & Associates, Inc. described the geometric design decisions that occur throughout the project development process and identified performance metrics that are sensitive to those decisions. They also reviewed tools that are available for evaluating the performance of a particular design. This work culminated in the interim report that also presented a plan for developing a process framework.

In NCHRP Project 15-34A, Kittelson & Associates, Inc. and the University of Utah developed the process framework. The framework includes both an approach for integrating performance-based analysis into geometric design decisions and information on the effects that different geometric elements have on project performance measures. It is expected that future research will build upon the latter to improve designers' abilities to assess the performance of a design.

Supplemental material (including a summary of the work done in both projects, suggested future research, and draft text for AASHTO's *A Policy on Geometric Design of Highways and Streets*) is available on the TRB website (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3322).

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Performance-Based Analysis of Geometric Design of Highways and Streets

This report establishes an approach practitioners can use to evaluate the performance tradeoffs of different project development and design decisions. The motivation for integrating performance-based analysis into project development and geometric design decisions is two-fold.

1. Roadway agencies have limited resources to invest and often are developing projects within a physically constrained environment (e.g., limited right-of-way in an urban area, minimizing impacts in environmentally sensitive areas). It is not always fiscally possible or reasonable to categorically construct roadways to meet design standards. Through initiatives such as context-sensitive solutions and practical design, as a profession, we have learned that in many circumstances we must construct roadways using flexible design approaches to adapt to the unique needs of each contextual design environment.
2. The form of highways, streets, interchanges, and intersections has a direct impact on performance measures beyond average delay or travel time for an automobile. The form of our streets and highways directly affects people's ability to comfortably travel by foot, bike, and transit. The form can influence safety performance or various users. It can have direct impact on a community's ability to attract new employers, manage air quality, meet the needs of lower-income households, and create a feeling of livability and vitality for residents, visitors, and employers. Our highways and streets have many more purposes and can bring great value to communities. Our streets and highways directly influence the quality and substance of how we live.

In practice, we encounter projects that are motivated by a desire to reduce crashes, increase community livability, improve air quality, revitalize corridors, and other related desires. Historically, we have sometimes used increased capacity or reduced vehicle delay as the surrogate performance measure to select street and highway design elements. This surrogate was meant to represent the needs of the various roadway users. Increasing capacity or providing flatter and faster designs may reduce vehicle delay through increased speeds. However, this could simply result in a change in the severity of crashes.

This report presents an approach for understanding the desired outcomes of a project, selecting performance measures that align with those outcomes, evaluating the impact of alternative geometric design decisions on those performance measures, and arriving at solutions that achieve the overall desired project outcomes. Part A (Chapters 1 through 4) of this report presents the body of knowledge that forms the basis for performance-based analysis to inform geometric design decisions. Part B (Chapters 5 and 6) presents applications guidance to incorporate performance-based analysis into project development and geometric design decisions.

CHAPTER 1

Introduction

This section provides a foundation for the subsequent process framework by describing the role and value of performance-based activities in geometric design of highways and streets. It provides the guiding principles of this report while outlining the fundamental model of the performance-based approach. The chapter closes with an overview of the concepts of overall project and geometric design performance. These basic concepts are central to the process framework.

1.1 Role of Performance-Based Analysis in Transportation Activities

Gone are the days of large publicly funded projects where funding magnitude was a primary consideration. Federal and state dollars were available as long as a state or local match could be generated. Public transportation funds are typically restricted to maintaining the integrity of the existing highway system and providing *focused improvements for safety and/or operations within the current built-out system.* Public works projects of all scales are more sensitive to funding than ever before. And in many cases, cost magnitude and cost effectiveness play increasingly large roles in scoping projects. Often, reconstruction projects are limited in scope or available funding, or may be affected by physical constraints or social or environmental considerations. In some locations, especially constrained locations, designing to "full standards" simply is not feasible, with design variances, deviations, or exceptions becoming commonplace. Adaptive and flexible designs customized to each project context become increasingly preferred to make the most of project investments.

Public-private partnerships are becoming more prevalent as transportation agencies consider new or retrofitted corridors serving managed lanes or freight facilities. Design-build contracting methods have been well established, resulting in significant design process differences compared to historical design-bid-build contracts. Financial catalysts and return-on-investment needs add a new dimension to low-cost and efficient designs. As cost-effective solutions of public-private partnerships and modified contracting vehicles become more prevalent, engineers and planners will remain responsible for making the most of project investments.

Performance-based analysis of geometric design provides a principles-focused approach that looks at the outcomes of design decisions as the primary measure of design effectiveness.

Regardless of a project's origin, performance-based analysis of geometric design provides a principles-focused approach that looks at the outcomes of design decisions as the primary measure of design effectiveness. As public agencies meet transportation needs with less funding or engage in partnerships to support locally generated (sometimes development-funded) projects, the ability to make informed design decisions will likely increasingly rely on performance-based analysis results.

1.2 Role and Value of Geometric Design of Highways and Streets

The Federal Highway Administration (FHWA) publication *Flexibility in Highway Design* (*1*) and American Association of State Highway and Transportation Officials (AASHTO) publication *A Guide for Achieving Flexibility in Highway Design* (*2*) emphasize the importance of applying "flexibility" as documented in the recent editions of AASHTO's *A Policy on Geometric Design of Highways and Streets* (*3*). Flexibility in geometric design has been supported for years, and increasingly in recent years, tools like the Interactive Highway Safety and Design Model (*4*) and publications such as the *Highway Safety Manual* (HSM) (*5*) and FHWA's *Speed Concepts: Informational Guide* (*6*) provide the means to consider and measure geometric design performance. There is an increasing realization within the design community, supported by the tort liability and risk management community, that simply designing to standards does not reduce a professional's risk for being sued. In addition, designing to standards does not always achieve an optimum design. Performance-based analyses are an integral part of project design documentation, providing a foundation for tracking and supporting design decisions. A solid documentation regimen supported by performance-based analyses can support flexible geometric design decisions. This flexibility allows designers to implement solutions in financially or physically constrained environments and makes project design decisions informed by anticipated geometric design performance.

1.3 Guiding Principles of the Approach

The following principles will guide users in creating usable, practical, and long-lasting highways and streets:

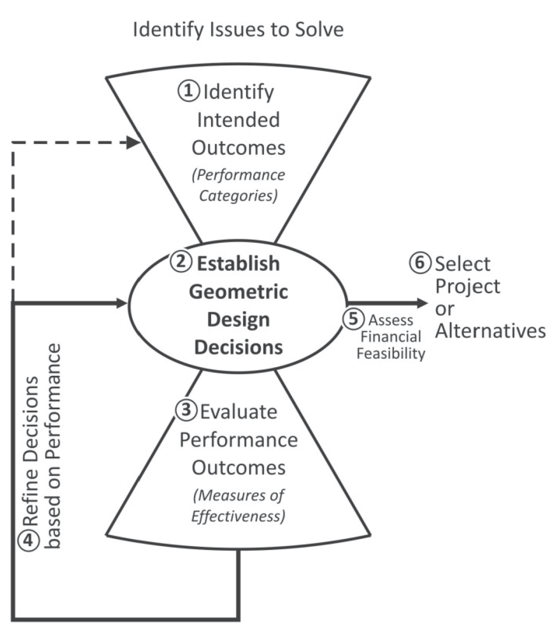
- **Intended outcomes:** Fundamentally, the intent is to document the importance of and need for establishing each project's "intended outcomes" and then focusing on performance-based analysis of geometric design to assess if intended outcomes have been achieved. In some cases, general project intended outcomes may influence geometric design elements and targeted performance. In other cases, geometric design performance may influence general project outcomes. During any of the project development stages, varying degrees of performance analyses guide discrete design decisions.
- **Connection to project development process:** Users benefit from considering the project development process and the discrete activities (such as environmental evaluation and documentation). This considers the opportunities to apply performance-based analysis to the geometric design of highways and streets, where and how the range of flexibility to influence project or design outcomes varies within each project development stage, and the general availability of data needed to support performance-based analysis at different project development stages.
- **Performance measures of design decisions:** The primary focus is the performance effects of geometric design decisions. In some cases, other intended outcomes of the project may influence geometric design decisions; in other cases, the resulting effects of geometric decisions may influence or support broader project outcomes. This document summarizes and prioritizes specific measures that are sensitive to geometric design decisions within the categories of access and accessibility, mobility, reliability, safety, and quality of services. These categories are consistent with broader, national performance-based transportation decision-making efforts (such as with those in the Moving Ahead for Progress in the 21st Century Act (MAP-21), described in Section 3.2).

1.4 Fundamental Model of the Approach

Exhibit 1-1 illustrates the following basic steps in performance-based analysis to inform geometric design:

1. **Identify intended project outcomes** (desired project performance). This may include any number of project context-driven categories that help to identify a project need or purpose. Chapter 3 summarizes USDOT strategic goals, including "economic competitiveness," "livable communities," "safety," and "state of good repair." The 2012 surface transportation bill (MAP-21) identified performance categories, including "congestion reduction," "environmental sustainability," "freight movement," and "system reliability." Community residents and stakeholders may use terms such as "livability," "community cohesion," and "economic development." Regardless of the nature of the source, these project outcomes (or project performance) help establish the measures by which project and geometric design performance might be measured.
2. **Establish geometric design decisions.** This could include establishing design criteria and developing preliminary designs. Whether the project is as discrete as finding ways to channelize a right-turn lane to improve pedestrian crossing times or as broad as conducting an urban freeway corridor study, design options are considered by way of a variety of geometric design decisions. Chapter 2 discusses geometric design decisions and their changing emphasis through the various stages of the project development process.
3. **Evaluate the performance of the geometric design.** This is the point at which the performance outcomes of the geometric design choices are evaluated. Whether this is the general footprint of an interchange or the computed speed of the right-turn lane of a roundabout, establishing the geometric performance allows an assessment of the effectiveness of the design decision in relation to intended project outcomes. Chapter 4 presents information on assessing geometric design decisions and performance. Chapter 5 presents a performance-based analysis application framework. Chapter 6 provides six project examples and applications of the Chapter 5 framework considering the content of the balance of the report.

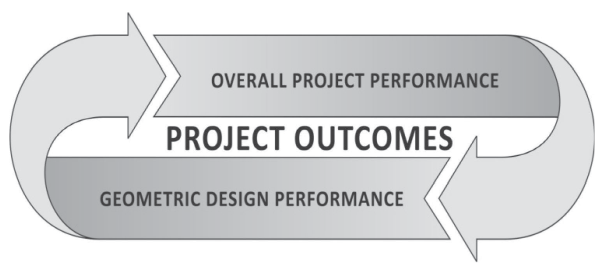
Exhibit 1-1. Fundamental model for performance-based analysis of geometric design of highways and streets.



4. **Iterate design and outcomes to optimize.** Depending upon the results of the assessment of geometric design performance in relation to intended project outcomes, there can be an iterative process to refine geometric design decisions to bring resulting performance in line with intended project outcomes. If an acceptable solution is not attainable, it may be necessary to re-evaluate intended outcomes. For example, if the original intended outcome was to provide congestion relief between two roadways and all interchange forms have unacceptable impacts, it may be necessary to reconsider intended project outcomes and establish a range of potential solutions offering congestion relief at some lower-than-originally-desired target performance.
5. **Evaluate benefit/costs.** In this step, the benefits and associated design choices are assessed to establish the value of the geometric solution compared to the intended project outcomes. If two concept solutions may meet project objectives and all other considerations are equal, the one providing the greater value would likely be advanced.
6. **Select or advance project(s) or alternatives.** As project alternatives are deemed viable within the project context, they may be advanced for more detailed evaluations and/or environmental reviews. Chapter 2 describes some typical relationships between alternatives evaluations and environmental review considerations in relationship to the project development stages.

In summary, once specific issues to be addressed have been clearly articulated, identifying a project's intended outcomes (project performance) as the basis for evaluating performance results is the first step in performance-based evaluations. In some cases, the project may be a well-defined and focused technical exercise to enhance a segment or node geometrics (for example, considering options to increase intersection sight distance). In other cases, the project may include a variety of intended outcomes where selected solutions vary with desired project performance (for example, addressing traffic capacity needs in a multimodal, sensitive way through an historic downtown main street corridor). With intended outcomes defined (project or geometric), users may assess the performance results of alternative geometric design values or configurations to optimize potential project solutions within each project's contextual design environment.

1.5 Overall Project and Geometric Design Performance



An overall project performance *goal may be to reduce crash frequency and severity.* Geometric design performance goals may be to reduce conflict points and vehicle speeds.

Overall project performance may influence and may be influenced by geometric design decisions and their resultant performance. Measuring the effectiveness of overall project performance depends on the goal, intended outcome, nature, or catalyst for the project. Is a safety project initiated to address a documented crash severity or frequency issue? Are certain users overrepresented in crashes? If so, overall project performance might be measured by the expected change in crash frequency or severity, or by the expected change for certain users. Clearly, geometric design choices or geometric design alternatives will influence the outcomes. However, the ultimate measure of project success may not hinge upon the specific geometric element or value of a specific treatment, solution, or mitigation. For example, a single-lane roundabout may be a geometric solution with better expected safety performance than a signalized intersection in a given location. However, if the footprint of the roundabout precludes its application, the signalized intersection with protected left-turning movements may be the most appropriate geometric configuration for the project conditions. And even though the signalized intersection may not offer the theoretical safety performance benefits of the roundabout, its application could lead to a "successful" project outcome compared to the existing and forecast no-build scenario.

Project performance can include other elements that may not be specific to common transportation outcomes of capacity, safety performance, or quality of service for multimodal users. Project performance could include other aspects such as implementing a highway, street, or design element within a specified project budget or construction timeline. The perceived success of the project may not rely on any specific design element; however, the design elements or choices may, in fact, influence the project performance. Consider two intersection alternative configurations. One option might require right-of-way or result in expensive utility impacts compared to another configuration. Or one alternative could impact sensitive lands (wetlands or park land), requiring additional time to attain local, state, or federal permitting approval. In these two examples, the choice of the geometrics could influence the cost and implementation schedule that was a measure of success for overall project performance.

In some cases, an acceptable project outcome may be simply achieving an acceptable geometric solution. For example, a local community wishing to support living-wage jobs may welcome a new manufacturing plant requiring a new interchange on a state highway. The project area may be constrained or the spacing between adjacent interchanges may be less than desirable. The potential employer may have some defined monetary contribution or investment for the improvement, above which it is not economically or financially feasible for the employer to establish operations in that location. In this case, project sponsors and state transportation providers may be incentivized to find creative solutions to develop a financially feasible interchange that allows new access and supports the desired land uses. The overall success of the project may be to obtain the new access and do so in a way that adapts to the constrained environment, while being implemented within a limited budget and project time frame. Geometric design performance may be measured by the ability to achieve acceptable (not ideal) traffic operations, geometric design, safety performance, and signing and marking. Performance-based analysis can help guide project decision making.

Geometric performance can greatly influence whether a project achieves intended outcomes. Specific design choices will result in operating speeds, operating environment, driver expectations, and safety performance. Depending on the intended project outcomes, the results of geometric design decisions (geometric design performance) may or may not meet overall project needs. Consider a community where "Main Street" is a state highway. A local community may be striving for a walkable community with reduced travel speeds that promote adjacent development or facilitate comfortable and safe street crossings. A desired overall project performance measure may be to retain the local community culture and character or to improve economic vitality by changing the traffic volumes and patterns on Main Street. The choices made by the designer can directly influence the community's character and the transition into and out of that community. Designing gateway features or cross-section changes at the highway transitions to Main Street can influence the tone and character for approaching drivers. As drivers leave Main Street to continue on the highway, the transition design elements can help maintain an environment or operational quality established through Main Street. The choice of on-street parking, curb radii, and lane widths may influence speeds, crossing distances, or characteristics in the community. The choice of roundabouts at the community edge will directly influence travel speeds and predictive safety performance. In this example, the choice of geometric design elements will yield explicit operational and safety characteristics for each user. The overall project performance may be directly linked to the specific design choices—and the specific performance of the design alternatives considered.

In summary, performance-based analysis of geometric design provides a principles-focused approach that looks at the outcomes of design decisions as the primary measure of design effectiveness. Identifying project intended outcomes (project performance) as the basis for evaluating performance results is the first step in performance-based evaluations. Geometric performance can greatly influence whether a project achieves intended outcomes. Specific design choices greatly influence operating speeds, operating environment, driver expectations, and safety performance. Depending on intended project outcomes, the results of geometric design decisions (geometric design performance) may or may not meet overall project needs. As professionals address transportation needs in various project contexts, performance-based analysis results will support informed decision making.

1.6 References

1. Federal Highway Administration. *Flexibility in Highway Design.* Washington, D.C.: 1997.
2. American Association of State Highway and Transportation Officials. *A Guide for Achieving Flexibility in Highway Design.* Washington, D.C.: 2004.
3. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets.* Washington, D.C.: 2011.
4. Federal Highway Administration. Interactive Highway Safety and Design Model. Washington, D.C.: 2003.
5. American Association of State Highway and Transportation Officials. *Highway Safety Manual.* Washington, D.C.: 2010.
6. Federal Highway Administration. *Speed Concepts: Informational Guide.* Washington, D.C.: 2009.

CHAPTER 2

Geometric Design Decision Making and Performance

This chapter provides an overview of geometric design decisions within the project development process and the relationship between project-level and geometric design performance measures. In addition, the geometric design activities within each project stage, environmental evaluations, and context-sensitive design approaches are discussed.

2.1 Overview of Geometric Design Decision Making

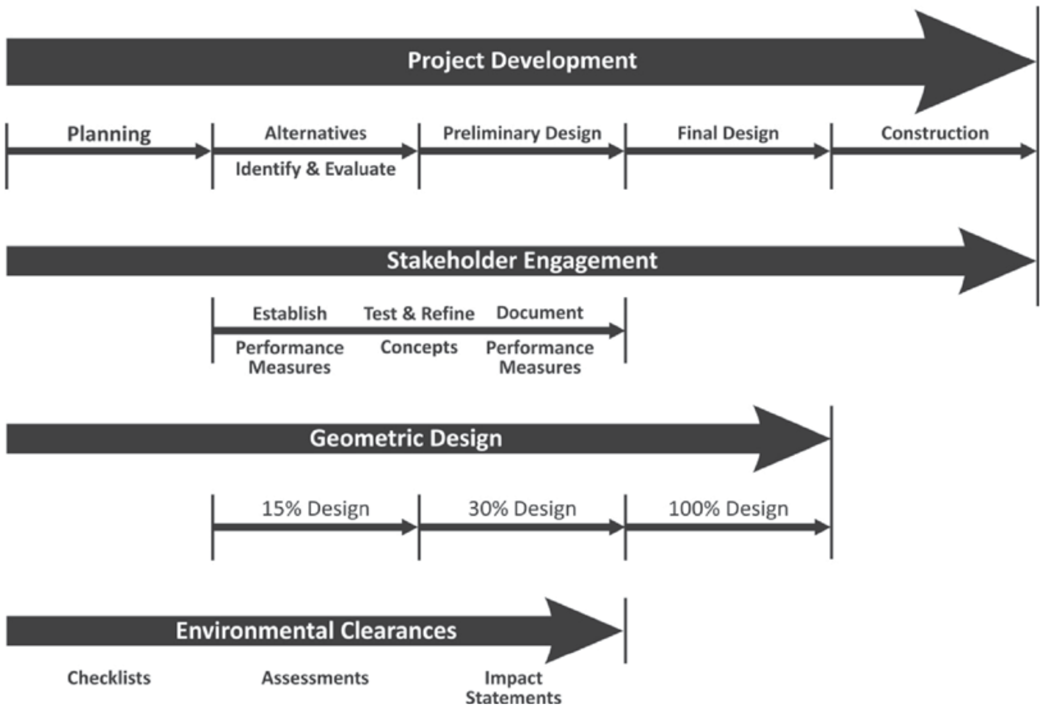
This section outlines the various activities of the project development process and the role of and relationship between geometric design activities within the various project development stages. Geometric design has limited roles in system planning; performance considerations and outcomes of geometric design decisions become most relevant during the alternatives identification and evaluation and preliminary design stages. Beyond that point, as more key design decisions are made, there is less flexibility to make significant performance-based decisions. Discrete design choices become increasingly finite through final design as plans, specifications, and estimates are prepared. Projects are commonly identified via actions associated with planning activities. Catalysts could include categories such as safety, operations, economic development, land development, capital improvement, maintenance, or other initiators. Many of these catalysts could be the same as intended project outcomes.

Systems planning may include rudimentary considerations of geometric design in the broadest terms of classifying the roadway facilities (i.e., a rural, multilane, limited-access facility with interchanges or grade separations at major roadways and minor cross streets). As projects are advanced from planning, there may be some consideration of the intended outcomes such as an improvement in safety, an increase in localized segment or node capacity, or general upgrading of roadway corridor elements. In all cases, there are broad ideas of the nature and magnitude of the project, and the impending project development activities help define, refine, and select solutions within the unique context of each project.

This document is focused on geometric design decisions and their performance effects. Understanding where a geometric design activity fits within the project development process and how geometric design decisions and activities influence or are influenced by other activities within the project development process may guide geometric design decision making. Section 2.3 provides descriptions of the project development stages used within this document. For the purposes of this report, the project development stages are defined as planning, alternatives identification and evaluation, preliminary design, final design, and construction.

The diagram shown in Exhibit 2-1 highlights some of these general relationships. The exhibit is simplified to show general relationships and is not intended as an absolute. For example,

Exhibit 2-1. Geometric design decisions within the project development process.



meaningful stakeholder engagement can begin in the planning stages and continue through construction. Similarly, a designer may investigate roadway profiles or bridge type constructability while identifying and evaluating alternatives even if the overall geometrics are at the 15% design level.

2.2 Relationship between Project and Geometric Design Performance

Within the project development activities, the project's overall effectiveness can be estimated or predicted and evaluated through construction when the facility is open. Once constructed, the actual project performance can be observed. Performance evaluations of the permanent geometric design elements (i.e., not the construction work zone design elements) generally peak in the middle stages of preliminary design (15% to 30%). Beyond 30% plans, the design choices and performance measures become increasingly discrete as the plans, specifications, and estimates are completed.

The perceived effectiveness of a project will be influenced by geometrics and their corresponding performance.

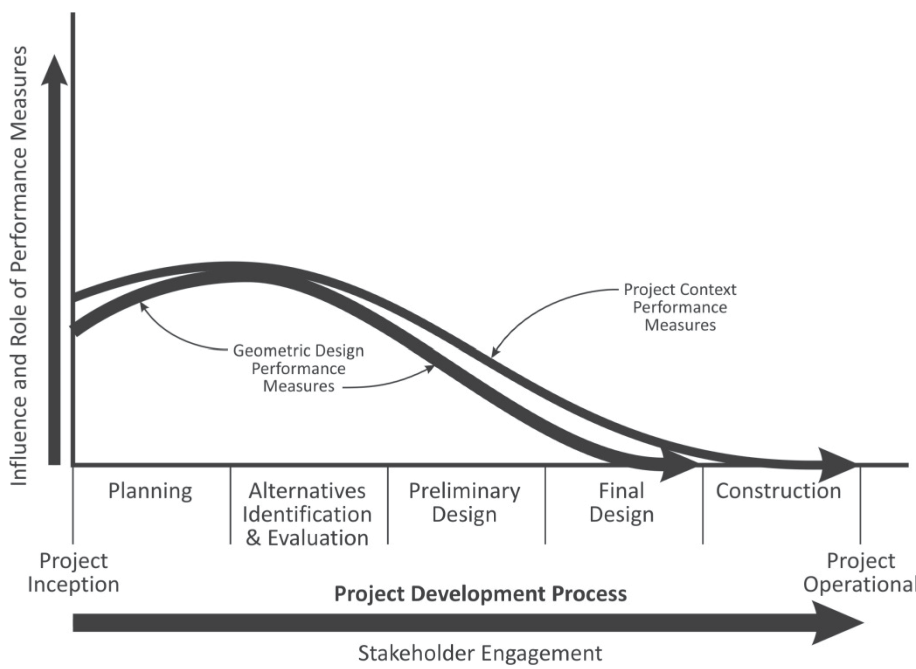
Project-level outcomes can relate catalysts such as safety performance targets, congestion relief, or better service for multimodal users. However, project drivers may also include elements such as "livability," "community cohesion," or "economic development." In some project contexts, attributes of livability may include maintaining a rural character, making the area "walkable," or preserving an area's history or culture. Community cohesion might include strong land use connections and relationships, network connectivity to support various users' mobility, or having projects with a minimal footprint. The perceived effectiveness of a project will be influenced by geometrics and their corresponding performance. For example, the choice of signalization or curb and gutter could be perceived as diminishing the rural character of an area. Or, increasing vehicle or bicycle capacity by removing parking in a commercial/business area may be seen as counter to economic development. Section 3.2, Project Performance, discusses project performance goals and measures. This section also highlights USDOT strategic goals along with performance target categories from MAP-21. Geometric design choices and their resulting performance can directly influence and be influenced by project performance goals, objectives, or targets.

Exhibit 2-2 conceptually depicts the level at which performance outcomes of geometric design decisions are central to decision making throughout the project development process. The exhibit shows geometric design performance is less of a consideration in the early planning stages when so many project issues are being considered. In the alternatives development stage, geometric design decisions and their outcomes become central to project discussions and considerations. As alternatives and concepts are screened and others refined and advanced to more detailed evaluations, other project considerations may become more of a focus. As final design plans are completed, the role of geometric decisions diminishes. As a project advances to construction, other project issues may be central to decision making.

Measures related to overall project context may be identified early and conceptually in planning stages. They are a critical element in helping inform and guide the range of alternatives. Each identified alternative's general evaluation and corresponding performance measures are closely connected to the geometric design elements and their individual and collective performance. These stages create some of the highest amount of interaction between the geometric design outcomes and the intended project outcomes as the concepts are refined and advanced. Performance measurements for the geometric design elements become more refined. During preliminary design, more design details and evaluations are performed on a decreasing number of alternatives. Ultimately, a single alternative is selected and advanced to final design. Project decisions are documented and the selected alternative is developed to a level of detail to support construction. When the project advances to final design, the geometric design measures become increasingly discrete, as needed, to finalize the design details.

Project context performance measures are then focused on quantifying context-sensitive impacts during construction. This could include topics such as preserving access during construction,

Exhibit 2-2. Geometric design performance measures within the project development process.



defining the number of lanes that will remain open at any given time, or the quality of service expected for the range of work zone users. As outlined in *NCHRP Report 581: Design of Construction Work Zones on High-Speed Highways* (*1*), there could be some geometric design decisions associated with constructing temporary roadways or configurations. For the purposes of this discussion, those are not included in this report.

2.3 Geometric Design and the Project Development Stages

For the purposes of this report, the project development process is defined as consisting of the following five stages. Federal, state, and local agencies may have different names or other nomenclature, with the objective being to advance from planning to implementation. As shown in Exhibit 2-2, overall project objectives and performance measures are a primary consideration. Geometric design performance measures are considered at a lower level of detail.

2.3.1 Planning Studies

Planning studies are not explicitly included in this report. However, planning could include limited geometric concepts of the general type or magnitude of project solutions to support programming.

2.3.2 Alternatives Identification and Evaluation

The project needs identified in prior planning studies inform concept identification, development, and evaluation. Geometric design decisions and geometric design performance become paramount considerations at this stage. Understanding the project context and intended outcomes allows potential solutions to be tailored to meet project needs within the opportunities and constraints of a given effort. FHWA describes context-sensitive solutions as “a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting” (*2*). In considering the concept of “context-sensitive design/solutions,” this stage continues the meaningful and continuous stakeholder engagement to be carried throughout the project development process.

This stage establishes and documents intended project outcomes that will influence and be influenced by geometric design decisions. Design elements may be developed to a 15% design level, and it is possible a single alternative could be selected at this stage. It is not uncommon for multiple alternatives to be advanced to preliminary design for additional review and evaluation before identifying a preferred alternative. The overall elements that often occur in this project development stage include the following (*3*):

- Project initiation
- Purpose and need
- Traffic analyses
- Preliminary alternatives
- Public outreach
- Technical studies
- Cost/benefit evaluations
- Refined analyses
- Selected alternative(s)

If needed, state or federal environmental review and impact documentation efforts begin in this stage. A discussion of the general environmental review and impact documentation activities is included in Section 2.4, which highlights where and how geometric design and project performance in the alternatives identification and evaluation and preliminary design stages support the environmental review and impact documentation activities.

2.3.3 Preliminary Design

Concepts advancing from the previous stage are further refined and screened during preliminary design. In more complex, detailed, or high-impact projects, the preliminary design (30% plans) and subsequent documentation is used to support more complex state or federal environmental clearance activities. The corresponding increased geometric design detail allows refined technical evaluations and analyses that inform environmental clearance activities. Preliminary design builds upon evaluations conducted as part of the previous stage (alternatives identification and evaluation). Some of the common components of preliminary design include the following (*3*):

- Horizontal and vertical alignment design
- Typical sections
- Grading plans
- Structures
- Traffic/intelligent transportation systems
- Signing and striping
- Illumination
- Utilities

The expected performance effects of geometric design influence project outcomes and, ultimately, inform project decision making. As design concepts advance from concept to 30% design, iterations and revisions help hone the design, and the performance effects of geometric design decisions have a relatively significant influence on project decisions. As the designs advance from 30% to 100%, there are relatively few significant geometric changes.

Based on the proposed performance-based model depicted in Exhibit 1-1, during these iterations the concepts are refined as needed to best achieve the intended outcomes. These could be broader project outcomes (e.g., speed management or attaining a certain level of mobility) or design specific (e.g., providing an acceptable horizontal alignment while avoiding an environmentally sensitive property).

2.3.4 Final Design

The design elements are advanced and refined in the final design stage. Typical review periods include 60%, 90%, and 100% plans before completing the final set of plans, specifications, and estimates. During this stage there is relatively little variation in design decisions as the plan advances to 100%. Functionally, in this stage of the project development process, the targeted performance measures have a lesser degree of influence on the form of the project. This relationship was presented in Exhibit 2-2.

2.3.5 Construction

Construction activities are not explicitly included in this report. Geometric design decisions may be related to temporary roadways, connections, or conditions that facilitate construction. Project performance measures may relate to project context elements and could guide or inform temporary construction decisions within the intended project outcomes and within the completed project.

2.4 Geometric Design and Environmental Evaluations and Clearance

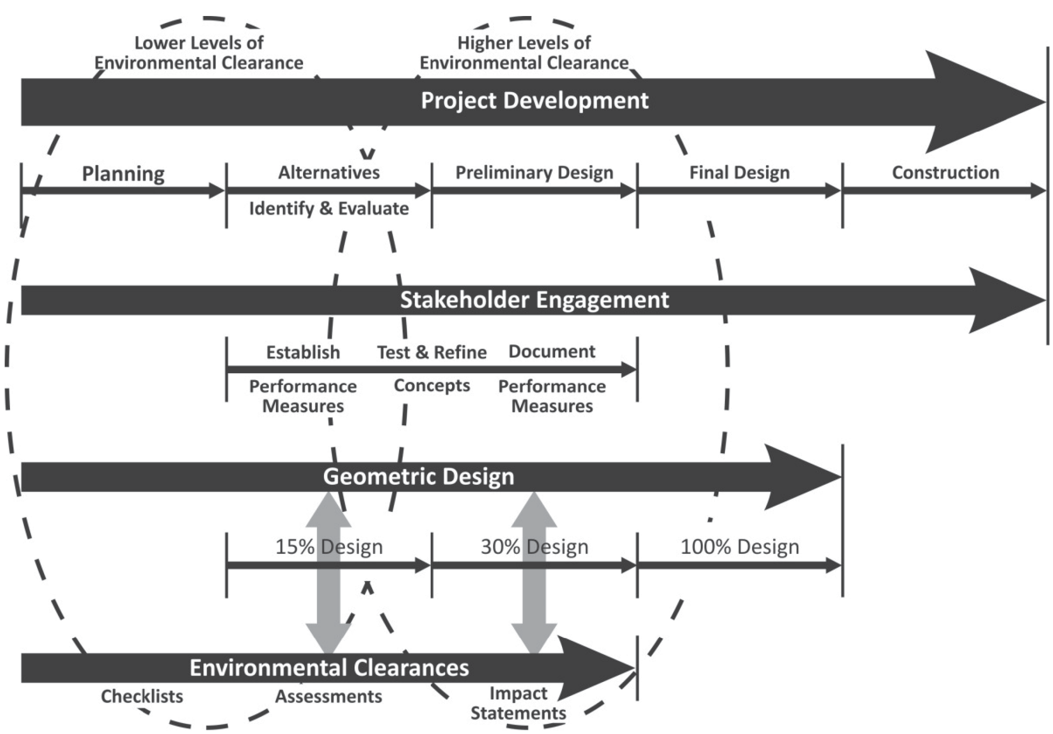
This section summarizes how geometric design and performance-based decisions relate to state and federal environmental policy act considerations. Even without environmental clearance needs, the early stages of project development strive to understand project scope and develop alternatives responding to a project-specific purpose and need. If an environmental review and documentation effort is needed, performance-based evaluations of geometric design can support environmental activities. This section is intended to help establish where and how environmental review processes may influence or be influenced by performance-based analysis of geometric design of highways and streets. Whether state or federally mandated, environmental evaluations typically occur in the early stages of the project development process, often being completed at the early stages of preliminary design. Preliminary design intended outcomes, and measured or projected performance, are often documented in technical reports supporting associated environmental documentation requirements.

The following are the general elements of an environmental evaluation process:

- Project scoping
- Purpose and need
- Alternatives analysis
- Affected environment
- Environmental consequences
- Mitigation

Exhibit 2-3 depicts where environmental clearance often occurs. The encircled areas highlight the relationship between the level of environmental clearance and the project development

Exhibit 2-3. Geometric design and environmental clearance during project development.



stage. The circle on the left reflects relatively low levels of environmental clearance needs such as a categorical exclusion in the National Environmental Policy Act (NEPA). As described by FHWA, "NEPA established a national environmental policy intentionally focused on federal activities and the desire for a sustainable environment balanced with other essential needs of present and future generations of Americans" (*4*). State-level environmental evaluation commonly includes similar checklist-type documentation efforts.

The circle on the right reflects projects that might be more complex or extensive or have project sensitivities. These complex projects often require more extensive design details (up to 30% design) to provide the engineering and technical evaluations and documentation to support applicable environmental reviews and clearances (such as a finding of no significant impact or record of decision in NEPA environmental assessments and environmental impact statements, respectively).

If a project has an environmental review component, existing conditions and no-build analyses help define the scope and magnitude of the range of possible solutions. Project goals and objectives help define the purpose of, and need for, the solutions. Early stakeholder engagement helps define the intended project outcomes and performance measures. In some cases, these may be project context measures related to elements outside the geometric design performance outcomes (such as having a walkable community, preserving a rural character, or creating a high level of traffic capacity). Section 3.2.2 describes some of these types of goal topics. Stakeholder engagement and the resulting project "scope" will influence fundamental design choices during the alternatives identification and evaluation stages of the project development process.

In summary, environmental review and documentation efforts for relatively low-impact projects can range from checklists and categorical exclusions to more complex environmental processes such as environmental assessments or environmental reports. More complex or higher-impact projects may require the highest level of environmental review and documentation such as an environmental impact statement in NEPA. As the degree of environmental review complexity increases, it is common for corresponding engineering evaluations to become more detailed because preliminary design stage efforts guide the technical support and studies. In this case, completed preliminary design in conjunction with environmental clearances allows a project to advance to final design.

Throughout the environmental review efforts, performance-based analysis of geometric design elements can inform and support project decision making.

2.5 Context-Sensitive and Flexible Design Approaches

Several published documents, such as AASHTO's *A Guide for Achieving Flexibility in Highway Design* (*5*), discuss the role of context-sensitive approaches to considering project solutions that are adapted to the local planning and design context. "Flexible" designs may be used to adapt to a local context and to achieve intended project outcomes. Sections 3.1.1 and 3.1.2 present fundamental questions for understanding project context elements and considering intended project outcomes. Context-sensitive and flexible design approaches can stem from considering "Whom are we serving?" and "What are we trying to achieve?" By understanding the various users to be served and the overall project outcomes, applicable geometric solutions can be explored. Considering geometric performance of potential solutions can inform project decision making since intended project outcomes may be influenced by the geometric design considerations.

FHWA and AASHTO have emphasized "flexibility in highway design" as a means to help establish context-sensitive solutions. In addition, FHWA and AASHTO emphasize the importance of continuous and meaningful stakeholder engagement to help establish each project's context and identify a range of possible solutions applicable to each project environment. Performance-based analyses of geometric design elements provide the means to support flexible design solutions or elements to adapt to unique project needs. Early stakeholder engagement can influence and be informed by geometric design considerations. The concept of flexible design and the degree of centrality of the geometric design in the early project development stages is reflected in Exhibit 2-2. As projects evolve from preliminary to final design, the design choices and influences become increasingly finite.

Performance-based analyses of geometric design elements provide the means to support flexible design solutions or elements to adapt to unique project needs.

Documenting design decisions and the considerations supporting those choices that result in flexible design solutions is a key component in managing tort liability. Having a process framework for understanding intended project outcomes, and a logical means to consider a range of design choices and solutions, provides a reproducible and objective methodology. Adapting a project to a context may lead to design variances or exceptions. Flexible design approaches may lead to geometric values or configurations outside published design values.

FHWA's Interactive Highway Safety Design Model (IHSDM) is a suite of software analysis tools used to evaluate the safety and operational effects of geometric design decisions on highways (*6*). IHSDM is a decision-support tool. It provides estimates of a highway design's expected safety and operational performance and checks existing or proposed highway designs against relevant design policy values. Results of the IHSDM support project decision making by summarizing the geometric performance elements of alternative geometric design elements or configurations.

The AASHTO HSM (*7*) provides factual information and proven analysis tools for crash frequency prediction. The HSM helps users integrate quantitative crash frequency and severity performance measures into roadway planning, design, operations, and maintenance decisions. HSM analytical tools allow users to assess the safety impacts of transportation project and program decisions. These tools support context-sensitive or flexible design decision making.

Performance-based tools such as IHSDM and HSM applications can support and inform design decision making for projects of any context. And documenting the evaluation methods and factors leading to geometric design values contributing to flexible design configurations can support a comprehensive risk management strategy. A repeatable process for performance-based analysis of geometric design can help manage risk in general, and support design decisions and documentation content for design variances and exceptions.

2.6 References

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CHAPTER 3

Project Outcomes

This chapter provides an overview of possible project outcomes and considerations in identifying those outcomes. It also defines the concepts of project performance and geometric design performance, and describes the relationship between these two concepts.

3.1 Audience and Goals

Chapter 1 began by describing the role of performance-based analysis in transportation activities and, specifically, the role and value of performance-based analysis in geometric design of highways and streets. Paramount to performance-based analyses is the fundamental model depicted in Exhibit 1-1 that focuses on first identifying intended project outcomes. With outcomes determined, geometric design solutions may be assessed by how well their performance relates to intended outcomes. Section 3.2 describes considerations in defining project performance. Project goals or performance measures can range from strategic goals of the USDOT to performance categories of MAP-21. Stakeholders or community members may share or express project goals that have connections to federal goals and policies. Livability, community cohesion, economic development, or congestion reduction objectives are common intended outcomes.

Understanding whom a project is intended to serve and the ultimate purpose or goal of a project is critical to determining the appropriate performance measures for evaluating both the effectiveness of individual design decisions as well as the collective design of a street or highway.

Understanding whom a project is intended to serve and the ultimate purpose or goal of a project is critical to determining the appropriate performance measures for evaluating both the effectiveness of individual design decisions as well as the collective design of a street or highway. Gaining this understanding is also critical to identifying the design elements and decisions most likely to positively or negatively impact the ability to serve different users and other stakeholders and achieve the desired project outcomes.

This section will highlight how to consider the following fundamental questions:

- Whom are we serving?
- What are we trying to achieve?

The question “Whom are we serving?” focuses on identifying the key road users and stakeholders for a given project and project context. The question “What are we trying to achieve?” focuses on identifying and articulating a project’s core desired outcomes.

Understanding “whom we are serving” is integral to understanding and defining the intended project outcomes. Defining the intended project outcomes and considering the specific users and other stakeholders helps professionals determine the geometric design elements and options that are more likely to achieve the intended outcomes. Considering the expected performance effects of geometric design decisions for highways and streets, defined as geometric design performance in this document, allows designers to assess the level at which their individual decisions and the culmination of their decisions will support the intended project outcomes.

3.1.1 Whom are We Serving?

Road users and other project stakeholders tend to be the two fundamental groups that compose the primary audience served by a specific project. Facility owners and operators typically strive to best meet the groups' needs.

A sporting event may create special peaking, and a place with high tourism such as Florida may notice many "new" users. In addition, road user needs in a place like Minnesota may be different than those of users in Arizona.

Different road user types can be identified and considered by mode: bicyclists, pedestrians, motorists, motorcyclists, drivers of large commercial/freight vehicles, drivers of agricultural/logging/mining equipment/vehicles, and drivers and users of transit vehicles. Road users can also be defined by a target demographic (e.g., younger road users, older road users, and/or transit-dependent populations) and/or a geographic sub-population (e.g., rural town center, central business district, suburban community, and/or industrial area). Other factors can influence the characteristics of road user types, including special events, recreational uses, seasonal variations, or weather patterns and events that influence how users operate.

Project stakeholders can encompass a wide range of individuals, groups, and organizations. They can be agency stakeholders who are facility owners and operators or cooperating partners [e.g., city, county, state, or metropolitan planning organization (MPO)] with full or partial ownership of the project. The cooperating partners may also be involved at just a cursory level because of the project's influence on or proximity to their jurisdiction. Stakeholders can also be local business owners whose economic livelihood (perceived or actual) is directly or indirectly influenced by the project. Residents who live, work, and/or recreate within the influence area of the project can also be stakeholders. There also may be interest groups with specific concerns they would like to have considered and addressed within the project (e.g., environmental concerns, safety for a specific group or demographic).

Given the wide range of potential road users and other project stakeholders, the key is to identify the core audience the project is intended to serve. This is often directly tied to understanding intended project outcomes (defined and discussed in the following section). Key questions that help to isolate the core audience of a project might include the following:

- What is the purpose and function of the existing or planned highway or street?
- What are the existing and planned land uses adjacent to and in the vicinity of the highway or street?
- What road users will likely desire to use the highway or street given the existing and planned land uses?
- What are the existing and anticipated future socio-demographic characteristics of the populations adjacent to and in the vicinity of the existing or planned highway or street?
- What are the perceived or actual shortcomings of the existing highway or street?
- Who has jurisdiction over the facility?
- Where is capital funding for the project originating (or expected to originate)?
- Who will operate and maintain the facilities?

Project Example 5 in Chapter 6 expands upon the example discussed here.

Answering the previous questions can help frame a project's target audience, consisting of potential users and other stakeholders. A brief example demonstrates the general approach.

- What is the purpose and function of the existing or planned highway or street?
  - *A desire to construct a new street and upgrade existing intersections to improve access to an existing industrial area.*
  - *Considered a critical new street to attract additional businesses and associated jobs to a city.*

- What are the existing and planned land uses adjacent to and in the vicinity of the highway or street?
  - *An industrial area with existing manufacturing facilities, warehouses, and distribution centers.*
  - *The industrial area is located between the downtown business district/residential neighborhoods and a popular regional park attracting recreational bicyclists.*
- What road users will likely desire to use the highway or street given the existing and planned land uses?
  - *Heavy vehicles transporting raw materials and finished products to and from manufacturing facilities, warehouses, and distribution centers.*
  - *Bicyclists and motorists traveling to and from the regional park and downtown districts.*
- What are the existing and anticipated future socio-demographic characteristics of the populations adjacent to and in the vicinity of the existing or planned highway or street?
  - *Existing primary demographics are those associated with employees working within the industrial area. Secondary demographics are made up of a wide range of individuals traveling to/from the regional park.*
- What are the existing perceived or actual shortcomings of the existing highway or street?
  - *Insufficient connectivity within the existing industrially zoned area to enable its additional development.*
  - *Limited access from the industrial area to key regional facilities (e.g., an Interstate).*
  - *A roadway and intersection configuration that limits service to large trucks and anticipated truck volumes.*
  - *A lack of bicycle facilities to serve the bicyclists traveling to/from the adjacent regional park.*
- Who has jurisdiction over the facility?
  - *The city will have jurisdiction of the facility.*
- Where is capital funding for the project originating (or expected to originate)?
  - *The city plans to seek federal funding for part of the project.*
  - *A local improvement district (LID) and traffic impact fees from current and anticipated land owners will address other project costs.*
- Who will operate and maintain the facilities?
  - *The city will operate and maintain the primary facility (roadway and traffic control devices). A local development agency will maintain ornamental streetlights and special landscape features.*

Based on the answers to these questions, three groups of road users and other stakeholders influence whether this particular project is ultimately successful:

- Primary—heavy-vehicle operators accessing the industrial businesses and the associated industrial-oriented businesses
- Important Secondary Audience—bicyclists and motorists traveling to and from the regional park and downtown districts
- Other Participating Audience—business owners and local development agency funding lighting and landscaping features

Heavy-vehicle operators and the associated industrial-oriented businesses are the primary audience or group the project is intended to target. Their needs for access by heavy vehicles to existing and future planned industrial land uses within the subarea as well as their access to regional higher mobility facilities (e.g., an Interstate, freight rail line) should directly influence the performance measures used to evaluate design decisions.

Bicyclists and motorists traveling to and from the regional park and downtown districts are the secondary audience or group the project will influence. While they are not the targeted users of the new facility, the proximity of the new street to their desired origins and destinations will attract them to use it. Multimodal quality of service can be influenced by roadway and intersection geometric design elements. Within the project context, a decision could be made to design and construct a completely separate facility that addresses bicyclist needs with them as the primary audience (e.g., a separated multiuse path for bicyclists). The project could also move forward as one shared use facility. Evaluating both possible alternatives should include performance measures that address the transportation outcomes for bicyclists, motorists, and heavy vehicles.

Finally, the city plans to seek federal funding for a portion of the project; therefore, some of the project performance measures used to evaluate design decisions may need to reflect unique requirements of that funding source (e.g., a project's impact to wetlands). Similarly, the development district is contributing to the operations and maintenance of the facility. Their practical funding limits and ability to support future maintenance costs will need to be considered and factored into project decision making.

3.1.2 What Are We Trying to Achieve?

Being able to identify and articulate the intended project outcomes will help clarify the key project performance measures, including transportation performance measures, and the associated design elements and decisions most likely to influence whether a project will fulfill those desired outcomes. The intended project outcomes are often closely linked to who the project is intended to serve (see discussion in previous section).

The motivation for a project often originates from a planning activity or a community's expressed desire highlighting a perceived or actual need for an improvement. A project could originate for many reasons, including crash history, traffic operations (existing or forecasted), lack of pedestrian/bicycle/transit facilities, and/or a desire to attract employers to an area.

In the prior example of an industrial area, the physical ability to serve freight vehicles (including vehicle swept paths and forecasted freight volume) is a motivator for advancing complementary design elements that address existing freight movement limitations while facilitating expansion of the industrial area. The way in which a project originates often sets the framework for understanding what the project is intended to achieve.

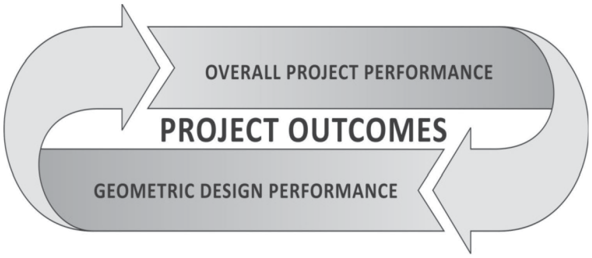
Continuing to build on the industrial area example, there may not be project performance measures to assess the degree to which a design will attract new employers. However, there are performance measures that can assess how well a design provides access and connectivity for heavy vehicles and potential employees as well as the degree to which a design balances the quality of service provided to other road users (e.g., bicyclists, transit riders). These performance characteristics of the design would, in turn, influence key elements an employer would consider in determining whether to establish a presence in the industrial area.

Performance-based analysis of geometric design can help inform discrete design decisions so that a preferred alternative design is identified and better aligned with the purpose and function of the roadway. Understanding, at the broadest level, what the project is intended to achieve sets the stage for identifying the performance categories, specific performance measures, and associated design characteristics that are critical for aligning a project to achieve the original intended outcomes.

The following section discusses how project performance can be defined once a practitioner has established and articulated who the project is intended to serve and what the project is intended to achieve.

3.2 Project Performance

3.2.1 Overview



Section 1.5 provided an overview of overall project performance and how it may influence and be influenced by geometric design performance. Overall project performance and respective performance measures depend on the nature or catalyst for the project. Section 3.1 considered "whom are we serving?" and "what are we trying to achieve?" with the intent of guiding geometric design solutions to meet user needs and achieve stakeholder objectives. Understanding whom a project is serving and the ultimate purpose or goal of a project helps identify appropriate performance measures for evaluating the effectiveness of individual design decisions. Understanding how the design elements and decisions positively or negatively impact the project performance can help assess how to best achieve desired project outcomes.

Once users and objectives are understood, the performance criteria for assessing the effectiveness of design alternatives (whether at the conceptual or more detailed design phase) can begin to be defined. Section 3.3 discusses geometric design performance, while Section 3.3.2 presents geometric design performance categories from which geometric design performance can be evaluated.

The transportation engineering and planning profession is continually evolving to a more holistic approach in how the need for improvement projects is understood and identified. It is increasingly common for transportation planning activities to include considerations such as sustainability, livability, economic vitality, societal health impacts, and environmental health impacts—and to use these considerations to identify the need for projects as well as evaluate the merit of potential projects based on their estimated impact to those broader performance categories ultimately connected to quality of life.

Measuring the effectiveness of overall project performance depends on the goal, intended outcome, nature, or catalyst for the project. Overall project performance may influence and may be influenced by geometric design decisions and their resultant performance. Geometric design choices or geometric design alternatives will have an influence on the outcomes. However, the ultimate measure of the project's success may not hinge upon the specific geometric element or value of a specific treatment, solution, or mitigation.

3.2.2 Project Performance Goals and Measures

The holistic approach evolving in the profession is consistent with values and project catalysts at the community level and is generally consistent with goals of the USDOT. The USDOT's Strategic Plan for 2012–2016 includes six strategic goals and, with one exception that is organizational, the goals generally apply to community values or agency objectives (*1*). These USDOT goals are briefly described in Exhibit 3-1, along with comments on the parallels of the goals with common community values and agency objectives.

Opportunities exist to connect the themes of the USDOT and the community with project performance measures consistent with emerging trends and national policies.

On July 6, 2012, President Obama signed into law P.L. 112-141, the Moving Ahead for Progress in the 21st Century Act (MAP-21) (*2*). MAP-21 funds surface transportation programs at over $105 billion for fiscal years 2013 and 2014. Of significance to performance-based analysis of geometric design and overall project performance is how MAP-21 transitions the Federal Aid program to a performance-based and outcome-based program. States and metropolitan areas

Exhibit 3-1. USDOT's strategic goals.

Area	Focus	Comment
Economic Competitiveness	Achieve maximum economic returns on policies and investments by implementing strategies such as developing intercity, high-speed passenger rail and a competitive air transportation system; increasing travel-time reliability in freight-significant highway corridors; improving the performance of freight rail and maritime networks; advancing transportation interests in targeted markets around the world; and expanding opportunities in the transportation sector for small businesses.	Project catalysts or objectives commonly include desires of economic development or economic vitality. This can include providing employment opportunities, supporting trade and enterprise, or providing vigor or support to local community retail, commercial, and residential areas.
Environmental Sustainability	Address the challenges associated with the environmental impacts of transportation through strategies such as fuel economy standards for cars and trucks; more environmentally sound construction and operational practices; and expanding opportunities for shifting freight from less fuel-efficient modes to more fuel-efficient modes.	In addition to efficient designs that improve capacity and mobility, air quality, noise levels, and water quality treatments and features continue to become increasingly important outcomes to communities, stakeholders, and agencies.
Livable Communities	Pursue coordinated, place-based policies and investments (e.g., coordinated transportation, housing, and commercial development policies and decisions) that increase transportation choices and access to public transportation services for all Americans.	Common project objectives are "quality of life" measures that promote balanced communities serving residential and commercial areas while preserving the nature, character, and historical significance of the community.
Organizational Excellence	Make the USDOT a high-performance, outcome-driven agency.	While not necessarily a direct project catalyst or project performance measure, there is a general interest in efficient and responsive government activities in managing and executing projects and processes.
Safety	Reduce transportation-related fatalities and injuries.	In addition to reducing crashes and resulting injuries for all users, there is an increasing awareness about the quality of experience upon a project's completion and the importance of comfort and security in using transportation facilities.
State of Good Repair	Improve the condition of transportation infrastructure by making optimal use of existing capacity, minimizing life cycle costs, and applying sound asset management principles.	Whether it is for pedestrians, cyclists, transit users, or vehicle drivers, each user values good conditions and these good conditions support some of these other strategic goals.

will explicitly show how program and project selection will help achieve a set of performance targets related to the following categories:

- Congestion reduction
- Infrastructure condition
- Environmental sustainability
- Freight movement and economic vitality
- Reduced project delivery delays
- Safety
- System reliability

These categories have common elements and themes to USDOT goals and to the way communities and stakeholders increasingly measure the success of projects. With MAP-21, agencies are required to formally establish performance measures. Many agencies have incorporated performance outcomes and goals into their strategic planning for some time. These project goals and performance targets have common elements and themes desired by the public and stakeholders as part of successful projects. Geometric design choices and considerations directly influence many of these topic areas. Conversely, the desired project performance and project outcomes can directly influence geometric design decisions. Being able to assess "geometric design performance"—the performance effects of geometric design decisions and outcomes—becomes instrumental in guiding decisions that lead to successful projects.

3.3 Geometric Design Performance

3.3.1 Overview

This chapter began by asking the fundamental questions of "whom are we serving?" and "what are we trying to achieve?" Within the context of those questions, Section 3.2 presented a discussion on the broad aspects of defining project performance by way of the project goals and themes of project performance considerations. Project goals and performance considerations provide the means of assessing how well project solutions attained desired objectives.

Chapter 2 included an overview of geometric design decisions and discussion about the relationship between intended project outcomes and corresponding performance measures. A resonant theme in these discussions is how project-level needs influence geometric design decisions and how geometric design decisions influence project outcomes. This section of the process framework focuses on geometric design performance and the considerations of how geometric design decisions influence and guide overall project performance. Geometric design performance is defined as those aspects of performance that are influenced by the roadway and roadside geometrics.

Geometric design performance can greatly influence the project outcomes and overall project performance. Specific design choices may result in certain types of speeds, operating environments, driver expectations, and safety performance. A desired overall project performance measure may be to retain the local community culture and character while improving the safety performance of a transportation facility in anticipation of increased volumes on a roadway segment or intersection. The choices made by the designer can directly influence the character of the solutions, and therefore, the ability of potential solutions to meet overall project objectives. Discrete design choices—such as median type, shoulder width, or intersection form—can directly influence the long-term expected safety and operational performance of a facility.

Overall project performance may be directly linked to the specific design choices—and the specific performance of the design alternatives considered. This section helps the user consider specific performance categories and the how design choices might influence performance measurements. The focus is on the multimodal transportation performance effects of geometric design decisions for highways and streets.

3.3.2 Geometric Design Performance Categories

Geometric design decisions for highways and streets affect overall project performance in discrete ways that ultimately may affect broader concepts such as sustainability or livability. Within the context of conducting performance-based analysis to inform geometric design in this document, the critical transportation performance categories that influence and are influenced by geometric design elements and their characteristics are of interest. These transportation performance categories are as follows and are described in the supporting subsections:

- Accessibility
- Mobility

- Quality of service
- Reliability
- Safety

Project performance can include other elements that may not be specific transportation outcomes of accessibility, mobility, quality of service, reliability, and safety. As described in Section 2.2, concepts such as environmental stewardship, livable communities, or economic development may be project performance measures that are fully or partially sensitive to geometric design decisions. The example presented in Section 3.1 focused on better serving trucks on existing facilities while attracting more freight users. It included recreational users and the need to appropriately serve non-auto users such as bicyclists and pedestrians. Geometric design performance will be influenced by discrete design choices. Considering the target project needs in terms of the five transportation performance categories allows the transportation-related results of design element choices and dimensional values to be more easily evaluated.

Design elements or choices may directly or indirectly influence project performance by how they affect the five transportation performance categories. Transportation terms can be used in many forums and venues. Terminology can be interpreted or used to support a variety of purposes. The following terms are used in this report to convey their specific application to performance-based analysis of geometric design of highways and streets.

3.3.2.1 Accessibility

Accessibility is defined as the ability to approach a desired destination or potential opportunity for activity using highways and streets (including the sidewalks and/or bicycle lanes provided within those rights-of-way). In this definition of accessibility, the ability to approach a desired destination or potential opportunity for activity is interpreted as encompassing three concepts: (1) access by a specific user type or vehicle type to use a facility, (2) the opportunities for activity near the facility, and (3) the convenience of reaching the activity destinations from different trip origins. Candidate accessibility performance measures with geometric design sensitivity are discussed in the Supplemental Research Materials Report (*3*) associated with these guidelines. They include "access to a facility by a road user type," "cumulative opportunity," and "travel impedance." As noted in the supplemental research report, these performance measures have not traditionally been considered during geometric design stages of project development, and they tend to require performance prediction tools that are typically not used by designers. Additional research in this area is needed. In this report, accessibility is captured using surrogates for accessibility performance measures that are characteristics of the infrastructure, including driveway density, transit stop spacing, and presence of pedestrian and/or bicycle facilities.

3.3.2.2 Mobility

Mobility is defined as the ability to move various users efficiently from one place to another using highways and streets. The term "mobility" can sometimes be associated with motorized vehicular movement and capacity. For the purposes of this report, "mobility" is meant to be independent of any particular travel mode. Performance measures for mobility that are sensitive to geometric design include speed and measures that involve speed (e.g., delay, travel time). As noted, these measures can be equally applied to any travel mode; however, non-motorized movement performance may be more meaningfully quantified using measures of accessibility and quality of service. Queue characteristics (e.g., queue length, queue storage ratio) and volume-to-capacity ratios also give some insights into expected levels of mobility for different travel movements. Chapter 4 also utilizes one surrogate for mobility that is a measure of the infrastructure design—inferred design speed—with the idea that inferred design speed is associated with free-flow speeds and therefore with mobility.

3.3.2.3 Quality of Service

Quality of service is defined as the perceived quality of travel by a road user. It is used in the *Highway Capacity Manual* 2010 (HCM2010; *4*) to assess multimodal level of service (MMLOS) for motorists, pedestrians, bicyclists, and transit riders. The TRB Highway Capacity and Quality of Service Committee has taken a leadership role in identifying performance measures most related to user perception of quality of service, expressed as a level of service (LOS). These measures include average travel speed, control delay, density, percent time-spent-following, driveway density, separation between motorized and non-motorized modes, amount of space provided for pedestrians and bicyclists, frequency of transit service, transit service amenities, and frequency of opportunities for pedestrians to cross a street. The latter measures are examples of those that capture infrastructure and operational characteristics that affect the quality of service experienced by non-motorized users. HCM2010 (*4*) served as the primary reference for both the primary and additional quality-of-service measures.

Quality of service may also include the perceived quality of travel by design vehicle users such as truck or bus drivers. The quality of service may differ between a geometric solution configured to regularly serve a design vehicle and one configured to accommodate the vehicle, if necessary. Quality-of-service measures may also capture user security, defined in this document as users' perceptions of safety.

3.3.2.4 Reliability

Reliability is defined as the consistency of performance over a series of time periods (e.g., hour-to-hour, day-to-day, year-to-year). Reliability has become a critical transportation performance measure over the last decade, as evidenced by its role as a theme in the second Strategic Highway Research Program (SHRP 2) and in performance-based decision-making aspects of MAP-21 (*2*). Reliability of transportation service is commonly linked to travel-time variability, but the basic concept applies to any other travel-time-based metric (e.g., average speed, delay). Reliability is sensitive to geometric design, because the geometric design may affect the ability of a highway or street to "absorb" random, additional traffic demand as well as capacity reductions due to incidents (e.g., crashes, vehicle breakdowns), weather, and maintenance operations, among others. Reliability also is indirectly related to geometry inasmuch as the geometry affects the frequency and severity of random events that impact travel time (e.g., crashes). A more detailed discussion of the expected relationships between reliability and the geometric design of highways and streets is provided in the Supplemental Research Materials Report associated with these guidelines (*3*).

3.3.2.5 Safety

Safety is defined as the expected frequency and severity of crashes occurring on highways and streets. Expected crash frequencies are often disaggregated by level of crash severity and crash type, including whether or not a crash involves a non-motorized user or a specific vehicle type (e.g., heavy vehicle, transit vehicle, motorcycle). Measures that combine crash frequencies and severities into a common unit (e.g., crash cost, equivalent property damage only, relative severity index) are sometimes used when comparing design alternatives.

3.3.3 Role/Influence of Geometric Design Features

The role or influence of geometric design on transportation performance is relatively well documented for some performance categories compared to others. In some cases, the role of geometric design has a clear relationship to specific performance category outcomes. For example, there is relatively extensive documentation related to safety performance functions or crash modification factors of various geometric forms or elements (e.g., roundabouts compared to signalized intersections, paved shoulders compared to unpaved shoulders, left-turn-lane presence at intersections).

However, there is comparatively less information about the role of geometric elements on reliability and accessibility. In the case of reliability, the presence of shoulders or shoulder width and construction type may improve reliability by allowing incidents to be removed from the traveled way more efficiently, or by allowing through traffic to use the shoulder when one or more travel lanes are blocked. Full-width, hard shoulders are sometimes used as travel lanes in managed motorway facilities during peak periods. The presence of sidewalks or magnitude of roadway grade may influence pedestrian accessibility and quality of service, but there may not be a way to predict a related performance metric to differentiate between design choices. Another example is the difference in performance of a 4-ft-wide sidewalk versus a 6-ft-wide one. If a local jurisdiction requires a minimum sidewalk width of 4 ft, providing that width in the project may meet code compliance but might not necessarily provide the optimal performance level for users. In these cases, combining information from various sources could help inform performance-based decisions to a level that is currently practical. In this sidewalk-width example, applying the HCM2010 (*4*) MMLOS evaluation procedures could help a designer assess the relative expected quality of service of alternative sidewalk widths independently of whether the width complies with an agency's design criteria. Accessibility performance may not be quantifiable in this case, and subjective judgments may still be needed (e.g., the magnitude of roadway grade likely increases pedestrian travel impedance, reducing pedestrian accessibility).

Exhibit 3-2 presents performance categories and identifies how well the defined role and influence of geometric design features have been documented. The exhibit also highlights some of the national reference documents that include geometric design elements as inputs or contributors to performance prediction procedures. Chapter 4 will summarize current information on the relationships between geometric design elements, design decisions, and their specific performance effects. The information in Chapter 4 will be used to identify key geometric characteristics for supporting the desired project outcomes. This will be useful information in developing potential solutions that make progress towards the intended project outcomes as measured within the transportation performance categories.

3.3.4 Geometric Design Decisions

Geometric design decisions should consider overall intended project outcomes, project performance, and transportation performance. Specifically, geometric design decisions should be made considering how the features or qualities of the features may influence performance measures related to accessibility, mobility, quality of service, reliability, and safety. Designers make these choices considering intended project outcomes and understanding how the performance categories or specific performance measures may influence geometric characteristics and decisions. By understanding a process framework for considering performance-based evaluations of geometric design of highways and streets (outlined in Chapter 5), professionals will have a systematic, flexible, and adaptable range of activities to inform design choices.

Geometric design decisions for highways and streets may have incremental and cumulative effects. Discrete choices may ultimately impact broader concepts such as sustainability, economic competitiveness, or livability. Within the context of conducting performance-based analysis to inform geometric design decisions, one must first consider the identified project needs and set forth the appropriate design controls consistent with an overall project or specific design context. Design controls help establish a baseline from which to measure design performance. For example, 10-ft-wide vehicle travel lanes may be desired to provide bike or parking lanes or to

Exhibit 3-2. Documentation levels of the defined role/influence of geometric design features.

Performance Category	Defined Role/Influence of Geometric Design Features: Well Documented	Moderate Documentation	Limited Documentation	Reference Documents
Accessibility		X		• Fundamental access concepts/definitions [from FHWA's Functional Classification Guidelines, TRB's *Access Management Manual* (*5*)] • *Transit Capacity and Quality of Service Manual* (*6*) • HCM2010 (*4*) • Published literature on accessibility [references in Supplemental Research Materials Report (*3*)]
Mobility	X			• HCM2010 (*4*) • *FHWA Speed Concepts: Informational Guide* (*7*) • *NCHRP Report 672: Roundabouts: An Informational Guide* (*8*)
Reliability			X	• Reports from SHRP 2 Projects L07 and L08 (*9*, *10*) • Published literature on reliability [references in Supplemental Research Materials Report (*3*)]
Safety		X		• *Highway Safety Manual* (*11*) • Final report of NCHRP Project 17-45/ Enhanced Interchange Safety Analysis Tool (ISATe) (*12*) • Crash Modification Factors Clearinghouse (*13*) • *NCHRP Report 687: Guidelines for Ramp and Interchange Spacing* (*14*)
Quality of Service		X		• HCM2010 (*4*)

maximize shoulder width within the paved right-of-way. This may be adequate in serving tractor trailer vehicles (e.g., WB-62) on a collector roadway in a tangent section, but the turning paths of this design vehicle may dictate wider lanes on curved portions of the roadway to accommodate off-tracking on turning roadways.

Understanding the intended project outcomes helps define the design controls and allows a designer to customize the design elements to each project's contextual design environment.

Identifying project design controls (intended operating speeds, design vehicle type, driver performance, and human factors) leads to appropriate design criteria to meet those design control needs. Understanding the intended project outcomes helps define the design controls and allows a designer to customize the design elements to each project's contextual design environment. This applies whether the context is a complex urban freeway or right-turning movements at an at-grade intersection. Geometric design decisions are influenced by the project considerations and specifically by the choices needed to define the elements of segments and nodes. Segments define the character of the corridor or design element. Nodes define the qualities and attributes of the intersecting roadways and can include intersections or interchanges. The design decisions of an interchange can include investigating appropriate ramp terminal intersection forms.

3.3.5 Project Design Controls and Influences

The street or highway function fundamentally influences geometric design decisions. In many cases, functional classification and hierarchies of movements help define the characteristics of facility features for roadway segments and nodes. However, there are frequent cases with no clear definition of or agreement on the facility type or, sometimes, even the facility function. A state transportation agency has the responsibility of managing the National Highway System (NHS). These specific, designated facilities consist of roadways important to the nation's economy, defense, and mobility. As such, transportation agencies are responsible for managing, maintaining, and operating these facilities to meet those needs. However, NHS facilities run through communities and, while passing through communities, may have additional purposes, for example, being the city's main street or other key arterial network component serving community needs that differ from national defense or pure mobility. In these cases, design controls and the selected elements of design must be evaluated with a broader lens, that of meeting national objectives while considering and (to the extent possible) adapting to local community needs.

3.3.5.1 Speed Concepts and Design Decisions

Understanding the project context helps establish project limits, modal connection and integration, node type (intersections versus interchanges), capacity targets, access management strategies, and other features influencing geometric design decisions. The jurisdiction(s) engaged with the segments or nodes help establish applicable design standards that can be augmented with national and state guidelines and customary practices. One of the key elements influencing geometric design decisions is that of "speed." While often considered as "design speed," there are numerous other speed-related considerations with the ability to significantly influence geometric design choices. The designated design speed is used explicitly for determining minimum, maximum, and ranges of values for highway design such as minimum horizontal curve radius, minimum sight distance, and maximum grade. The designated design speed influences a number of geometric design elements and, therefore, the ability to consider design speeds in combination with posted and intended operating speeds could help refine geometric design decisions by establishing "target" operating speeds for each unique project context.

Actual operating speeds (i.e., 85th percentile free-flow speed) may be different than both the design speed and the originally intended posted speed. The differences become more substantial for "intermediate" and "lower" speed facilities. The FHWA's *Speed Concepts: Informational Guide* (*7*) introduces the concept of "inferred design speed." Inferred design speed is applicable to features and elements that have a criterion based on (designated) design speed (e.g., vertical curvature, sight distance, superelevation). The inferred design speed of a feature may be different than the designated design speed and provides designers with the ability to consider side friction, superelevation, and lateral acceleration to potentially tailor vertical and horizontal alignment decisions with intended speed-related outcomes.

3.3.5.2 Sight Distance Concepts

Chapter 3 of the 2011 *A Policy on Geometric Design of Highways and Streets* (AASHTO Green Book) (*15*) provides a complete summary of sight distance concepts and their associated design elements. Sight distance concepts are summarized for stopping, decision, and passing conditions. Stopping sight distance values result in geometric configurations allowing drivers to perceive, react, and stop to avoid collision. Decision sight distance provides additional time to interpret possible choices and react to complex conditions such as at an interchange or intersection. Passing sight distance supports complete passing maneuvers. Intersection sight distance concepts are well presented in *NCHRP Report 383: Intersection Sight Distance* (*16*), which provides a comprehensive overview of the concept. Intersection sight distance is intended to provide drivers at or approaching intersections with an unobstructed view of the entire intersection and of sufficient lengths of the intersecting highways to permit the approaching drivers to anticipate and avoid collisions.

The methods of determining the criterion for a particular sight distance type are related to speed. Fundamentally, higher speeds mean a driver travels a greater distance during the perception and reaction time compared to a lower speed. Therefore, higher speeds can have an effect on requisite sight distance values, which, in turn, can increase the nominal dimensions of design elements. Therefore, selecting an appropriate target speed and understanding the potential inferred speeds of a facility can provide designers with more flexibility and precision in selecting design values for those geometric features that are directly influenced by design speed. Ultimately, this approach could provide designers with more flexibility to meet desired performance targets through their informed geometric design decisions.

3.3.5.3 Design Choices for Segments and Nodes

While geometric design is presented in final plan sets consisting of basic plan, profile, and cross section, the number of design choices possible within these three-dimensional categories is vast. The resulting performance for these design elements is not necessarily documented for each and every element nor is the interactions between them fully documented or known. Exhibit 3-3 lists example design choices for segments and nodes. The sheer number of elements provides

Exhibit 3-3. Example design choices for segments and nodes (intersections and interchanges).

Segments	Nodes
• Access points and density • Design speed and target speed • Horizontal alignment • Number of travel lanes • Sidewalk and pedestrian facilities • Bicycle accommodation features • Transit accommodation features • Design vehicle accommodation • Median provisions • Travel lane widths • Auxiliary lane widths • Type and location of auxiliary lanes • Shoulder width • Shoulder type • Lane and shoulder cross slopes • Superelevation • Roadside design features • Roadside barrier • Minimum horizontal clearance • Minimum sight distance • Maximum grade • Minimum vertical clearance • Vertical alignment • Bridge cross section • Bridge length/termini • Rumble strips	• Intersection form, control type, and features • Interchange form and features • Design speed and target speed • Number and types of lanes • Sidewalk and pedestrian facilities • Bicycle accommodations facilities • Transit accommodations facilities • Special/vulnerable user treatments • Design vehicle accommodations • Traffic islands • Lane widths • Auxiliary lane lengths • Shoulder width and composition • Approach or ramp cross section • Horizontal alignment of approaches or ramp • Mainline ramp gores and terminals • Cross road ramp terminals • Vertical alignment of approaches or ramp • Auxiliary lane terminals and transitions • Pavement cross slope and superelevation • Intersection sight distance • Median opening configuration • Curve tapers & radii • Ramp roadside • Ramp barriers

designers with many degrees of freedom in creating geometric designs to meet the wide array of project contexts. From this exhibit, it is easy to see how design choices for segments and nodes (intersections and interchanges) include similar broad categories of plan, profile, and cross section. The design of a ramp proper will closely mimic the design elements and process of roadway segments.

3.4 Summary

This chapter began by first considering, fundamentally, who is being served and what a project is trying to achieve. It continued with a discussion of how to consider and define project performance. That led to defining geometric performance, a subset of which included transportation performance—the focus of this document. The transportation performance was divided into performance categories that could help support overall project objectives. This chapter concluded by considering the role and influence of geometric design features on achieving project outcomes and desired project performance.

Chapter 4 presents a series of tables and other information to help identify which geometric features may influence performance measures related to accessibility, mobility, quality of service, reliability, and safety—and, in turn, which performance measures may influence geometric characteristics and decisions. Chapter 5 presents a performance-based analysis application framework for incorporating performance-based evaluations into the geometric design of highways and streets. Chapter 6 includes project examples intended to reinforce the principles and approach outlined in this report while guiding the user through the application framework.

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CHAPTER 4

Geometric Design Elements

4.1 Introduction

This chapter presents information regarding the relationships between geometric design elements and performance measures for the categories described in Chapter 3. The information presented in this chapter focuses on the established and known relationships between geometric design elements and the performance of highways and streets. In some cases, surrogate performance measures are presented where knowledge is limited (e.g., accessibility) or where the surrogate provides a meaningful design assessment (e.g., inferred design speed). There is a wide range of relationships the broader transportation profession continues to research to be able to better quantify and describe those relationships. While future applied research will continue to document and summarize relationships between geometric design decisions and associated performance measures, the information in this chapter mainly highlights the current state of practice. This information and the process framework outlined in Chapter 5 are intended to set a pattern for the future, with flexibility to adapt to new research findings for maximum, long-term utility. In summary, while this report is static, the geometric design and performance relationships will continue to evolve. The process framework is intended to be adaptive to future research findings, methodologies, and tools.

The Supplemental Research Materials Report (*1*) documents opportunities for additional research to better support performance-based analysis of geometric design. This chapter focuses on key established and direct relationships between performance measures and geometric design elements so practitioners are able to direct their attention to geometric elements and design decisions most likely to affect the performance characteristics that are most applicable to a given project or design. The early chapters of this report emphasized understanding and defining overall project outcomes, project performance, and geometric design performance. This chapter is intended to support geometric design evaluations and decision making by summarizing information about the relationships between geometric design decisions and performance measures related to accessibility, mobility, quality of service, reliability, and safety.

The intent of this chapter is to summarize the critical or high-priority known relationships between design elements and performance, document the general relationship, identify possible performance tradeoffs, and present resources and tools that can be used to analyze a given design decision's impact on performance measures in greater detail. Chapter 5 presents an application process for integrating this information into a performance-based analysis framework to inform geometric design decisions on projects within various stages of development. Chapter 6 presents project examples that (1) reinforce the background and foundational concepts of Chapters 1, 2, and 3; (2) apply the process framework described in Chapter 5; and (3) integrate specific example applications of the geometric design performance relationships presented in this chapter.

4.2 Geometric Sensitivity

A key fundamental concept in performance-based analysis to inform design decisions is geometric sensitivity. Geometric sensitivity refers to the degree to which varying the dimensions related to a geometric element has an impact on performance. It is at the core of what performance-based analysis is intended to communicate to practitioners. For example, geometric sensitivity is at the heart of being able to answer: In terms of crash expectancy, how much of a difference is there between a horizontal curve with a 1,000 ft radius and a horizontal curve with 1,100 ft radius? The degree to which crash frequency is sensitive to changes in curve radius for a given context is the relationship that will help practitioners accurately answer that question and make informed decisions regarding design tradeoffs.

More precisely, geometric design sensitivity refers to a relationship that shows an expected impact on some aspect of transportation performance as a direct result of a geometric design decision. The level of sensitivity refers to the amount of the impact. Some relationships are highly sensitive (e.g., number of travel lanes versus passenger car mobility); others are less sensitive (e.g., lane width and average travel speed). Certain relationships are sensitive only for certain ranges of geometric dimensions. An example is provided in Exhibit 4-1, which shows the relationship between horizontal curve radius, operating speed, and the change in expected crash frequency. Horizontal curve radius influences vehicle operating speeds; however, operating speed is relatively insensitive to curve radius until the radius falls below approximately 1,000 ft. Similarly, the expected crash frequency is insensitive to curve radius until the horizontal curve radius falls below 1,000 ft.

NCHRP Report 687: Guidelines for Ramp and Interchange Spacing (*9*) provides a similar example of the geometric design sensitivity of ramp spacing on predicted safety. Exhibit 4-2, taken from *NCHRP Report 687* (*9*) for entrance-exit configurations (EN-EX), shows there is little change to relative crash risk as ramp spacing values increase beyond 2,600 ft. Similarly, it shows increasing relative crash risk as ramp spacing values decrease from 1,200 ft.

In many cases, geometric design sensitivity is expected but has not been uncovered by research to date. For example, research conducted to create the HSM chapter on urban and suburban arterials began with the expectation that "an understanding of the relationship between lane width and safety is central to design decision making concerning urban and suburban arterials." However, the research concluded that "No consistent relationship was found between lane width and safety. Therefore, lane width was not included in the model [predictive method]." This does not necessarily mean that safety is insensitive to lane width on urban and suburban roads, only that the relationship was not uncovered by this particular research.

Exhibit 4-1. Relationship between horizontal curve radius and speed (*11*).

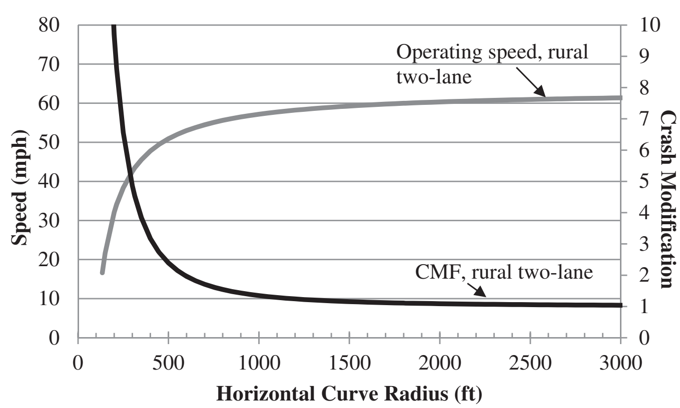
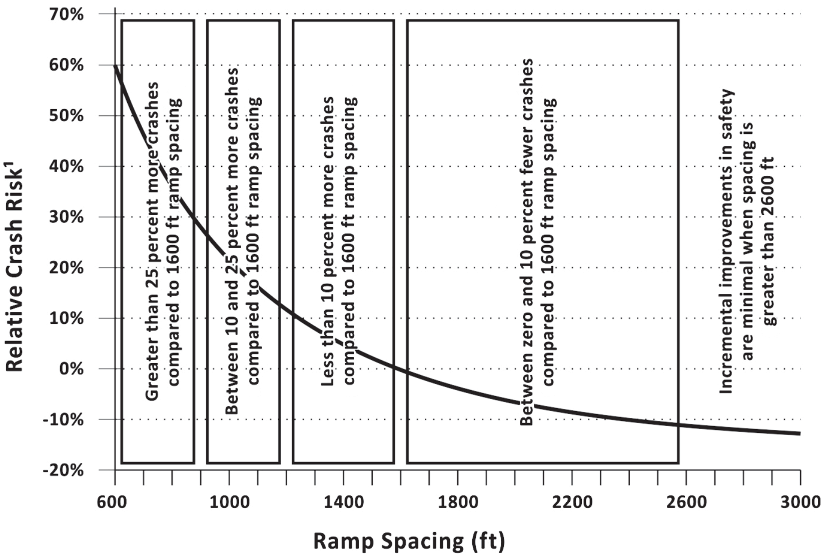


Exhibit 4-2. Preliminary safety assessment tool for ramp spacing: entrance ramp followed by exit ramp (*9*, Exhibit 5-5).



[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.

4.3 Relationships between Geometric Design Elements and Performance Categories

The information presented in this section has been assembled from a number of published documents and research findings. A full list and description of resources consulted is provided in the Supplemental Research Materials Report (*1*). Key resources included AASHTO's *Highway Safety Manual* (*2*); *Highway Capacity Manual* 2010 (HCM2010) (*3*); *Transit Capacity and Quality of Service Manual*, Second Edition (*4*); FHWA's *Speed Concepts: Informational Guide* (*5*); draft HSM chapters for freeways and interchanges developed as part of NCHRP Project 17-45, "Enhanced Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges" (*6*); Interactive Highway Safety Design Model (*7*); procedures in macroscopic, mesoscopic, and microscopic simulation tools; and published and ongoing research that includes significant aspects of geometric design and performance relationships.

The information in this section mainly focuses on presenting high-priority, well-established, and direct relationships between geometric design decisions and performance. Practitioners should also be aware of the broader range of expected relationships, since there are likely relationships that exist but have not yet been clearly defined, quantified, and documented because of limitations in data, analysis techniques, and other similar challenges. The remainder of this section identifies expected or likely relationships between performance and geometric elements, even if they have not been uncovered by research or published findings. The information on "expected" or "likely" relationships is summarized in Exhibits 4-3 through 4-5, which provide the expected relationships between geometric design elements and performance categories for segments, intersections, and interchanges, respectively. The process used to arrive at these exhibits is described in the Supplemental Research Materials Report (*1*) associated with these guidelines and is also summarized in the following paragraphs.

The research team used three possible notations to classify each geometric characteristic or design decision and performance category combination as either "expected direct effect,"

Exhibit 4-3. Segments: expected geometric elements and performance relationships.

Segment Geometric Elements/Characteristics	Accessibility	Mobility	Quality of Service	Reliability	Safety
Access points and density	●*	●*	●*	□◇	●*
Design speed and target speed	—	□◇	□◇	□◇	□*
Horizontal alignment	—	●◇	●◇	□◇	●*
Number of travel lanes	●*	●*	●*	□*	●*
Sidewalk and pedestrian facilities (including ADA)	●	●*	●*	□x	●x
Bicycle accommodation features	●	●*	●*	□x	●x
Median provisions	●◇	●*	●*	□◇	●*
Travel lane width(s)	●◇	●*	●*	□*	●*
Auxiliary lane width(s)	●x	●x	●x	□x	●x
Type and location of auxiliary lanes	●◇	●*	●*	□◇	●*
Shoulder width(s) and composition	●◇	●*	●*	□*	●*
Shoulder type(s)	●◇	●x	●x	□◇	●*
Lane & shoulder cross slopes	—	—	—	□x	●x
Superelevation	—	●x	●x	□◇	●*
Roadside design features	●x	●x	●x	□x	●*
Roadside barriers	●◇	●*	●*	□◇	●*
Minimum horizontal clearances	●◇	●*	●*	□◇	●*
Minimum sight distance	●x	●x	●x	□x	●x
Maximum grade(s)	□◇	□*	□*	□◇	□*
Minimum vertical clearances	●◇	□x	□x	□x	□x
Vertical alignment(s)	—	●*	●*	□*	●*
Bridge cross section	●◇	●*	●*	□*	●*
Bridge length/termini	—	—	—	□◇	●*
Rumble strips	●◇	—	—	□x	●*

● = expected direct effect
□ = expected indirect effect
— = expected not to have an effect
* = relationship can be directly estimated by existing performance prediction tools
◇ = relationship can be indirectly estimated using more than one existing tool
x = relationship cannot be estimated by existing tools

"expected indirect effect," or "no expected effect." These classifications are based on the research team's professional opinion drawing from members' knowledge of the state of related research. A definition of each classification is as follows:

- **Expected direct effects** are performance effects caused by the geometric design decision that occur at the same time and place (e.g., a given horizontal curve radii affects expected crash frequency at that location immediately).

Exhibit 4-4. Intersections: expected geometric elements and performance relationships.

Intersection Geometric Elements/Characteristics	Accessibility	Mobility	Quality of Service	Reliability	Safety
Intersection form, control type, and features	●◇	●*	●*	□x	●*
Number and types of lanes	●◇	●*	●*	□x	●*
Sidewalk and pedestrian facilities (including ADA)	●*	●*	●*	□x	●x
Bicycle accommodation facilities	●*	●*	●*	□x	●x
Design vehicle accommodations	□x	□x	□x	□x	□x
Traffic islands	●x	●x	●x	□x	●x
Lane widths	●x	●x	●x	□x	●x
Auxiliary lane terminals and transitions	●◇	●*	●*	□x	●x
Shoulder width and composition	●x	●x	●x	□x	●x
Horizontal alignment of approaches	●x	●x	●x	□x	●*
Vertical alignment of approaches	●◇	●*	●*	□x	●*
Pavement cross slope and superelevation	—	—	—	□x	●x
Intersection sight distance	●x	●x	●x	□x	●x
Median opening configuration	●◇	●◇	●◇	□x	●x
Curve tapers and radii	●x	●x	●x	□x	●x

● = expected direct effect
□ = expected indirect effect
— = expected not to have an effect
* = relationship can be directly estimated by existing performance prediction tools
◇ = relationship can be indirectly estimated using more than one existing tool
x = relationship cannot be estimated by existing tools

- **Expected indirect effects** are performance effects caused by the geometric design decision that occur later in time (e.g., providing additional auto capacity induces more auto travel) or farther removed in distance. Indirect effects may include growth-inducing effects and other effects related to induced changes in the pattern of land use and traffic patterns from the geometric change. For example, a new interchange providing access to a freeway may result in travel pattern changes on the freeway and surrounding surface streets, thus impacting mobility and safety on those facilities. This would be noted as an indirect effect. In some instances, indirect effects may influence the intended project outcomes and so, to the extent possible, the potential implications of indirect effects should be considered. In this example, the new interchange would increase vehicle traffic on a street or connecting streets that did not have access to the freeway before. This new access could increase network connectivity and achieve goals of increasing economic competitiveness and vitality. However, the increase in motorized traffic could affect quality of service for pedestrians and bicyclists. It may also influence businesses along the street that now have access and increased exposure to potential patrons. There would obviously also be direct safety and operational effects due to the presence of the new ramp terminals immediately at the terminal locations.

Exhibit 4-5. Interchanges: expected geometric elements and performance relationships.

Interchange Geometric Elements/Characteristics	Accessibility	Mobility	Quality of Service	Reliability	Safety
Interchange form and features	●◊	●◊	●x	□x	●*
Sidewalk and pedestrian facilities (including ADA)	●x	●x	●x	□x	●x
Bicycle accommodation facilities	●x	●x	●x	□x	●x
Auxiliary lane lengths	●◊	●*	●*	□x	●*
Horizontal alignment of ramp	●◊	●◊	●x	□x	●*
Vertical alignment of ramp	●x	●x	●x	□x	●x
Pavement cross slope and superelevation	●x	●x	—	□x	●x
Ramp cross section	●◊	●*	●*	□x	●*
Mainline ramp gores and terminals	●◊	●*	●*	□x	●*
Ramp roadside	●x	●x	—	□x	●x
Ramp barriers	●x	●x	●x	□x	●*
Cross road ramp terminals	●◊	●*	●*	□x	●*

● = expected direct effect
□ = expected indirect effect
— = expected not to have an effect
* = relationship can be directly estimated by existing performance prediction tools
◊ = relationship can be indirectly estimated using more than one existing tool
x = relationship cannot be estimated by existing tools

- **No expected effect** expresses that the geometric characteristic or design decision is not expected to impact the respective aspect of performance, either directly or indirectly.

A second set of notations in Exhibits 4-3 through 4-5 indicates whether the expected relationship has been uncovered by research and is included as part of a performance prediction tool, an accepted publication, or other knowledge base. The secondary notation classifies each relationship as one of the following:

- The relationship can be directly estimated by existing performance prediction tools.
- The relationship can be indirectly estimated using more than one existing tool or supplemental calculations.
- The relationship cannot be estimated by existing tools.
- Not applicable (i.e., the relationship is not expected to exist).

Exhibits 4-3 through 4-5 presented what direct and indirect relationships are expected to exist as well as related, current performance prediction capabilities. The many gaps in the profession's knowledge base highlight the importance of additional research to better understand the effect our design decisions have on different performance categories. The following section, Section 4.4, presents the critical performance measures for each performance category that are expected to influence or are influenced by geometric elements. Section 4.4 is limited in scope to allow practitioners to focus attention on the performance measures and geometric elements most likely to substantially influence the degree to which a project is able to meet its intended project outcomes from a transportation performance perspective.

4.4 Performance Categories and Measures

This section presents information about design elements/decisions related to segments, intersections, and interchanges and their relationship to performance measures from each of the transportation performance categories identified and defined in Chapter 3. In some cases, surrogates for transportation performance are presented where knowledge is limited (e.g., accessibility) or where the surrogate provides a meaningful design assessment (e.g., inferred design speed). Information is organized by basic facility type (i.e., segment and node—interchange or at-grade intersection) and performance category. Interchanges can, in general, be treated as a series of segments and intersections. In a few instances, they are identified as a specific facility type. Performance measures associated with segments and intersections can also typically be applied to interchanges. For example, the design of an interchange ramp proper closely mimics the design process and elements of roadway segments. Ramp terminal intersection treatments at service interchanges follow the design considerations of at-grade intersections.

4.4.1 Accessibility

Accessibility is defined as the ability to approach a desired destination or potential opportunity for activity using highways and streets (including sidewalks and/or bicycle lanes).

Exhibit 4-6 summarizes, by facility type, the performance measures specific to access and accessibility, the sensitive geometric design elements influencing those performance measures, the basic relationship between the design element and the performance measure, potential tradeoffs between the design element and the performance of other transportation elements, and resources that can be used to evaluate the sensitivity of that geometric relationship in greater detail.

Exhibit 4-6. Access and accessibility performance measures.

Facility Type	Performance Measure	Definition	Geometric Design Elements	Basic Relationship	Potential Performance Tradeoffs	Evaluation Resources
Segment	Driveway density	Number of driveways per mile	Access points and density	Higher density of driveways associated with higher motor vehicle access	Degrades bicycle LOS, increases crash likelihood, increases average travel speed	HCM2010 Chapters 16 and 17 (*3*), HSM Part C Chapters (*2*)
Urban/ Suburban Segment	Transit stop spacing	Distance between transit stops along a roadway segment	Transit accommodation features	Higher frequency increases access for transit riders	Increases transit travel time and may degrade mobility for other vehicle modes	*Transit Capacity and Quality of Service Manual* (*4*)
Segment	Presence of pedestrian facility	Presence of a sidewalk, multiuse path, or shoulder	Sidewalk and pedestrian facilities	Greater connectivity and continuity of pedestrian network increases access for pedestrians	Implementing pedestrian facilities in a constrained environment may require removing capacity or parking for vehicle mode	HCM2010 Chapters 16 and 17 (*3*)
Segment	Presence of bicycle facility	Presence of bicycle lanes, multiuse path, or shoulder	Bicycle accommodation features	Greater connectivity and continuity of bicycle network increases access for bicyclists	Implementing bicycle facilities in a constrained environment may require removing capacity or parking for vehicle mode	HCM2010 Chapters 16 and 17 (*3*)

The performance measures shown in Exhibit 4-6 are intended to document critical considerations related to access and accessibility and design considerations. The measures are focused on elements that would be considered and would be influential within the alternatives identification and evaluation, preliminary design, and final design stages of the project development process. There are system-level accessibility and access metrics that would be more applicable within broader system-wide planning activities. System-wide access or accessibility metrics could consider broader access issues such as access to transit for transportation-disadvantaged populations and/or freeway or highway access to industrial areas that may serve as an attractor for potential employers. These system-level access considerations support identifying future transportation network needs. In the broadest sense, these considerations are often influenced by identifying and trying to attain overall project outcomes. The intent of the performance measures in Exhibit 4-6 is to identify access and accessibility considerations that are directly applicable at the project level.

4.4.2 Mobility

Mobility is defined as the ability to move various users efficiently from one place to another using highways and streets.

Exhibit 4-7 summarizes, by facility type, the performance measures specific to mobility, the sensitive geometric design elements influencing those performance measures, the basic relationship between the design element and the performance measure, potential tradeoffs between the design element and the performance of other transportation elements, and resources that can be used to evaluate the sensitivity of that geometric relationship in greater detail.

Improving many of the mobility-oriented performance measures shown in Exhibit 4-7 for vehicles has the potential to negatively affect the quality of service for pedestrians, bicyclists, or transit users. The tradeoff that often occurs in providing additional vehicle capacity is increased motor vehicle speeds. Increased speeds are associated with lower quality of service (e.g., lower comfort and safety) for pedestrian, bicycle, and transit modes. Additional vehicle capacity can also come at the expense of providing pedestrian or bicycle facilities. However, in some cases, providing a bicycle lane can provide a de facto shoulder or a shoulder can serve as a de facto bicycle lane. The concept of using inferred speed as a performance measure that is able to inform geometric design decisions is illustrated in Chapter 6, Project Example 2.

4.4.3 Quality of Service

Quality of service is defined as the perceived quality of travel by a road user. It is used in the HCM2010 to simultaneously assess LOS for motorists, pedestrians, bicyclists, and transit riders (i.e., MMLOS). It may also include the perceived quality of travel by users of larger vehicles such as trucks or transit vehicles.

Exhibit 4-8 summarizes, by facility type, the performance measures specific to quality of service, the sensitive geometric design elements influencing those performance measures, the basic relationship between the design element and the performance measure, potential tradeoffs between the design element and the performance of other transportation elements, and resources that can be used to evaluate the sensitivity of that geometric relationship in greater detail.

The quality of service metrics summarized in Exhibit 4-8 represent a combination of recent advancements in how the transportation profession understands, evaluates, and attempts to quantify quality of travel experience for different road users and fundamental considerations related to critical design vehicles that need to be served within a project. Ongoing research on multimodal quality of service especially related to pedestrian and bicycle quality of service will

Exhibit 4-7. Mobility performance measures.

Facility Type	Performance Measure	Definition	Geometric Design Elements	Basic Relationship	Potential Performance Tradeoffs	Evaluation Resources
Segment	Average travel time	The mean amount of time it takes a road user to travel from one point to another point along a roadway segment	Number of travel lanes	Increased vehicle lanes decrease average travel time for autos and increases vehicle speed	Degrades quality of service for pedestrians and bicyclists Degrades mobility for pedestrians and bicyclists Higher vehicle speeds are associated with higher severity crashes	HCM2010 Chapters 10 Freeway Facilities, Chapter 14 Multilane Highways, Chapter 15 Two-Lane Highways, Chapter 16 Urban Streets (*3*)
Segment	Inferred speed	The maximum speed for which all critical design-speed-related criteria are met at a particular location	Horizontal alignment, vertical alignment, and cross section	Higher inferred speeds associated with higher free-flow speeds and higher mobility	Higher vehicle speeds are also associated with higher severity crashes	*FHWA Speed Concepts: Informational Guide* (*5*)
Two-Lane Segment	Average percent time spent following	The average percentage of total travel time that vehicles must travel in platoons behind slower vehicles due to an inability to pass	Horizontal and vertical alignment, sight distance, type and location of auxiliary lanes	Increased opportunities to pass slow-moving vehicles reduces percent time spent following, providing a passing lane can reduce crashes	Increases vehicle speeds, increases potential for higher severity crashes	HSM Chapter 10 (*2*); HCM2010 Chapter 15 (*3*)
Freeway Segment	Freeway speed	The freeway speed down-stream of an entrance ramp and before an exit ramp or another entrance ramp	Ramp spacing dimensions as defined in *NCHRP Report 687* Use of downstream auxiliary lane	At relatively high exit ramp volumes, ramp spacing affects freeway speeds	Decreased freeway speeds are possible with decreased ramp spacing An auxiliary lane may improve freeway speeds	*NCHRP Report 687* (*9*); HCM2010 Chapters 11, 12 and 13 (*3*)
Intersection	Delay	Average control delay experienced by road users at an intersection	Intersection form, control type, and features; number and types of lanes	Lower control delay for any road user improves mobility for that mode	Often tradeoffs occur between delay experienced by different modes depending on the type of traffic control present	HCM2010 Chapters 18 through 22 (*3*); *NCHRP Report 672* (*8*)
Intersection	Volume-to-capacity (v/c) ratio	The ratio of volume present or forecasted and the available capacity at the intersection	Intersection form, control type, and features; number and types of lanes	Increased vehicle capacity associated with lower v/c ratios	Degrades quality of service for pedestrians and bicyclists Degrades mobility for pedestrians and bicyclists	HCM2010 Chapters 18 through 22 (*3*); *NCHRP Report 672* (*8*)

Exhibit 4-8. Quality of service performance measures.

Facility Type	Performance Measure	Definition	Geometric Design Elements	Basic Relationship	Potential Performance Tradeoffs	Evaluation Resources
Urban/ Suburban Segment	Pedestrian LOS	A letter grade associated with the quality of travel experience for a pedestrian; based on HCM2010 methodology	Sidewalk and pedestrian facilities, width of pedestrian lanes, buffer from vehicle traffic, driveway density, crossing frequency	Increasing width of pedestrian facility, increasing distance from vehicle traffic, decreasing driveway density, and increasing opportunities to cross a street improve pedestrian LOS	Meeting performance metrics for pedestrians may degrade travel quality for other modes – e.g., on-street parking improves pedestrian LOS and degrades bicycle LOS	HCM2010 Chapters 16 and 17(*3*)
Urban/ Suburban Intersections	Pedestrian LOS	A letter grade associated with the quality of travel experience for a pedestrian; based on HCM2010 methodology	Crossing distance, traffic control delay	Decreasing pedestrian crossing distance and delay to cross a street improves pedestrian LOS	Meeting performance metrics for pedestrians may degrade travel quality for other modes	HCM2010 Chapters 16 and 17 (*3*)
Urban/ Suburban Segment	Bicycle LOS	A letter grade associated with the quality of travel experience for a bicyclist; based on HCM2010 methodology	Bicycle accommodation features, physical separation from motor vehicle traffic, access points and density, on-street parking	Increasing width of bicycle facility, decreasing driveway density, increasing separation from moving vehicle traffic, and removing on-street parking improves bicycle LOS	Meeting performance metrics for bicyclists may degrade travel quality for other modes	HCM2010 Chapters 16 and 17 (*3*)
Urban/ Suburban Intersections	Bicycle LOS	A letter grade associated with the quality of travel experience for a bicyclist; based on HCM2010 methodology	Traffic control delay	Decreased delay for bicyclists increases quality of travel experience	Meeting performance metrics for bicyclists may degrade travel quality for other modes	HCM2010 Chapters 16 and 17 (*3*)
Urban/ Suburban Segments and Intersections	Transit LOS	A letter grade associated with the quality of travel experience for a transit rider; based on HCM2010 methodology	Transit accommodations facilities (presence of transit-only lane, bus pullout areas, bus merge/diverge lanes, bus queue jump lanes)	Providing bus-only lane, queue jump lanes, merge/diverge lanes decreases bus travel time and improves transit rider quality of travel	Incorporating transit-only features often comes at the expense of providing additional auto or bicycle capacity or treatments	HCM2010 Chapters 16 and 17 (*3*)
Urban/ Suburban Segments and Intersections	Auto LOS	Number and duration of stops along an urban/suburban corridor	Number of travel lanes; intersection form, control type, and features	Reducing the number of stops and duration of stops along a corridor improves auto LOS	Increased vehicle lanes and speeds degrade pedestrian and bicycle MMLOS	HCM2010 Chapters 16 and 17 (*3*)
Intersections and Segments	Large-vehicle turning and off-tracking characteristics	Ability and ease with which large vehicles are able to physically move through an intersection or along a segment	Curve radii, curb radii, lane width	Generally larger curve radii, larger curb radii, and wider vehicle lanes enable easier navigation for larger vehicles	Increasing curve radii, curb radii, and lane width often degrades pedestrian and bicycle MMLOS due to the longer crossing distances	AutoTURN, truck turning templates

likely continue to evolve as the collective profession increases its focus and attention on creating and retrofitting existing roadways to "complete streets" that better serve a wide range of road users. While many of the performance measures in the exhibit are noted as applying to urban and suburban conditions, the same principles can be applied to more rural conditions when considering the design tradeoffs and multimodal implications or benefits in providing wider shoulders along a roadway segment and/or the physical footprint of an intersection.

4.4.4 Reliability

Research is ongoing within the transportation profession to develop performance measures to be used to connect reliability to specific geometric design elements or decisions. Variation in travel time and variation in speed are two more common performance measures used to understand potential reliability of a facility. At the time of assembling this guidance document, there is no clear set of performance measures available for practitioners to easily integrate into design decisions. A number of design considerations can be applied to highways and streets:

- Tradeoffs between mobility gained in implementing peak period hard shoulder running on a freeway segment and risk associated with a disabled vehicle during the peak period.
- Tradeoffs between congestion pricing strategies on freeway segments to improve reliability and potential equity implications for lower-income households.
- Tradeoffs between ramp metering strategies to preserve the quality of mainline traffic flow at the expense of degrading mobility on adjacent local streets.
- Tradeoffs between implementing transit signal priority, bus-only lanes, and/or queue jumps for transit vehicles along an urban corridor to improve the reliability of bus service with the potential impact of degrading mobility for side street vehicle traffic.
- Tradeoffs between implementing concrete median barriers with heights that eliminate distractions from incidents on opposing roadway lanes ("rubbernecking") and the potential safety performance degradation by introducing a fixed object.
- Considerations of on- or off-facility incident or enforcement pull-off areas and overall effectiveness compared to secondary effects such as delay and congestion caused by rubbernecking.

The preceding considerations are a sampling of potential tradeoffs that may exist between implementing strategies for one or more performance measures and the corresponding potential tradeoff with reliability. For additional information regarding reliability, see the research materials and reports related to the following SHRP 2 projects:

- L07, "Evaluation of Cost-Effectiveness of Highway Design Features" (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2181)
- L08, "Incorporation of Travel Time Reliability into the *Highway Capacity Manual*" (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2197)
- L09, "Incorporation of Non-recurrent Congestion Factors into the AASHTO Policy on Geometric Design" (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2196)

4.4.5 Safety

Safety is defined as the frequency and severity of crashes occurring on or expected to occur on highways or streets.

Exhibit 4-9 summarizes, by facility type, the performance measures specific to safety, the sensitive geometric design elements that influence those performance measures, the basic relationship between the design element and the performance measure, and resources or tools that can be used to evaluate the sensitivity of that geometric relationship in greater detail.

Exhibit 4-9. Safety performance measures.

Facility Type	Performance Measure	Definition	Geometric Design Elements	Basic Relationship	Potential Performance Tradeoffs	Evaluation Resources
Rural two-lane segments	Crash frequency and severity	Expected number and severity of crashes	Horizontal alignment, shoulder width and composition, shoulder type, lane width, type and location of auxiliary lanes, rumble strips, roadside design features, lighting, two-way left-turn lane, grade	See HSM	Some safety improvements reduce mobility, reduce access (e.g., reducing driveway density), or negatively affect another performance measure	HSM Chapter 10 (*2*)
Rural two-lane intersection			Intersection form, control type, and features, number and types of lanes, lighting, skew	See HSM		HSM Chapter 10 (*2*)
Rural multilane segments			Shoulder width and composition, shoulder type, lane width, lane and shoulder cross slopes, median provisions, lighting, two-way left-turn lane	See HSM		HSM Chapter 11 (*2*)
Rural multilane intersection			Intersection form, control type, and features; number and types of lanes; lighting; skew	See HSM		HSM Chapter 11 (*2*)
Urban/ suburban segments			Basic cross section, access points and density, fixed object density, median provisions, on-street parking	See HSM		HSM Chapter 12 (*2*)
Urban/ suburban intersection			Intersection form, control type, and features; number and types of lanes; signal phasing	See HSM		HSM Chapter 12 (*2*)
Freeway Segments			Lane width, shoulder width and composition, ramp spacing, use of auxiliary lanes, ramp entrance/exit configurations	See final report for NCHRP 17-45		Final report for NCHRP 17-45 (*6*), *NCHRP Report 687* (*9*)
Interchange			Interchange form and features, number and types of lanes, horizontal alignment, cross section, roadside	See final report for NCHRP 17-45		

The information in Exhibit 4-9 focuses on quantifying safety impacts using crash frequency and severity as the key performance measures. In some instances, the tools listed in the exhibit may not apply to a given project; in which case, it may be necessary to use surrogate measures for safety such as the number of conflict points or consideration of speed or speed differentials as surrogates for severity. Other resources that may be beneficial in considering safety performance include FHWA's Crash Modification Factors (CMF) Clearinghouse (*10*).

4.4.6 Summary

The prior subsections presented the key performance measures and related geometric elements based on what is currently documented within the transportation profession. As highlighted in Section 4.3, a number of other relationships are indirect in nature and therefore more difficult to quantify or clearly understand the geometric sensitivity a given element has on performance. Other relationships have yet to be explored extensively enough to understand what relationship may exist between a performance measure and geometric element.

Chapter 5 presents an application framework for integrating the information presented in Section 4.4 into performance-based analysis to inform geometric design decisions. For example, Section 5.3.1 discusses how to identify the geometric features influencing the intended project outcome discussed in Chapter 3 as well as Section 5.2.2. Chapter 6 illustrates how to apply the framework and foregoing information to projects at different stages within the project development process. For example, Project Example 2 integrates safety and mobility performance measures for a rural two-lane roadway segment, focusing on the influence shoulder width and horizontal curve characteristics have on crash frequency (safety measure) and inferred speed (mobility measure).

4.5 References

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CHAPTER 5

Process Framework

5.1 Introduction

This chapter presents the performance-based analysis application framework. This chapter describes how performance-based analysis can be used to inform geometric design decisions within multiple phases of the project development process and within or outside of an environmental review process. The chapter provides a framework for applying the information in Chapter 4. Specifically, Section 4.4 highlights the relationships between different performance measures and geometric elements. Chapter 6 presents project examples illustrating how to apply the framework described below.

Exhibit 5-1 illustrates the basic framework for integrating performance-based analysis into geometric design.

This framework is applicable across the different stages of the project development process and within or outside of an environmental review process. The stages of the project development process were presented in Section 2.3. The specific considerations within the framework vary depending on where a project is within its development. As noted previously, as a project progresses further toward final design, there are increasingly limited opportunities to significantly change its form, function, or performance.

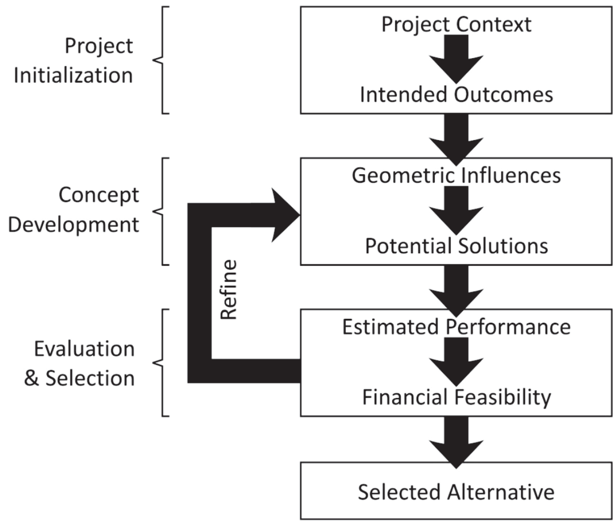
The application framework is organized into three broad phases:

1. Project initiation
2. Concept development
3. Evaluation and selection

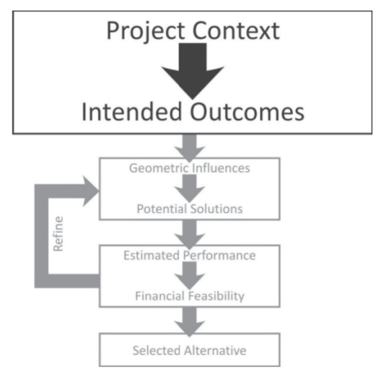
These three broad phases generally represent the activities leading up to the final project activities of developing project plans, specifications, and estimates. During project final plan preparation, new project developments can arise that might require "initiating" an evaluation of a design element or configuration and "developing concepts" that might appropriately address the needs of the new situation. Ultimately, the project designers will evaluate and select a solution for that geometric element or configuration. The ultimate decision, even for a relatively discrete component, may include estimating performance and financial feasibility of the design choices.

Each of these phases contains steps or activities to meet the needs of each phase and build incrementally through the activities needed to initiate a project, develop concepts, evaluate options, and ultimately select or advance a project or design recommendations. The steps within each phase are presented in Sections 5.2 through 5.4. The information presented within those sections is applicable across the project development process. Considerations specific to environmental review are presented in Section 5.5, Environmental Review Process.

Exhibit 5-1. Performance-based analysis application framework.



5.2 Project Initiation



The project initiation phase sets a foundation for understanding the project context and overarching intended outcomes. There are a variety of names for these activities depending on the transportation agency involved. And while the names may vary between agencies, the general intent of an activity initiating a project is consistent. Section 3.2 noted some of the examples of project catalysts generating a project. Regardless of the reason for a project's inception, all projects have a unique context requiring customized solutions to meet project and geometric design outcomes.

The project context often includes considerations about the following:

- The existing site constraints
- Current performance related to operations, safety, access, reliability, and quality of service
- Surrounding land uses
- Planned improvements for the future
- Existing and future anticipated form and function of the facility
- Other similar considerations

Identifying and succinctly articulating the intended project outcomes include understanding the catalyst and motivations for the project, the target audience to be served by the project, the critical desired performance characteristics, and ultimately the performance measures that will be used to inform design decisions and solution development. These performance measures may stem from project-specific design controls, tailored to the unique project needs, helping to define the design criteria and dimensional design values targeted to achieve desired performance.

The outcomes of the project initiation phase are as follows:

1. Clarity of the characteristics defining the current and desired future of the site
2. A clear and concise understanding of the primary project purpose
3. A set of performance measures to be used to evaluate a design's impact on the desired project purpose

The following subsections highlight activities and considerations for the two steps within the project initiation phase:

1. Project context
2. Intended outcomes

5.2.1 Project Context

Understanding a project's context helps (1) define the boundaries that improvements or project considerations should fall within and (2) identify critical surrounding characteristics potentially dictating the type, form, or function of a site-specific improvement or design decision. This step within the project initiation phase helps identify the facility users or special needs influencing geometric design decisions. This could include design controls such as vehicle type or target speeds of a facility in total, or for specific elements such as an interchange ramp. Understanding the user types and modal considerations helps establish target performance parameters.

For example, if an intersection improvement project is identified for an intersection adjacent to an elementary school, the improvements should consider school bus circulation, crossing needs of school-age children on foot and on bicycles, parent drop-off and pick-up activities, broader transit needs for school employees (e.g., teachers), and parking needs for school employees and visitors. Even if the overarching focus of the intersection project is not directly related to the elementary school, the design solutions should take into consideration the school and the associated road users who will use the intersection to access the school.

If, in this example, one of the intersecting roadways served as a designated freight route, the design controls and associated performance measurement would balance the needs of vulnerable user crossing needs with dimensional values for design elements (i.e., lane width or turning radii) appropriate for the freight user needs. Similar considerations should be made for design solutions in agricultural areas, industrial areas, large employment centers, central business districts, and other locations where the surrounding land uses and destinations generate a wide range of road users and a wide range of needs.

The following questions outline some considerations useful in helping to define the project context. As the needs of a given project can vary by element or combinations of conditions, each professional may use his or her own judgment to consider and customize the following questions to fit project-specific needs:

- Where in the project development process is the project?
- Is it a rural, suburban, or urban setting?
- Who has jurisdiction of the roadways influenced by the project?
- Are there pre-existing constraints?
  - Design concepts already identified?
  - Right-of-way constraints or limitations?
  - Community objectives or interests?
  - Funding limitations?
  - Environmental concerns or constraints?
  - Constructability challenges?
  - Project schedule challenges or critical milestones?
- What is the highway's or street's role in the overall network? What is its functional classification? How does the facility need to adapt to various context zones along its route while meeting its intended purpose?

- What are the current defining geometric characteristics?
  - Segment considerations
    - Cross section (e.g., number of through lanes, turn lanes, medians, on-street parking, bicycle lanes, sidewalks, landscaping)
    - Horizontal alignment (e.g., curve radii, curve length, superelevation)
    - Vertical alignment
    - Target speed
    - Posted speed
    - Design speed
    - Locations and treatments of mid-block crossings
  - Intersections
    - Traffic control
    - Target, posted, and design speed on approaches
    - Signal phasing and timing
    - Lane configurations
    - Pedestrian treatments present
    - Bicycle treatments present
    - Design vehicle or special vehicle needs
- What are the current performance characteristics of the highway or street?
  - Quality of service for road users (e.g., presence and condition of bicycle facilities or ability to serve design vehicles)?
  - Safety performance for road users (e.g., crash frequency and severity)?
  - Access available relative to street functional classification and role in the network?
  - Operational characteristics at the project location?
    - 85th percentile speeds
    - Average annual daily traffic
    - Delay during and outside of peak periods
  - Reliability of operational performance (e.g., variability in travel time)?

The preceding questions serve as a guide for practitioners to characterize and document the project context their design (or designs) should fit within. The full set of questions may not always be applicable to a given project or scenario, and in some instances additional considerations or unique attributes will surface as key defining characteristics of a project. All project participants have the flexibility to consider and define the context for their design environment.

5.2.2 Intended Outcomes

The step of identifying the intended project outcomes (during the project initiation phase) helps focus the performance measures and evaluation criteria on the characteristics reflecting the core purpose of the project investment. Transportation improvement projects tend to be identified as needed based on any one or combination of the following activities (project catalysts):

- Long-range planning activities by an agency
- An acute operational deficiency (e.g., congestion in the peak period)
- Community concerns (e.g., pedestrian crossing needs near schools, speeds on neighborhood streets)
- Severe recent crash events
- Private development (e.g., opportunity to attract employers and/or accommodating new trip generators)

At the root of such a project catalyst is the purpose of the project and a desired outcome from the investment. The desired outcomes help define design controls leading to appropriately selected criteria to meet targeted design and operational performance. Once the desired outcome is articulated, performance categories and specific performance measures can be selected to evaluate how well the project or decisions made within the project's development will help make progress toward the intended outcome.

The results from the intended outcomes step are the identification of the following:

1. The primary and supplemental target audience for the project
2. The project objectives and intended outcomes
3. Performance measures to evaluate progress toward the intended outcomes

Section 3.3.2 describes geometric design performance categories (accessibility, mobility, quality of service, reliability, and safety) that influence and are influenced by geometric design elements and their characteristics. These transportation performance categories have corresponding performance measures that can help a designer or analyst compare various geometric solutions and guide decision making based on how well a project or geometric element meets project objectives and intended outcomes. The information presented in Section 4.4 can be used to help inform performance category and measure selection.

Results 1 and 2 listed previously can have a direct impact on the performance categories and associated measures selected to evaluate the decisions made in the project's development and the project as a whole. These directly influence project design controls and resultant criteria. For example, a project to improve transit riders' experience along a corridor (i.e., the desired project outcome is improved transit rider experience) would include performance categories such as quality of service, accessibility, and safety. These could result in performance measures such as street crossing distance for pedestrians, proximity of controlled or marked pedestrian crossings to transit stops, and other similar attributes that would influence the quality of service for transit riders as they access and use the transit service. Potential solutions would be sure to include design parameters to accommodate transit vehicles as a key design vehicle and modal considerations along and across the roadway (e.g., crossing distances for pedestrians, median types, operating speeds, and pedestrian and bicyclist accommodation). Therefore, Results 1 and 2 (i.e., identifying the target audience and intended project outcome) help inform the range of performance categories and the specific performance measures selected to evaluate design decisions within the project.

The following items should be considered when working toward the three results previously listed (each user has the flexibility to consider items related to his or her unique project needs.):

1. When identifying the primary and supplemental target audience, consider the following:
    - Who is being served by the project?
        - Specific road users such as pedestrians, bicyclists, motorists, freight haulers, agricultural users, logging users, industrial users, commuter traffic, tourists/visitors
        - Specific community groups such as local businesses, targeted employers, a neighborhood, a school or school district, a community center
    - What are the planned land uses in the vicinity of the project area? What are they now and how do they need to be served? How might they change in the future?
    - What is the purpose and function of the street and/or intersection at the time the project is expected to be completed?
    - What road users are likely to desire the use of the highway or street given the role it plays in the network and the existing and planned land uses?
    - What are the existing and anticipated future socio-demographics of the population adjacent to and in the vicinity of the existing or planned street?

- What are the existing perceived or actual shortcomings of the highway or street?
- How do the transportation elements best fit within the existing and future land use context?

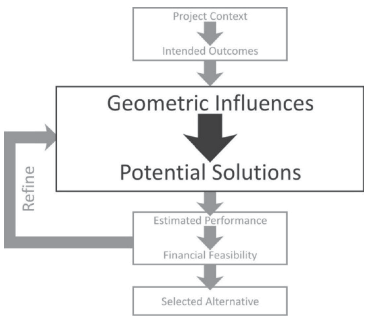
2. When identifying the project objectives and intended outcomes, consider the following:
   - What is the project trying to achieve?
     - What is the broader project purpose or catalyst?
       - For example, to facilitate economic development, improve livability, make progress in sustainability, enhance safe routes to school for children, attract new employers and jobs, improve air quality
     - What are the engineering performance categories influencing the broader project purpose or catalyst?
       - For example, accessibility—access to destinations, access to facilities (bicycle lanes, sidewalks, transit service)
       - For example, mobility—average travel time, mobility, average travel speed, inferred speed
       - For example, quality of service—improve (or provide) facilities for pedestrians, bicyclists, and transit riders; improve travel experience for road users; ability to serve or design vehicles
       - For example, reliability—variability in travel time
       - For example, safety—number of crashes, crash severity, users feeling safe
3. When identifying performance categories and performance measures that apply to the intended project outcomes, select the following:
   - Performance categories and measures that evaluate the actual performance of interest, examples:
     - Accessibility—identify access for whom and to what. For example:
       - Heavy vehicles to/from industrial area and freeway
       - Residents from residential area to/from regional parks
       - Pedestrians to/from origins/destinations and transit service
     - Mobility—consider average travel time, delay, inferred speeds, target speeds
     - Quality of service—consider for whom, condition of facilities, ease of travel for user, direct traveler experience
     - Reliability—identify road user and corridor of interest, consider variability in travel time under range of potential operating conditions (e.g., incidents, weather events, recurring congestion)
     - Safety—consider expected crash frequency and severity, management of conflict points, speed as related to crash severity
   - Select a manageable number of performance measures to apply to alternatives
   - Select performance measures that can be assessed (qualitatively or quantitatively) given the project data and scope

Some design decisions will occur in later stages of the project development process where the intended outcomes of the project were previously identified. In such instances, the purpose of revisiting the previously defined intended outcomes is to remind designers and the project team of the collective project purpose to help keep design decisions on track to support the overarching intended outcome of the investment. A project originally intended to reduce the severity and number of crashes on a high-speed rural highway should not unintentionally evolve into a project with design elements promoting higher speeds (e.g., larger radii, increased superelevation). A project originally intended to improve pedestrian and bicycle facilities should not evolve to sacrificing bicycle lane and/or sidewalk width to provide more auto capacity. The resulting performance of a roadway or intersection due to design decisions should be evaluated against the original intended project outcomes.

The purpose of revisiting the previously defined intended outcomes is to remind designers and the project team of the collective project purpose to help keep design decisions on track to support the overarching intended outcome of the investment.

In some projects, solutions may evolve to a configuration or magnitude outside the intent of the original project outcomes. In these rare cases, project participants have had to re-evaluate and agree upon the intended project outcomes. This can result in costs exceeding project budgets and project implementation delays. The principles of context-sensitive solutions are based on identifying and agreeing on overall project outcomes early in the project. The risk of project overruns and delays may be reduced by being sure geometric solutions are geared to address identified project needs. Performance-based outcomes help all parties develop and support appropriate project solutions.

5.3 Concept Development



Concept development primarily consists of developing potential solutions to address the intended project outcome and project issues at hand. Concept development could also include evaluating discrete design decisions of a geometric element or configuration. Early in a project's development, concept development will consist of identifying and developing overarching alternatives. This could include alternative intersection forms, roadway alignments, roadway cross sections, interchange forms, or similar broader project alternative solutions. As a project progresses toward final design, the concept development will be more focused on solving a specific issue. This could include adjusting specific horizontal curves to reduce the amount of cut or fill needed to construct or modify the roadway shoulder width and side slope to reduce the impact of the roadway prism in an environmentally sensitive area. The steps in this phase of understanding the geometric influences will help inform and guide the range of potential solutions.

In each of the instances just noted, there are (1) geometric features that will influence the performance of the ultimate roadway facility and (2) a set of potential solutions whose resulting performance can be evaluated to help determine which solution is preferred. The two steps within the concept development phase consist of identifying the geometric features influencing performance outcomes and developing a set of solutions to be evaluated. Each is discussed in the following subsections.

5.3.1 Geometric Influences

This step helps identify geometric influences, which are the geometric characteristics or decisions that can influence a project's performance as it relates to the categories of accessibility, mobility, quality of service, reliability, and safety. It also includes geometric characteristics or decisions influenced by the desired performance of a project. The focus of this step is to identify the following:

1. Geometric characteristics or decisions (e.g., type of intersection control) that have the potential to influence a project's performance
2. Geometric characteristics or decisions influenced by the desired performance of a project

The purpose of identifying these geometric characteristics and decisions is to create an awareness of the potential performance impacts design decisions have as project solutions are being considered. The information presented in Sections 4.3 and 4.4 are provided to help practitioners identify the key geometric elements critical to a given project's or potential solution's performance.

For example, intersection traffic control is a geometric design decision having the ability to influence a project's performance as it relates to safety (as well as other performance categories). Single-lane roundabouts have been consistently found to have fewer total and severe crashes than two-way, stop-controlled intersections. This is an example of a geometric design decision influencing a project's performance. Should a particular location not be compatible with implementing a roundabout, the designer may evaluate the performance qualities of other intersection forms and use performance categories and measures to help differentiate between concepts or design alternatives.

Using the same basic example as above, further along in the project development process (e.g., 15% design), the roundabout-specific design features will be influenced by the need to have entry speeds of about 20 mph. This desired speed performance will directly influence the approach and entry geometry to the roundabout. This is an example of a performance measure influencing geometric design decisions.

Section 4.4 presents a series of tables and information to help identify which geometric features on corridors and segments and at intersections and interchanges may influence performance categories of accessibility, mobility, quality of service, reliability, and safety—and, in turn, which performance measures may influence geometric characteristics and decisions. The information in Section 4.4 can be used to identify key geometric characteristics for achieving the desired project outcomes; this is useful information in developing potential solutions (see next subsection) that make progress toward the intended project outcomes.

5.3.2 Potential Solutions

Developing potential solutions is the core activity within the concept development phase. Potential solutions can be broad-based concepts early in the development of a project or more detailed, project-specific solutions to address a specific need, issue, or challenge.

Broad-based concepts commonly explored early in a project's development (e.g., alternatives identification and evaluation) include geometric design considerations such as the number of through lanes on an arterial, intersection traffic control options, intersection lane configurations, presence of a raised median, and other similar overarching design characteristics. In later stages of the project development process (e.g., preliminary design, final design), more detailed decisions are made, and in some instances, alternative design decisions are considered to address a project need, issue, or challenge. A designer may develop alternative solutions to consider, for example, different roadway shoulder widths and side slopes to reduce the impact of the roadway prism in an environmentally sensitive area. In a more urban context, designers may develop alternative solutions to consider the performance tradeoffs of narrowing vehicle lanes to provide bicycle lanes, widen sidewalks, or create a transit-only lane.

Regardless of where a project is in the project development process, designers, engineers, planners, and other transportation professionals go through a process of considering alternative solutions to address a specific need, issue, or challenge. The intent of the potential solutions step is to develop those potential solutions with a specific awareness of what has been learned in the previous activities—with a specific awareness of the following:

- Project context
- Intended outcomes from the project and the performance categories and measures reflecting those desired outcomes
- Geometric characteristics and decisions with the greatest ability to influence the degree to which the project (or ultimate design) achieves the desired outcomes

Within the potential solutions step, designers, engineers, planners, and transportation professionals may use the information they have learned and assembled in the previous steps (i.e., project context, intended outcomes, geometric influences) in combination with the prevailing design guidance applicable to their project to develop alternative solutions addressing the project need, issue, or challenge.

Potential design guidance applicable to a project can include a vast range of resources. For the purpose of illustrating some of the resources and examples of the range and diversity, these documents include the following:

- AASHTO *A Policy on the Geometric Design of Highways and Streets* (*1*)
- *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition* (*2*)
- State department of transportation design manuals or design guidance
- *Manual on Uniform Traffic Control Devices* (*3*)
- FHWA *Signalized Intersections: Informational Guide* (*4*)
- ITE *Freeway and Interchange Geometric Design Handbook* (*5*)
- *NCHRP Report 687: Guidance for Ramp and Interchange Spacing* (*6*)
- *NCHRP Report 613: Guidelines for the Selection of Speed Reduction Treatments at High-Speed Intersections* (*7*)
- FHWA *Speed Concepts: Informational Guide* (*8*)
- Other industry-published design guidance

Having a documented process identifying the intended outcomes, design choices considered, and influences leading to the ultimate design choices is one of the best ways to support legal questions or challenges to design decisions.

The design guidance used to develop the potential solutions should generally be used as guidance and not absolutes. Designers, engineers, planners, and transportation professionals should consider, but not necessarily be constrained by, the guidance; in the following phase—evaluation and selection—designers, engineers, planners, or transportation professionals will have the opportunity to evaluate the impact of their design decisions on a project's performance. This will help determine which alternatives perform at a level to meet the desired outcomes (or project requirements). Engineers are sometimes concerned about tort liability and lawsuits. Having a documented process identifying the intended outcomes, design choices considered, and influences leading to the ultimate design choices is one of the best ways to support legal questions or challenges to design decisions.

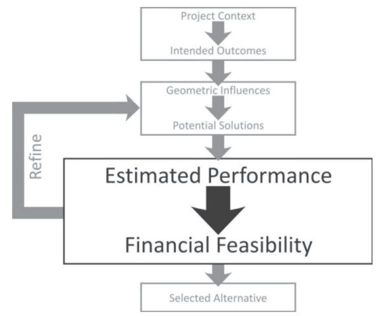
In some instances, transportation professionals may find some of the geometric elements in their preferred alternative do not meet the geometric criteria outlined in the prevailing design guidance and, in those instances, design exceptions or variances may be needed depending on the governing jurisdiction. Designers, engineers, planners, and transportation professionals should not assume a design exception is negative, nor that it is necessarily a reflection of a project's potential safety performance. The purpose of the evaluation and selection phase (discussed in the follow subsection) is to evaluate the anticipated performance of a project (in terms of accessibility, mobility, quality of service, reliability, and safety) and to learn whether a design exception or variation from published design criteria has a positive or negative impact on achieving the project's desired outcome. In other words, performance-based analysis of geometric design can support design variance or exception activities.

5.4 Evaluation and Selection

The evaluation and selection phase is where designers, engineers, planners, and transportation professionals directly integrate performance-based analysis to further refine the solutions they developed in the previous phase. Ultimately a design element or configuration is selected based on these efforts. The primary steps are to estimate performance and financial feasibility of potential project or design choices. The possible outcomes from this phase are (1) a return to the concept development phase for further solution development or refinement or (2) a selected project. To reach one of those two outcomes, the designer, engineer, planner, or transportation professional will evaluate the performance of a project relative to the previously identified performance categories and associated measures. They will consider the financial feasibility of each alternative and decide if there is an alternative that sufficiently meets the project's intended outcome and is financially feasible. The processes for evaluating the performance of the project and assessing its financial feasibility, and guidance for deciding when to select an alternative or further refine alternatives are discussed in the following subsections.

5.4.1 Estimated Performance and Financial Feasibility

The following subsections discuss steps to estimate performance of design choices and consider the financial feasibility of design alternatives. The subsections conclude with a discussion on interpreting results from the estimated project performance and financial feasibility evaluation activities.



5.4.1.1 Estimated Project Performance

Estimating or evaluating a project's likely performance during this step requires an awareness of the resources available to quantify specific performance measures or qualitatively describe the anticipated effect of a given roadway, intersection, or interchange design. For example, to evaluate the safety performance of a rural two-lane roadway, a user must know that Chapter 10 of the *Highway Safety Manual* (*9*) presents information to predict the number and severity of crashes on a two-lane rural roadway based on its cross-sectional characteristics, horizontal alignment, vertical alignment, traffic volume, and crash history. Therefore, Section 4.4 contains table summaries to help identify the available resources for evaluating the performance of roadway segments, intersections, and interchanges as related to accessibility, mobility, quality of service, reliability, and safety.

Estimating a project's performance is not intended to be a long or arduous process. Many of the performance-based resources available are supplemented with spreadsheet or software tools to help expedite their application, and some include graphical representations or table summaries of the relationships to provide guidance early in a project's development. For example, *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition* (*2*) includes a table summary of volume ranges to help determine the approximate number of lanes required for a roundabout (see Exhibit 5-2).

With respect to evaluating the performance of a design, designers, engineers, planners, and transportation professionals should be aware of the following critical elements:

- Selecting the evaluation resource or tool most appropriate for the stage in the project development process. More detailed and refined evaluations will likely only be possible at later stages in the project development process when more information is available.
  – For example, if considering alternative roadway segments in the alternatives identification and evaluation stage of the project development process, comparing the relative safety and

Exhibit 5-2. Planning-level analysis of roundabout lane needs (*2*, Exhibit 3-14).

Volume Range (sum of entering and conflicting volumes)	Number of Lanes Required
0 to 1,000 vehicles/hour	• Single-lane entry likely to be sufficient
1,000 to 1,300 vehicles/hour	• Two-lane entry may be needed • Single-lane entry may be sufficient upon more detailed analysis
1,300 to 1,800 vehicles/hour	• Two-lane entry likely to be sufficient
Above 1,800 vehicles/hour	• More than two entering lanes may be required • A more detailed capacity evaluation should be conducted to verify lane numbers and arrangements

mobility performance of two-lane, two-lane divided, three-lane, and four-lane facilities is sufficient. In later stages, the impact of the specific horizontal alignment (e.g., curve radii, superelevation) on performance would be considered.

  – Specific to safety performance, this difference in level of detail could mean that, in earlier stages of the project development process, consulting graphs or charts from the *Highway Safety Manual* is sufficient to understand the crash performance tradeoffs, while a more detailed tool such as the Interactive Highway Safety Design Model (*10*) would be needed to assess the performance of decisions later in the design process.

- Selecting the evaluation resource or tool most applicable or transferable to the project context.
  – For example, when evaluating a rural two-lane roadway, using resources and tools applicable to rural two-lane roadways. While this may seem obvious, there may be some instances when a resource is not available for a specific context but is for another context. Using a tool applicable to multilane highways to evaluate the performance of a rural two-lane roadway will not yield reliable results.
  – In other instances, selecting a tool or resource to evaluate performance of a project may be related more to the surrounding context of the roadway. For example, a state highway passing through a rural community town center—while classified as a regional, major arterial—is more likely functioning as a rural main street needing to accommodate pedestrians, bicycles, and possibly transit service as well as motor vehicles. It also is probably a place for on-street parking and is serving as the front entrance/access to local businesses. In this context, downtown urban-type performance measures and tools may be more appropriate to capture the multimodal, slower speed, and access needs of the roadway.

Once the appropriate evaluation tool and resource is selected for the given project and performance measures, designers, engineers, planners, and transportation professionals can apply the tool or resource to assess the project alternatives' relative performance. The results for each alternative solution can be summarized in tabular summaries or figures depending on the scope of the project and the alternatives. Exhibit 5-3 is one example of how the information can be summarized. It illustrates alternative horizontal curve radii being considered for a rural two-lane roadway. The intended project outcome is to reduce the number of crashes, while minimizing the cut and fill required to realign the roadway. The posted speed is 45 mph. Project Example 2 in Chapter 6 presents the full performance-based application process for the project.

From the information summarized in Exhibit 5-3, it is clear Alternative 2 provides the greatest predicted safety benefit (four total crashes per year) while creating an inferred speed closest to the posted 45 mph. However, it does not result in the least amount of cut/fill for the project. This illustrates one of the many potential tradeoffs in meeting performance characteristics that may have relationships counter to each other. In this instance, larger curve radii tend to be associated

Exhibit 5-3. Example summary of evaluation results.

Alternative	Safety Performance[a]	Mobility Performance[b]	Average Cut or Fill Required per Station
No Project	13 total crashes/year	Inferred Speed of 15 to 55 mph	0 yd^3
1 – Minimal	11 total crashes/year	Inferred Speed of 15 to 55 mph	100 yd^3
2 – Ultimate	4 total crashes/year	Inferred Speed of 60 to 80 mph	700 yd^3
3 – Practical	7 total crashes/year	Inferred Speed of 35 to 40 mph	200 yd^3
4 – Subultimate	6 total crashes/year	Inferred Speed of 60 to 80 mph	450 yd^3

[a]Expected (average) annual total crashes per year
[b]Inferred speed of horizontal curves within study area

with fewer crashes but in mountainous or rolling terrain often result in more cut or fill and therefore higher project costs. To help further inform these types of decisions where tradeoffs between performance must be made, incorporating the financial feasibility or cost effectiveness of a project can be helpful in either selecting an alternative or refining one or more alternatives for continued analysis.

The following subsection discusses sample approaches for considering the financial feasibility of the project alternatives.

5.4.1.2 Financial Feasibility

Financial feasibility assessments of a project or set of alternatives during this step can be useful in helping to prioritize investments and the relative effectiveness of potential projects. This section highlights three basic approaches for considering the financial feasibility of an alternative:

- Total construction and maintenance cost of the alternative
- Cost effectiveness of the alternative
- Benefit/cost ratio of the alternative

The transportation profession includes other published documents that are more comprehensive resources for financial feasibility (i.e., economic appraisal) than this report is intended to be. For more detailed guidance and information about how to specifically conduct financial feasibility calculations, please refer to resources such as AASHTO's *User and Non-user Benefit Analysis for Highways, Third Edition* (*11*).

For a given alternative, the total construction and maintenance cost can be estimated and compared to the funding available. If the alternative meets the desired performance measures based on the analysis in the evaluation phase and funding is available to implement it, then in some instances this may be a sufficient level of consideration for the financial feasibility of the alternative.

In other instances, funding and resources may be limited and, therefore, a greater level of financial analysis is needed to determine the value provided by each alternative relative to the investment made to implement the alternative.

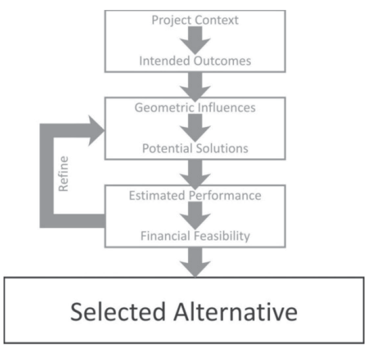
One approach to estimate the relative value of an investment is to calculate the cost effectiveness of each alternative. This is achieved by estimating the cost of constructing and maintaining each alternative and comparing that to the preferred performance measure. For example, alternatives intended to reduce crashes at a location could be prioritized based on their relative cost effectiveness at reducing crashes. If Alternative A is estimated to reduce five crashes per year at an annual cost of $2,000, then its cost effectiveness is $400 per mitigated crash. Alternative A could then be ranked or prioritized for further consideration based on how other alternatives perform. Project Example 1 in Chapter 6 employs this type of financial feasibility assessment.

A second approach for estimating the relative value of an investment is to use a benefit/cost ratio. Benefit/cost ratios greater than 1.0 indicate the benefits outweigh the costs of the alternative and therefore are a reasonable potential investment. In instances where multiple alternatives return a benefit/cost ratio greater than 1.0, an incremental benefit/cost ratio may be used to directly compare the incremental value that one alternative provides over the other. A key consideration for calculating benefit/cost ratios is this approach requires converting the engineering performance measures to a monetary value. For example, the estimated change in crashes, delay, or other similar metrics would need to be converted to a dollar amount for comparison to the project costs. Resources such as AASHTO's *User and Non-user Benefit Analysis for Highways, Third Edition* (*11*) provide guidance on best practices for conducting benefit-cost assessments.

5.4.1.3 Interpreting Results from the Estimated Project Performance and Financial Feasibility

The results from the steps to estimate the project performance and financial feasibility of the alternatives are intended to inform the geometric design decisions being made. Designers may choose alternatives that are not necessarily the most cost effective or even the highest performing relative to the preferred performance measure. The example scenario presented in Exhibit 5-3 presented a solution that may have best met safety and speed performance objectives but that may not be selected because of its anticipated cost and the cut/fill impacts on the surrounding area. The ultimate design decisions may also be influenced by additional qualitative factors (e.g., solutions consistent with a community's rural heritage) that cannot be captured with quantitative performance measures or financial assessments. The foregoing steps are intended to help designers, engineers, planners, and transportation professionals to be more aware of the performance tradeoffs their decisions have and how that affects the overarching intent of their project. The ultimate design decisions still reside at the discretion of the designer, engineer, planner, or transportation professional in charge of the project. Project decision making should include clear and complete documentation of the overall identification of intended outcomes and information highlighting the evaluation process and judgment used to make actual project design decisions. The following section presents considerations regarding when to consider selecting an alternative and when there may be value in refining and re-evaluating alternatives.

5.4.2 Selection



Based on the results from the estimated performance and financial feasibility step, designers, engineers, planners, or transportation professionals will need to either select a preferred alternative or decide to further refine alternatives and re-evaluate their performance.

The following are items to consider in making this decision:

- Are the performance evaluation results making progress toward the intended project outcomes? Do the alternatives serve the target audience and achieve the desired objectives?
  - If no, revisit the concept development stage, revise the alternatives, and re-evaluate the performance.
- Can reasonable adjustments be made to the geometric design elements most significantly influencing project performance?
  - If yes, consider refining one or two of the top performing alternatives and re-evaluating them.
- Do the performance measures help differentiate between the alternatives?
  - If no, consider adding or modifying the performance measures to help differentiate among the alternatives, or consider significantly modifying alternatives to better reflect desired performance.

As noted previously, there may be other external factors or qualitative performance measures driving the decision to select a preferred alternative or further refine and re-evaluate alternatives. The preceding questions are intended to help generate thought and considerations for how best to advance a project to the next stage in the project development process.

5.5 Environmental Review Process

This section discusses how the performance-based analysis framework presented in the previous sections can be incorporated into a basic environmental review process. For this research effort, the environmental review process is defined as three levels based on NEPA (*12*). Many states have adopted their own variation for non-federal projects. State Environmental Policy Act processes may use different terms; however, the state processes generally follow those of NEPA. The NEPA review processes include the following:

1. Environmental Checklist
2. Environmental Assessment (EA)
3. Environmental Impact Statement (EIS)

The level of technical analysis, documentation, and review increases as a project progresses from an Environmental Checklist to an EA or EIS. The following subsections discuss how performance-based analysis can be useful within each level of evaluation.

5.5.1 Environmental Checklist

An Environmental Checklist enables state agencies to screen projects relative to their potential for environmental impacts. Projects that "pass" the checklist qualify for a Categorical Exclusion (CE). A CE enables a project to move forward in its development without the need for additional environmental analysis, documentation, or review by the state or FHWA. Typically, a CE can be obtained if each of the following items is met (*12*):

- The action does not have significant environmental impacts as defined in 23 Code of Federal Regulations (CFR) 771.117(a).
- The action does not involve unusual circumstances as defined in 23 CFR 771.117(b).
- The action does not involve:
  - Right-of-way acquisition
  - Use of protected properties as defined by federal or state law
  - Permits from U.S. Coast Guard or Army Corps of Engineers
  - Wetlands
  - Encroaching on a floodway or base floodplain
  - Impacts to a river designated as part of the National System of Wild and Scenic Rivers
  - Changes to access control
  - Constructing temporary roads, detours, or ramp closures
  - Known hazardous materials or previous land uses with potential for hazardous materials
- The action conforms to the Air Quality Implementation Plan.
- The action is consistent with a state's Coastal Zone Management Plan.
- The action is in an area with no federally listed endangered or threatened species or critical habitat.

The level of analysis and documentation needed to complete an Environmental Checklist is usually confined to existing data or data readily available or observable in a field visit.

The performance-based analysis framework can be used to explore and consider project alternatives or adjustments to enable a project to be eligible for a CE. In some instances, by adjusting a preferred alternative's alignment or cross section, a designer may find limited to no impact on safety and mobility (or other project performance measure) and may be able to avoid actions that would prevent the project from qualifying for a CE. Once a project qualifies for a CE, the performance-based analysis framework can continue to serve as a useful tool for developing and evaluating alternative design decisions. It can also serve as a framework for documenting the project development process to support public outreach, facilitate coordination within and among partner agencies, and manage an agency's risk related to tort liability. If the design requires a variance or exception, the performance-based analysis and results can support documentation efforts. In summary, the performance-based analysis framework adds value to project development activities regardless of whether that project is being developed within or outside of an environmental review process.

If a project does not qualify for a CE, the level of environmental analysis, documentation, and review progresses to an EA.

5.5.2 Environmental Assessment

An EA is performed when the significance of impacts of a project is uncertain; an EA helps to determine whether a project will result in significant environmental impacts. If significant impacts are found to occur while developing or reviewing the EA, then an EIS is needed. The purpose of an EA is as follows:

- To briefly provide sufficient evidence and analysis to determine whether there is a significant impact
- To aid in an agency's compliance with NEPA when an EIS is not needed
- To facilitate preparation of an EIS, if one is needed

An EA must include a brief discussion of the project need, alternative solutions, documentation of the environmental impacts of the alternatives, and a list of people and agencies consulted (*12*).

In the process of preparing an EA, the project initiation phase of the performance-based analysis framework can serve as a useful resource in developing a clear, sound, and concise project purpose and need statement. The concept development and evaluation and selection phases of the performance-based analysis framework are great resources for developing alternatives that minimize the potential for environmental impacts. And, the performance-based analysis framework provides a means for documenting the alternatives considered, their respective performance, and the ultimate finding of significant impacts or finding of no significant impact (FONSI). A FONSI enables the project to move forward without additional environmental analysis, documentation, or review. A finding of significant impact requires additional environmental analysis, documentation, and review in the form of an EIS.

5.5.3 Environmental Impact Statement

An EIS is required for major federal actions (e.g., major transportation capital projects receiving federal funding) significantly affecting the quality of the human environment. It is considered a full disclosure document detailing the process employed to develop the project, including the range of reasonable alternatives considered and analysis of the potential impacts from the alternatives. It also demonstrates compliance with other applicable environmental laws and executive orders.

The EIS process consists of a Notice of Intent to initiate the process, a draft EIS, final EIS, and a Record of Decision (ROD). Public involvement and agency coordination are present throughout the EIS process. The draft EIS provides a detailed description of the proposed project, the purpose and need, reasonable alternatives, affected environment, and analysis of anticipated beneficial and adverse environmental effects of the alternatives. The final EIS addresses the comments received on the draft EIS and identifies the preferred alternative. The ROD identifies the selected alternative, presents the basis for the decision, identifies all of the alternatives considered, specifies the "environmentally preferable alternative," and provides information on the adopted means to avoid, minimize, and compensate for the environmental impacts.

The performance-based analysis framework can benefit practitioners in developing a draft EIS, selecting a preferred alternative in the final EIS, and identifying the means to avoid and minimize environmental impacts. The project initiation phase can be used to develop a clear and focused project purpose and need statement. The concept development and evaluation and selection phases can be used to develop reasonable alternatives that perform to a level to fulfill the project's purpose and need while avoiding or minimizing environmental impacts. The evaluation and selection phase can also be used to help identify the preferred alternative. The overall performance-based analysis framework can also be used to facilitate the comprehensive documentation needed within the EIS process.

5.6 Summary

This chapter presents the performance-based analysis application framework and provides a description of each phase and step within each phase. This chapter also noted where information from previous chapters can be integrated into the framework to facilitate its application. Chapter 6 presents project examples illustrating how the framework can be applied to different projects at different stages within the project development process. A brief overview of the project examples in Chapter 6 follows:

- Project Example 1 evaluates the safety performance of alternative intersection improvements on a rural two-lane highway. The intent of the project is to reduce the frequency and severity of crashes at the study intersection.
- Project Example 2 considers the safety and mobility performance of alternative roadway alignments (e.g., tradeoffs of different horizontal curve characteristics) on a rural two-lane roadway. The intent of the project is to reduce the frequency and severity of crashes along the study corridor, while maintaining reasonable mobility for local residents and minimizing the cost of the ultimate project.
- Project Example 3 evaluates the safety, mobility, accessibility, reliability, and quality of service performance of alternative roadway cross sections for a suburban arterial. The project is focused on converting the auto-oriented arterial into a roadway capable of serving a wider range of modes (e.g., pedestrians, bicyclists) without needing to acquire additional right-of-way.
- Project Example 4 analyzes the safety, mobility, and reliability performance of alternative roadway shoulder widths and side slopes on a rural collector. The project's intent is to improve safety, mobility, and reliability performance, while minimizing impacts to the adjacent environmentally sensitive areas.
- Project Example 5 assesses the performance tradeoffs between safety, quality of service, and accessibility for alternative alignment and cross sections of a new urban collector intended to serve large vehicles accessing an industrial area as well as bicyclists and recreational travelers accessing a regional park.
- Project Example 6 considers safety and mobility of alternative interchange forms in a rural area. The study area is evolving from rural to suburban. The existing grade-separated regional highway is expanding its grade-separated/access-controlled characteristics farther out from the urban core.

5.7 References

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11. American Association of State Highway and Transportation Officials. *User and Non-user Benefit Analysis for Highways*, Third Edition. Washington, D.C.: 2010.
12. US Department of Transportation, Federal Highway Administration Environmental Toolkit: http://www.environment.fhwa.dot.gov/projdev/docuceda.asp. Accessed: August 10, 2013.

CHAPTER 6

Project Examples

6.1 Introduction

These project examples are intended to help users apply the concepts, models, and performance evaluation framework element presented in Chapters 1 through 5. The project examples are based on a variety of specific projects, amalgams of projects, or project considerations that can be commonly found in practice. All roadway names and locations have been fictionalized and the key project elements emphasized to support and promote the principles of performance-based analysis of geometric design. Each project example includes authors' notes to provide background or insights to the user as they work through each project example. The project examples are unique and offer independent value and utility. They represent a range of projects containing fairly common scenarios potentially faced by practitioners.

Some of the project examples have been adopted and modified from actual projects that have integrated performance-based analysis into design decisions and/or could have benefited from incorporating performance-based analysis. Other project examples were created to illustrate the performance-based analysis process and communicate key learning objectives. In each project example, the names are changed and do not reflect the actual names of the facilities or agencies.

While numbered from 1 through 6, users do not need to review the project examples sequentially. Doing so will help reinforce the fundamental performance-based model, report concept, and the performance-based model application framework. Following the project examples sequentially will provide repetition of the framework via a variety of project applications. Reviewing the project examples sequentially reinforces the principles of performance-based evaluations within a variety of unique applications. This may help the user apply the principles and models in a way that most appropriately meets individual project context and design situations.

Users may also find the project examples a useful resource for recalling and applying specific performance-based tools and methods for a specific project type. For example, Project Example 6 considers a new interchange being evaluated on a highway. Project Example 3 presents a corridor evaluation where intended project outcomes include retrofitting an existing auto-oriented urban arterial to incorporate complete street attributes. The design solutions considerations focus on alternative street cross sections and the associated performance evaluation of the geometric choices of various alternatives. Users may also find value in focusing on a project example with similar qualities and characteristics as their own project.

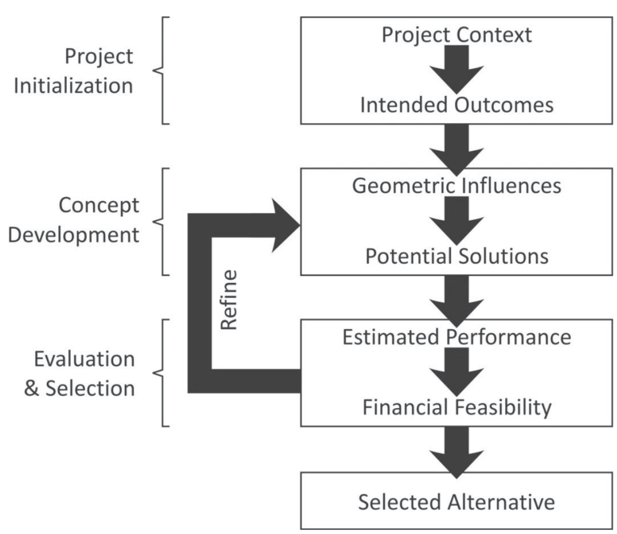
The project examples illustrate how the framework can be applied to projects within various stages of development and in a variety of contexts. Exhibit 6-1 summarizes the variety of project types, development stages, performance categories, and sites presented in the project examples.

Exhibit 6-2 illustrates the basic framework for applying performance-based analysis of geometric design of highways and streets. Sections 5.1 through 5.4 in Chapter 5 provided supporting

Exhibit 6-1. Summary of project examples.

Project Example	Site Area and Facility Type	Project Development Stage	Performance Categories	Project Type
1	US-21/Sanderson Road—Rural Collector (Two-Lane Highway)	Alternatives Identification and Evaluation	Safety	Intersection—Consider alternative intersection control to improve safety.
2	Richter Pass Road—Rural Collector	Preliminary Design	Safety Mobility	Segment—Consider alternative horizontal curve radii to improve safety while minimizing costs and maintaining appropriate speed.
3	Cascade Avenue—Suburban/ Urban Arterial	Preliminary Design	Safety Mobility Reliability Accessibility Quality of Service	Corridor—Retrofitting an existing auto-oriented urban arterial to incorporate complete street attributes. Focus on alternative street cross sections.
4	SR-4—Rural Collector	Preliminary Design	Safety Reliability Quality of Service	Segment—Consider alternative shoulder widths and sideslopes to minimize impact to an environmentally sensitive area.
5	27th Avenue—Urban Minor Arterial	Alternatives Identification and Evaluation	Quality of Service Safety Accessibility	Segment—Alignment and cross-section considerations for new urban minor arterial being constructed to entice employers to a newly zoned industrial area.
6	US-6/Stonebrook Road—Rural Interchange	Alternatives Identification and Evaluation	Safety Mobility	Interchange • Converting an at-grade rural intersection to a grade-separated interchange. • Focus on selecting the appropriate interchange form and location (e.g., spacing considerations).

Exhibit 6-2. Performance-based analysis application framework.



information regarding the actions and considerations within each stage of the framework. Chapter 3 provided an overview of project performance categories and associated performance measures that might be used in evaluating project solutions. Chapter 4 summarized the relationships between design elements and performance, identified possible performance tradeoffs, and presented resources and tools that can be used to analyze a given design decision's impact on performance measures. The six project examples within this chapter follow the process framework and steps shown in Exhibit 6-2.

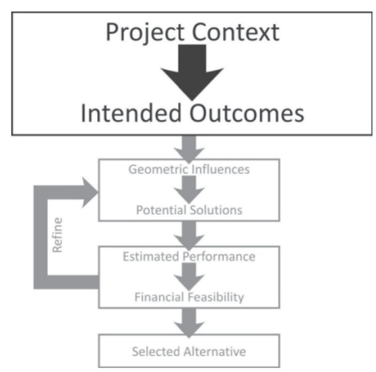
6.2 Project Example 1: US-21/Sanderson Road Intersection

Authors' Note: Project Example 1 illustrates how performance-based analysis can be integrated into the alternatives identification and evaluation stage of an intersection project located on a rural, two-lane highway (i.e., rural arterial). The intended outcome of the project is improved safety. The project example focuses on safety as the performance category of interest and uses expected crash frequency as the primary performance metric, drawing on information in Section 4.4.4. The learning objectives of this project example include the following:

- *Illustrate the process of applying performance-based analysis*
- *Demonstrate the use of resources beyond typical design manuals within the project development process*
- *Illustrate how a financial feasibility assessment can inform project selection*

6.2.1 Project Initiation

6.2.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context that are likely to help inform the intended project outcomes, performance categories, and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. As will be discussed, a key motivation for this project is to improve highway safety while also improving wayfinding.

The US-21/Sanderson Road intersection is located on a rural, two-lane highway (US-21). It is a two-way stop-controlled intersection serving as the primary entrance to a tribal reservation.

The US-21 highway is a regional east-west connection through a rural, agricultural area; the surrounding land uses are a mixture of agricultural land, undeveloped lands, wetlands, and low-density residential. The highway is adjacent to the tribal land, providing the primary access from the tribal land to other small communities in the area. The average annual daily traffic (AADT) is approximately 7,700 vehicles per day (vpd). In the vicinity of the project intersection, the posted speed is 55 mph and the 85th percentile speed is 58 mph. There is limited to no pedestrian or bicycle activity along the corridor or at the intersection. The intersection operational level of service is LOS B, indicating little to no delay for motorists traveling through the intersection.

Over the past 5 years, there were several fatal and serious injury crashes at the US-21/Sanderson Road intersection. Considering total crashes, 55% were angle or turning crashes and 26% were rear-end crashes. The most commonly cited contributing factors were failure to yield right-of-way (26% of crashes) and excessive speed (16% of crashes). Incremental solutions were applied to the intersection to improve safety—these included adding illumination as well as left-turn and right-turn lanes on US-21.

6.2.1.2 Intended Project Outcomes

Authors' Note: The following summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, the two are relatively closely aligned as both are focused on improving safety at the study intersection. In addition to improving safety, the tribe also has broader project interests: improving wayfinding to their tribal village and casino as well as creating the opportunity for more of a gateway treatment to their community.

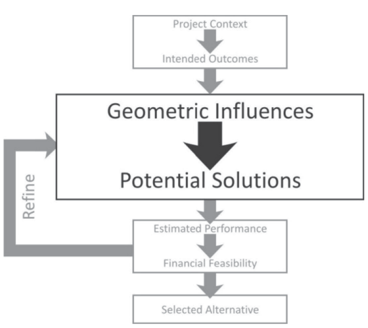
To inform the summary presented in this subsection of the intended project outcomes, we also used the information in Section 5.2.2 (which provides specific considerations for identifying the intended project outcomes), corresponding performance categories, and supporting performance measures. We used Section 4.4.5 to help select the performance measure: expected crash frequency and crash severity.

The continued severe crashes at the US-21/Sanderson Road intersection motivated the tribe and the state department of transportation (DOT) to initiate this study to identify additional safety projects. The tribal community would like those projects to reduce the number and severity of crashes as well as emphasize and enhance the intersection as the gateway to the community. The intersection modifications will need to accommodate a full range of motorized vehicles—agricultural equipment, logging trucks, and passenger vehicles of local residents and visitors.

The primary performance category of interest is safety for the full range of road users just noted. From a geometric design perspective, the primary project category is safety and the performance measures are reducing the number and severity of intersection crashes. As potential solutions are developed, elements such as wayfinding and gateway treatments will be considered qualitatively. As will be discussed, some potential solutions may lend themselves more easily to adding signs, landscaping, and other similar features to emphasize the intersection as the gateway to the tribal land. The geometric design decisions related to each potential solution will be driven more by how they influence potential crash frequency, crash severity, and/or speed as a key influencing factor to crash severity.

6.2.2 Concept Development

6.2.2.1 Geometric Influences



Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics likely related to the key project performance measures.

As a precursor to developing specific solutions for the US-21/Sanderson Road intersection, the project team identified the design elements that have been documented to influence crash frequency, crash severity, and other characteristics related to either frequency or severity of crashes—such as speed as it relates to crash severity or intersection visibility as it relates to frequency and severity of crashes.

Exhibit 6-3 summarizes the design elements related to crash frequency and/or severity. Guidance for identifying the design elements that influence or are influenced by a given performance measure can be found in Section 4.4.

Exhibit 6-3. Design elements related to crash frequency and/or severity.

Performance Target	Related Design Elements	Related Design Considerations
Reduce Total Number of Crashes; Reduce Severity of Crashes	Intersection Control	• Two-Way Stop • All-Way Stop • Traffic Signal • Roundabout
	Intersection Design Features	• Left-Turn Lanes • Right-Turn Lanes • Presence of Lighting • Visibility of Intersection
Increase Intersection Awareness/Visibility	Cross-Sectional Elements on Intersection Approach	• Lane Width • Rumble Strips • Median (painted or splitter island type)
Decrease Vehicle Speed on Intersection Approach	Cross-Sectional Elements on Intersection Approach	• Lane Width • Rumble Strips • Median (painted or splitter island type)
	Alignment on Intersection Approach	• Roadway Curvature • Sight Distance • Advance Signing

Identifying the design elements with the potential to influence crash frequency and severity serves as a starting place for brainstorming and exploring potential solutions. For example, there may be types of solutions that form a single alternative or a solution set that could be common across each alternative. In the case of identifying solutions for the US-21/Sanderson Road intersection, the project team identified the following groupings of alternatives to explore:

- Alternative intersection control
- Advance signing and pavement markings
- Changes in roadway cross-sectional features

As will be seen later in the project example, elements of the advance signing and pavement marking treatments and changes in roadway cross section were transferable across the intersection control alternatives. The added value of this approach was to be able to focus on incorporating a full range of design elements most likely to improve intersection safety.

6.2.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended outcomes, performance measures, and influential geometric elements.

In developing the specific potential solutions, the project team considered the three groups of alternatives noted above in concert with the information available regarding the prevailing crash types, contributing factors to crashes, mix of roadway users, existing roadway features, and surrounding land uses.

Resources Used to Develop Solutions. The prevailing crash types at this intersection were turning and angle crashes. The primary contributing factors cited were failure to yield and excessive speed. Based on the desire to emphasize Sanderson Road as the entrance to the tribal land, the project team identified potential intersection configurations to make the intersection more visible and more clearly identifiable as the main intersection to access the tribal land. This project considered the following:

- Implementing lane narrowing—pavement markings and rumble strips consistent with FHWA publications on low-cost treatment (see reference below)
- Constructing a single-lane roundabout
- Installing a traffic signal
- Implementing specific wayfinding signs and landscaping as gateway treatments

Given the context of the intersection and the potential solutions under consideration, the project team used the following resources to develop specific solutions concepts:

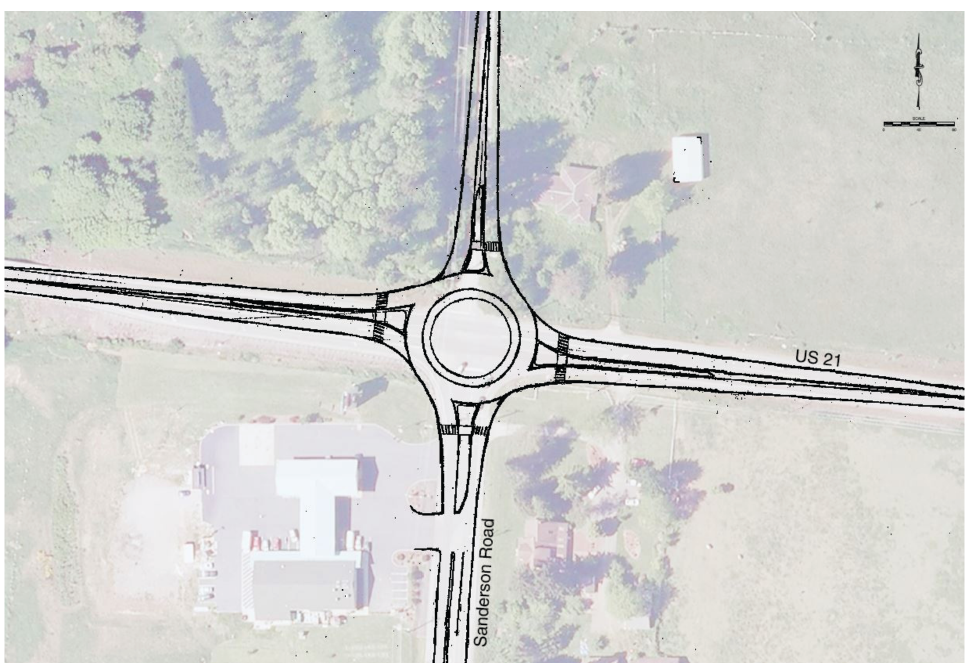
- AASHTO's *A Policy on Geometric Design of Highways and Streets* (*1*)
- *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition* (*2*)
- FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*)
- NCHRP Report 613: Guidelines for the Selection of Speed Reduction Treatments on High-Speed Intersections (*4*)

Solution Development. Using the previously listed resources, the project team developed functional designs of the potential alternatives to initially evaluate the feasibility and potential effectiveness of each concept. The following paragraphs discuss and illustrate this process and the considerations involved in developing the single-lane roundabout and traffic signal concepts.

Exhibit 6-4 illustrates a hand-sketched functional design of a single-lane roundabout alternative. The design is in scaled, sketch form [versus computer-assisted design (CAD)] and provides sufficient detail and information to assess the potential performance of this intersection form and to compare this roundabout treatment with other intersection forms.

The exhibit also notes roadway approach treatments or welcome sign and other enhanced wayfinding as additional elements augmenting intersection design solutions. The enhanced

Exhibit 6-4. Roundabout alternative for US-21/Sanderson Road.



wayfinding and related additional elements are an example of solution types that could be transferable across broader alternatives to help achieve project goals.

The design decisions reflected in Exhibit 6-4 include the following:

- Appropriate size (e.g., inscribed circle diameter) of the roundabout given the posted speed on US-21, design vehicles, and anticipated turning-movement volumes
- Number of entry and exit lanes on each approach given the anticipated turning-movement volumes
- Entry and exit curve radii given the design vehicles and estimated entry, circulating, and exiting vehicle speeds
- Appropriate length of the splitter islands on US-21 to help make the intersection visible and support appropriate speed reduction from the roadway segment to the roundabout entry

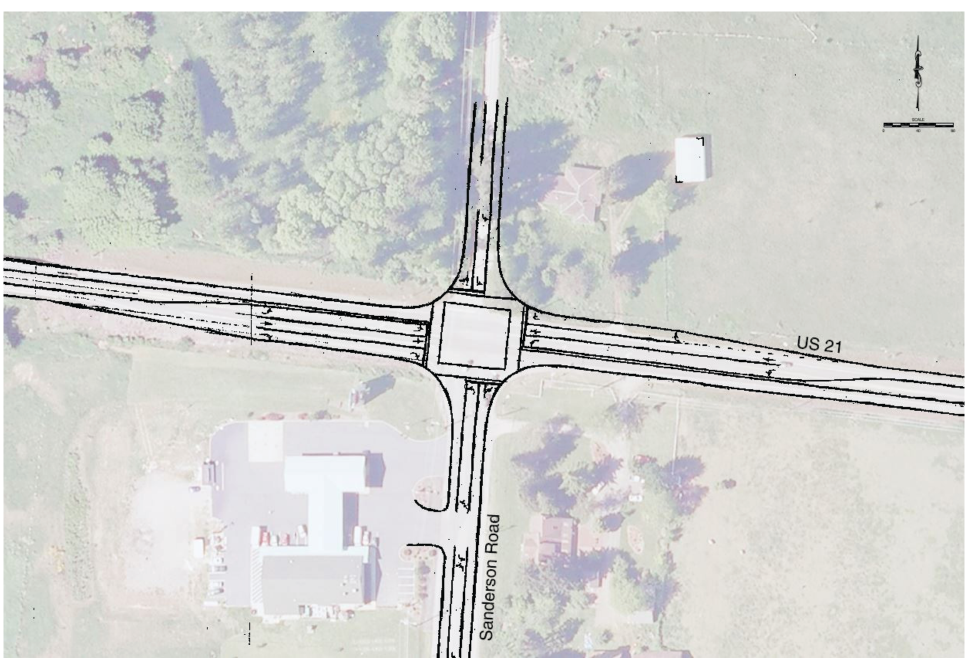
These design considerations and others are more comprehensively described for roundabout intersections in *NCHRP Report 672: Roundabout Informational Guide, Second Edition* (*2*). This document highlights a performance-based approach to assess vehicle speeds, design vehicles service, and ability to accommodate non-motorized travelers.

The key reasons for considering the previously noted roundabout design elements in the alternatives development and evaluation stage is to determine their impact on performance (safety and operations), assess the feasibility of the roundabout, and estimate potential right-of-way impacts of the alternative.

Exhibit 6-5 illustrates a similar level of functional design for the traffic signal alternative. The design decisions reflected in this exhibit include the following:

- Appropriate length of the approach medians on US-21 to help make the intersection visible
- Number of lanes and lane arrangement based on anticipated turning-movement volumes
- Appropriate curve radii based on design vehicles
- Appropriate taper lengths and deceleration lane lengths based on posted speed

Exhibit 6-5. Traffic signal alternative for US-21/Sanderson Road.



Similar to the roundabout alternative, the key reasons for considering these design elements in the alternatives development and evaluation stage is to determine their impact on performance (safety and operations), assess the feasibility of the traffic signal, and estimate potential right-of-way impacts of the alternative. While completed at a scaled sketch level, each intersection concept is completed at sufficient detail to allow a side-by-side comparison of the two forms.

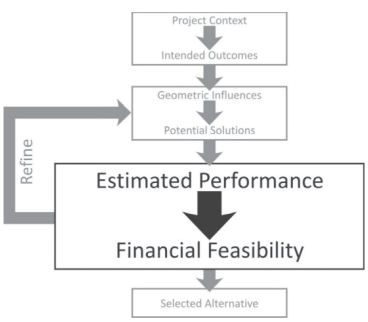
Primary Alternatives for Evaluation. The three primary long-term alternative solutions considered for the US-21/Sanderson Road intersection include the following:

- A single-lane roundabout with wayfinding and gateway treatments
- A traffic signal with wayfinding and gateway treatments
- Current two-way stop-controlled intersection form with enhanced wayfinding and gateway treatments

The overarching purpose of the wayfinding and gateway treatments is to help increase the intersection visibility for drivers on US-21, raise motorist awareness of the potential conflicts that may occur at the intersection, and direct visitors to use the US-21/Sanderson Road intersection as the entrance to the tribal land. Many of the wayfinding and gateway treatments were based on principles in *NCHRP Report 613: Guidelines for the Selection of Speed Reduction Treatments at High-Speed Intersections* (*4*) and FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*).

6.2.3 Evaluation and Selection

6.2.3.1 Estimated Performance and Financial Feasibility



Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.

The primary intent of the intersection project for US-21/Sanderson Road is to reduce the frequency and severity of crashes. The secondary consideration is incorporating wayfinding and gateway treatments at the intersection. The performance evaluation and financial feasibility used to evaluate the primary alternatives focused on evaluating safety effectiveness as related to the likelihood of reducing crash frequency and severity.

Estimating Performance. Exhibit 6-6 summarizes similar information as Exhibit 6-3 with the addition of tools or resources available to evaluate how those design elements and decisions relate to safety. Section 4.4 provides guidance on similar resources for safety, operations, access, and quality of service performance categories.

Of the resources noted in Exhibit 6-6, the HSM (*5*) and FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) were the primary resources used to quantify the anticipated crash reduction (severity and frequency) of the alternative solutions. *NCHRP Report 613* (*4*) and FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) also provided useful performance information regarding the potential for reduced speeds on the intersection approach.

Incorporating Financial Feasibility. The project team incorporated a financial assessment into the alternatives evaluation to identify the relative cost effectiveness of each alternative. In

Exhibit 6-6. Design elements related to crash frequency and/or severity.

Performance Target	Related Design Elements	Related Design Considerations	Tools or Resources to Evaluate Performance
Reduce Total Number of Crashes; Reduce Severity of Crashes	Intersection Control	• Two-Way Stop • All-Way Stop • Traffic Signal • Roundabout	• *Highway Safety Manual*, Chapters 10 and 14 (*5*) • Supporting Software Tools: HiSafe; IHSDM
	Intersection Design Features	• Left-Turn Lanes • Right-Turn Lanes • Presence of Lighting • Visibility of Intersections	• *Highway Safety Manual*, Chapters 10 and 14 (*5*) • Supporting Software Tools: HiSafe; IHSDM • FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) • *NCHRP Report 613* (*4*)
Increase Intersection Awareness/Visibility	Cross-Sectional Elements	• Lane Width • Rumble Strips • Median (painted or splitter island type)	• FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) • *NCHRP Report 613* (*4*)
Decrease Vehicle Speed on Intersection Approach	Cross-Sectional Elements on Intersection Approach	• Lane Width • Rumble Strips • Median (painted or splitter island type)	• FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) • *NCHRP Report 613* (*4*)
	Alignment on Intersection Approach	• Roadway Curvature • Sight Distance • Advance Signing	• FHWA's *Low-Cost Safety Concepts for Two-Way Stop-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways* (*3*) • *NCHRP Report 613* (*4*)

this project, the cost per mitigated crash was used as the performance measure to gauge the relative economic performance for an alternative. The evaluation did not quantify the potential benefits of reduced vehicle speeds, the wayfinding, or the gateway treatments because it is not currently possible to relate those attributes directly to anticipated reduction in crash frequency. In the ultimate improvement selection step, those attributes are considered qualitatively.

Exhibit 6-7 summarizes the expected safety performance and cost effectiveness of the alternatives for the US-21/Sanderson Road intersection. The project team estimated the safety performance expected to result from each alternative using the resources summarized in Exhibit 6-6.

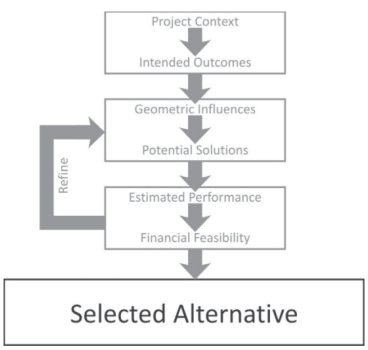
In this instance, planning-level cost estimates were developed to assess the relative cost effectiveness of each solution and to inform prioritizing implementation of the project elements. The functional design sketches helped identify that the signalized intersection approach configuration would require modifying an existing bridge west of the intersection. This bridge construction greatly increased the cost of the signalized alternative compared to the roundabout concept.

Benefit-cost ratios could also be used to assess the economic validity of alternative solutions; this would provide a sense of whether the potential benefits of a project are sufficient to justify its cost. The sole purpose of the financial assessment is to inform decisions of how best to allocate limited resources for greatest possible benefit.

Exhibit 6-7. Initial design decisions/potential solutions and estimated performance.

Location—Solution	Expected Crashes/Year (No.)	Estimated Reduction (%)	Crashes Mitigated/ Year (No.)	Design Life (Years)	Planning-Level Cost Estimate	Cost/Crash Mitigated Over Design Life
Sanderson Road TWSC Intersection—FHWA Lane Narrowing	2.2	31	0.7	5	$45,000	$13,196
Sanderson Road TWSC Intersection—FHWA Splitter Island	2.2	68	1.5	5	$112,500	$15,040
Sanderson Road—Single-Lane Roundabout	2.2	71	1.6	20	$3.15 million	$100,832
Sanderson Road—Traffic Signal	2.2	36	0.8	20	$5.61 million	$354,167

TWSC: Two-way stop-controlled



6.2.3.2 Selected Alternative

Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., radius of a horizontal curve). This information helped inform the following discussion and decision.

Based on the alternatives evaluation, the tribe and DOT decided to implement a roundabout at the US-21/Sanderson Road intersection. The roundabout, in combination with the wayfinding and gateway treatments, provides the greatest long-term potential for reducing the intersection crash frequency and severity. The roundabout also creates multiple opportunities for gateway treatments at and on approach to the intersection. Finally, the roundabout at the intersection proper and the splitter islands on the intersection approaches create definitive visual cues and changes in roadway geometry to capture motorists' attention and aid in reducing approach speeds.

Authors' Note: Constructing a single-lane roundabout at the US-21/Sanderson Road intersection is quantitatively the third most cost-effective solution intersection with regard to reducing crashes. The tribe and DOT selected it over the two lower-cost configurations because the roundabout provides the long-term safety benefits and creates the ability for the tribe to achieve some of its broader overarching goals of improving wayfinding to access the tribal village and casino as well as creating a gateway treatment to tribal land. This combination of considerations led to selecting the roundabout.

6.3 Project Example 2: Richter Pass Road

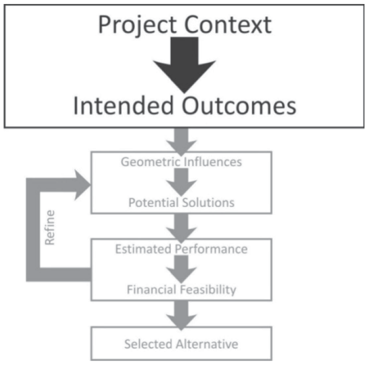
Authors' Note: Project Example 2 considers alternative alignments to improve safety and maintain mobility along a rural two-lane roadway. In this project example, we consider the tradeoffs related to the safety and mobility performance categories. Specifically, the project example demonstrates the tradeoffs between improving safety and maintaining a reasonable level of mobility, while minimizing project costs. The performance measure used for mobility incorporates the concept of inferred speed from FHWA's Speed Concepts: Informational Guide *(6).* Speed Concepts *outlines a performance-based perspective on the relationship between operating speed, posted speed, design speed, and inferred speed. The learning objectives of this project example include the following:*

- *Illustrate the tradeoffs to consider when trying to achieve performance characteristics that may be counter to one another*

- *Use* Speed Concepts *and the concept of inferred speed in informing design decisions*
- *Illustrate the design flexibility agencies have to not select the alternative with the lowest predicted number of crashes*

6.3.1 Project Initiation

6.3.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context likely to help inform the intended project outcomes, performance category, and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. In this project example, the topographic constraints and their influence on roadway geometry is a key influencing factor in the solution development, evaluation, and selected alternative.

Richter Pass Road is a two-lane rural roadway. Development has expanded from adjacent urban areas and begun to impact the hillside that Richter Pass Road traverses. Over the last several years, there has been a gradual increase in residential homes and other development adjacent to and accessing the roadway. Richter Pass Road traverses the top of a hill and ridge with sections also built into the side of steeper portions of the hill and ridgeline. As a result, the roadway has limited to no shoulders along its curvilinear alignment constrained by the topography. The roadway commonly has steep sideslopes with drop-offs on one side of the roadway and retaining walls or cuts through rock on the other side of the roadway. Exhibit 6-8 provides a schematic of the study area.

Exhibit 6-8. Project area schematic.

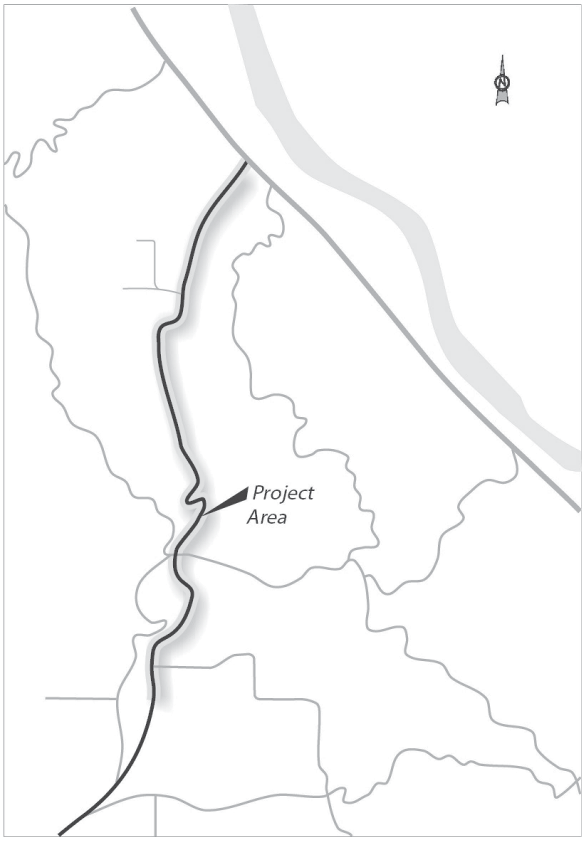


Exhibit 6-9. Speed feedback sign improvement.

With the steady increase in traffic volume along the roadway, there has also been an increase in crashes. The majority of crashes, approximately 72% within the last 3 years, were run-off-the-road crashes. In the past, the county and state DOT implemented a series of low-cost safety treatments including increased curve delineation, guardrail, and speed feedback signs. Exhibits 6-9 and 6-10 illustrate some of these treatments.

The designated facility design speed is 55 mph. The posted speed is 45 mph. Advisory speed signs for horizontal curves along the roadway are as low as 15 mph in some locations.

6.3.1.2 Intended Project Outcomes

Authors' Note: The following summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, similar to Project Example 1, the two are relatively closely aligned. The basic purpose is to improve safety while maintaining a reasonable level of mobility.

We also used Section 5.2.2 to inform the following summary of the intended project outcomes. Section 5.2.2 provides specific considerations for identifying the intended project outcomes, corresponding

Exhibit 6-10. Curve delineation improvements.

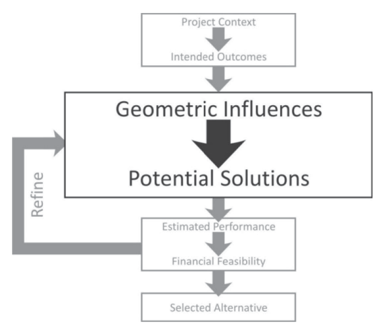
performance categories, and supporting performance measures. In this project example, safety and mobility are the performance categories of interest. We used Sections 4.4.2 (Mobility) and 4.4.5 (Safety) to select the performance measures: inferred speed and crash frequency.

Residents along Richter Pass Road want to reduce crashes and crash severity. The county and DOT have jurisdiction over adjacent segments of the roadway. Both agencies are interested in making the corridor more consistent in its design to better meet driver expectations. The roadway alignment currently has horizontal curves designed for speeds of 15 mph to 50 mph. There is limited budget for treatments; however, the county and DOT recognize to achieve long-term increases in safety performance (i.e., decreases in the number and severity of crashes) investments are needed beyond the previous low-cost improvements. The primary target audience for the project is the motorists traveling the roadway. This population comprises primarily residents in the area, commuting traffic, and some recreational traffic to access multiuse trails that traverse the hillside.

The primary performance categories of interest are safety and mobility. The project is intended to improve safety while maintaining a reasonable level of mobility for motorists. The primary performance measures related to safety are the number and severity of crashes. The performance measure for mobility is travel speed, with the intent of establishing a reasonable travel speed for the corridor. To evaluate mobility, the project team selected inferred speed relative to the posted speed as the performance measure. Inferred speed is explained in greater detail within FHWA's *Speed Concepts: Informational Guide* (*6*). The practical definition of inferred speed is the speed a motorist is able to drive without physically departing the travel lane; it is the speed as defined by the roadway geometrics.

6.3.2 Concept Development

6.3.2.1 Geometric Influences



Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics likely related to the key project performance measures.

The horizontal roadway alignment and potential for increased shoulder width were selected as the primary geometric elements on which to focus in developing alternative solutions for Richter Pass Road. These elements were selected as the focus because of the proportion of run-off-the-road crashes. Horizontal curvature (i.e., curve radii, superelevation, and length) has been found to have a definitive, quantifiable impact on crashes occurring on rural two-lane roadways. The same basic horizontal alignment elements also have a direct impact on inferred speed, which is the selected metric for mobility. Similarly, shoulder width, and to a lesser degree shoulder type, have also been found to definitively influence crash occurrence on rural two-lane roadways. Under the given project context, the combination of horizontal alignment and shoulder width are likely to have the largest impact on the intended project outcomes of improving safety and establishing reasonable mobility for the roadway. Additional guidance for identifying the design elements that influence or are influenced by a given performance measure can be found in Section 4.4.

6.3.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended outcomes, performance measures, and influential geometric elements.

The critical balancing act in developing potential solutions for Richter Pass Road, and ultimately selecting the preferred solution, will be the project costs.

The critical balancing act in developing potential solutions for Richter Pass Road, and ultimately selecting the preferred solution, will be the project costs. The terrain and topography through which Richter Pass Road passes likely necessitates cut, fill, and retaining walls for nearly any change in horizontal alignment or shoulder width. As a result, designs with greater requirements for cut, fill, and/or retaining walls are likely to be considerably more expensive than other alternatives.

Considering the project context, intended outcomes, and geometric elements most likely to influence the key project performance measures, the project team explored alternatives that reflect a range of investment and construction magnitude within which design solutions may be considered and evaluated These alternatives consist of four basic types:.

- **Basic Alternative 1—Minimal Improvements:** Maintain current alignment and increase shoulder width. This represents the minimal investment the County and DOT are expecting to make in improvements.
- **Basic Alternative 2—Ultimate Improvements:** Modify alignment to meet AASHTO criteria for 55 mph design speed and increase shoulder width. This represents a more traditional "ultimate" roadway build-out in which Richter Pass Road would be reconstructed to be consistent with design criteria that matched its current functional designation (e.g., design speed of 55 mph).
- **Basic Alternative 3—Practical Improvements:** Modify alignment for consistent inferred speed and change posted speed to match inferred speed; this may result in a lower posted speed than exists. This represents a moderate design that is intended to strike a balance between Alternatives 1 and 2 and provide a long-term alternative solution. In this instance, Alternative 3 may help the county and DOT redefine and re-establish Richter Pass Road's overarching purpose and function in the roadway network (i.e., does it really need to be a roadway that motorists can travel on at 55 mph?).
- **Basic Alternative 4—Subultimate Improvements:** Modify alignment to meet AASHTO criteria for 55 mph design speed without increasing shoulder width. This represents a more traditional "interim" or "subultimate" improvement in which Richter Pass Road would be reconstructed to match its currently designated design speed and additional investment needed for increasing the shoulder width would be put off to a future date.

The following subsections describe the resources used to develop the alternative solutions and considerations in further refining the basic alternatives into specific alternatives for evaluation.

Resources Used to Develop Solutions. The project team used *A Policy on Geometric Design of Highways and Streets* (*1*), the DOT's roadway design manual, and *Speed Concepts* (*6*) as the primary resources to develop and define the four alternatives.

Solution Development. The key differentiating elements for the alternatives are horizontal alignment and shoulder width. The horizontal alignment elements for Alternatives 2 and 4 are already defined since a design speed of 55 mph is specified for those alternatives. A specific shoulder width needs to be defined for Alternatives 1 and 2. A specific inferred speed needs to be established for Alternative 3 so the horizontal alignment elements can be designed. The project team does not have the scope, budget, or time to evaluate a full range of potential shoulder widths or a full range of potential inferred design speeds. Therefore, the project team narrowed the possible shoulder widths and inferred speeds to explore, based on the project context, intended project outcomes, and a fundamental understanding of how shoulder width and horizontal alignment influence safety and inferred speed.

Preliminary Shoulder-Width Considerations. The existing Richter Pass Road has no measureable shoulder width; therefore, any increase in shoulder width is likely to provide a safety benefit. If an investment is made to add shoulder width, the county and DOT would like to see sufficient shoulder width to enable a disabled vehicle to pull to the side and leave a total of 22 ft available for other motorists to pass and incident response activities. The current lane widths are 12 ft, providing 4-ft shoulders in each direction would provide the residual 22 ft if a disabled vehicle pulled to the side of the roadway. This provides 10 ft of width for the disabled vehicle. The project team did a preliminary analysis of the potential crash reduction [using Chapter 10 of the HSM (*5*)] and cost per linear foot of increasing shoulder width from 0 to 2 ft and 0 to 4 ft. The preliminary analysis indicated the following:

- Shoulder width 0 to 2 ft
  - 9% crash reduction
  - $20 per linear foot of 2-ft-wide paved shoulder (approximately $211,200 for 1 mi of 2-ft-wide paved shoulder in both directions)
- Shoulder width of 0 to 4 ft
  - 17% crash reduction
  - $60 per linear foot of 4-ft-wide paved shoulder (approximately $633,600 for 1 mi of 4-ft-wide paved shoulder in both directions)

Based on the preliminary screening and analysis, the county and DOT decided to carry forward Alternatives 1 and 2 using a shoulder width of 4 ft. The 4 ft of shoulder would provide 22 ft for vehicles to pass the disabled vehicle and for incident management activities. While the cost of adding 4 ft of shoulder is notably greater than 2 ft, the county and DOT decided it could be worth the investment given the potential crash reduction and space for incident management. There are limited alternative routes providing access to the residences off of Richter Pass Road; therefore, keeping the roadway open maintains local mobility and access.

Preliminary Inferred Speed Considerations. The county and DOT recognize Richter Pass Road is performing a different function and role in the overall roadway network than when it was originally constructed. Since it was built as a rural arterial, larger roadway facilities have been created that provide parallel and more efficient regional connections. As a result, Richter Pass Road functions more as a collector road providing mobility and access to residents living in adjacent developments. Given these changes to the surrounding context of Richter Pass Road, discussions with the County, DOT, and community arrived at the general consensus that the preferred operating speed for the roadway is 35 mph. Therefore, the inferred speed used to develop Alternative 3 was 35 mph.

Primary Alternatives for Evaluation. Based on the solution development [i.e., establishing dimensional values for the shoulder widths (4 ft) and selecting an inferred speed (35 mph)] and refinement of the initial broad alternatives, the project team identified the four specific alternative solutions for evaluation:

- **Alternative 1—Minimal Improvements:** Maintain current alignment and increase shoulder width from 0 to 4 ft.
- **Alternative 2—Ultimate Improvements:** Modify alignment to meet AASHTO criteria for 55 mph design speed and increase shoulder width from 0 to 4 ft.
- **Alternative 3—Practical Improvements:** Modify alignment for consistent inferred speed of 35 mph and change posted speed to 35 mph to match inferred speed.
- **Alternative 4—Subultimate Improvements:** Modify alignment to meet AASHTO criteria for 55 mph design speed without increasing shoulder width.

Once the alternatives were more clearly defined, the project team used aerial imagery, survey data, and CAD software to lay out the alternatives and estimate right-of-way impacts, cut and fill requirements, and potential need for retaining walls. This meant including the dimensional values of a shoulder width of 4 ft and the horizontal curve radius, length, and superelevation for 35 mph (for Alternative 3) and 55 mph (for Alternatives 2 and 4).

The team documented the resulting curve radii, length, superelevation, and shoulder width for each alternative. These geometric characteristics will be key inputs for calculating safety and mobility performance and estimating the cost for each alternative.

Exhibits 6-11 (Alternative 2) and 6-12 (Alternative 3) illustrate the difference between the horizontal curves within the alternatives. A relatively quick visual inspection of the two curves clearly illustrates key differences in horizontal curve characteristics and the tradeoffs between the two fundamentally different approaches.

- **Alternative 2** is the traditional approach to bring a roadway up to meet its established standard based on functional classification. Fewer curves, larger curve radii, and longer curves

Exhibit 6-11. Alternative 2 horizontal alignment.

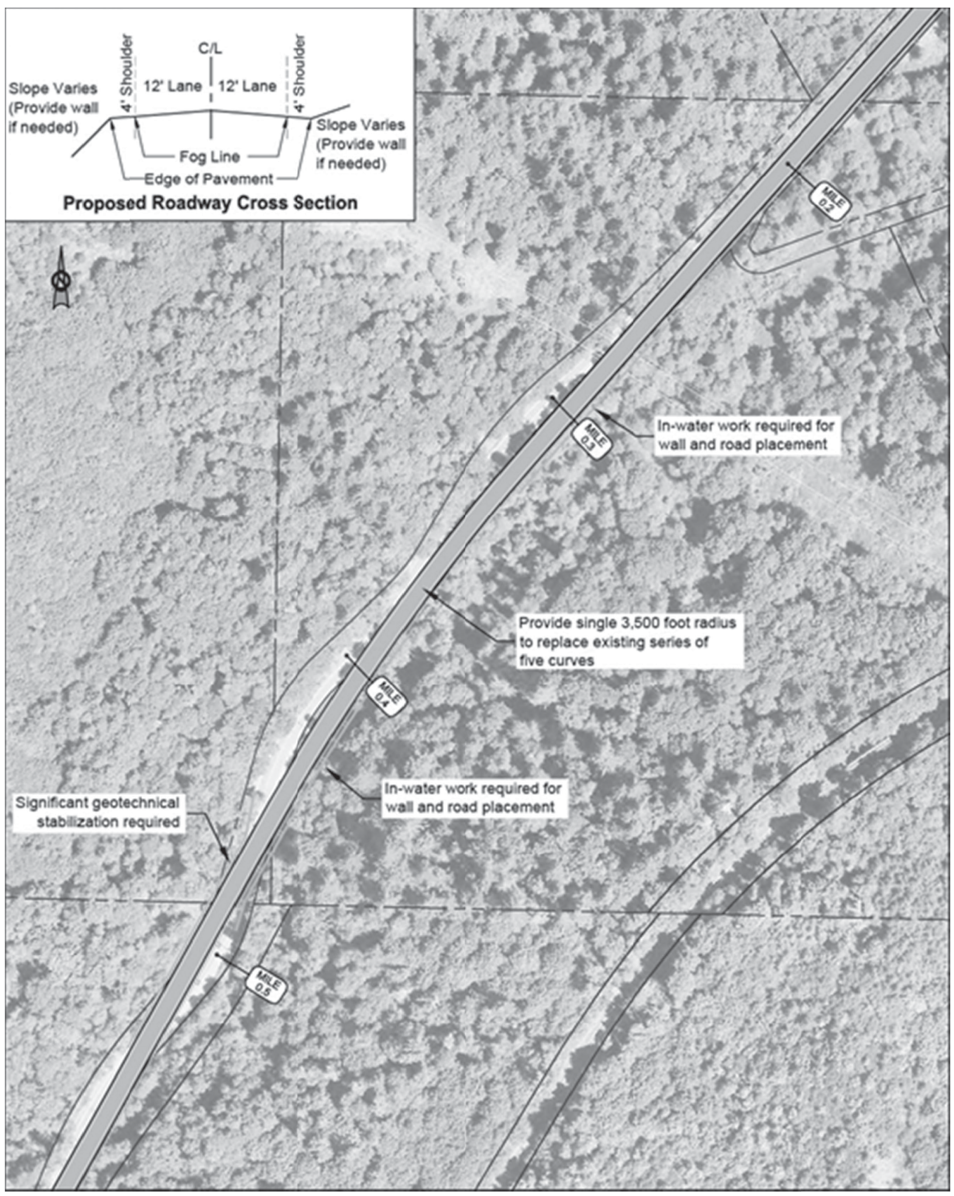
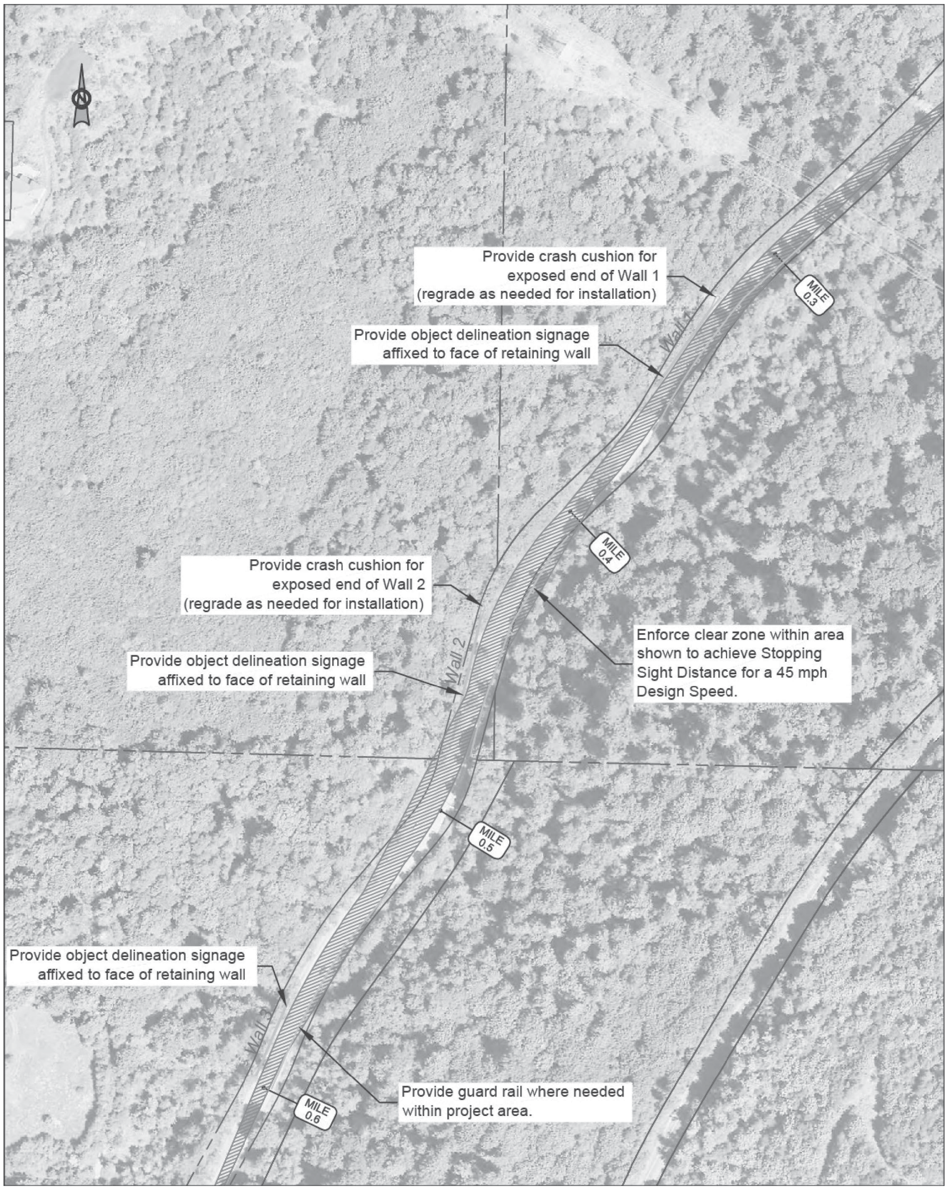


Exhibit 6-12. Alternative 3 horizontal alignment.



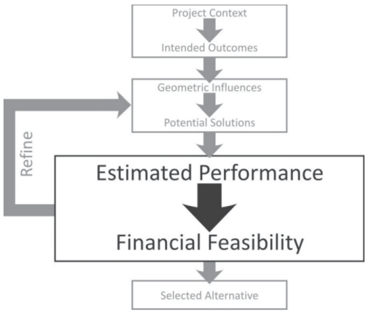
are key characteristics of the horizontal alignment in Alternative 2. This corresponds to higher inferred speeds, lower predicted crashes, higher cut/fill volumes, and higher construction costs relative to Alternative 3.

- **Alternative 3** is more of a pragmatic approach to modify the roadway to fit its physical context and current function and to establish consistent expectations for road users. The Alternative 3 horizontal alignment has more curves with smaller curve radii and is shorter in length compared to Alternative 2. This corresponds to the lower cut/fill estimates, lower construction costs, lower inferred speeds, and higher predicted crashes relative to Alternative 2.

As will be discussed further, the two alternatives have notably different performance characteristics, impacts, and costs. The following section summarizes and discusses the performance and financial feasibility evaluation of the alternatives.

6.3.3 Evaluation and Selection

6.3.3.1 Estimated Performance and Financial Feasibility



Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.

The performance evaluation focused on safety as defined by crash frequency and mobility as defined by inferred speed (used as a surrogate for operating speed).

Estimating Performance. Chapter 10 of HSM (*5*) was used to estimate the impact each alternative had on crash frequency. *Speed Concepts* (*6*) was used to evaluate each alternative's impact on inferred speed relative to posted speed. As discussed previously, the primary geometric features influencing these performance characteristics are horizontal curves (radii, superelevation, length) and shoulder width. Exhibit 6-13 summarizes the evaluation results for each alternative, including the estimated cut or fill required.

Based on the safety and mobility evaluation results, Alternative 2 is estimated to result in the lowest frequency of crashes; however, it has one of the higher ranges of inferred speed and the largest average requirement of cut and fill. Alternatives 3 and 4 are estimated to have the next lowest average crash frequencies. Alternative 3 has the most consistency with inferred speed and requires the second lowest amount of average cut and fill.

The tradeoffs shown in the table illustrate some of the considerations in trying to achieve multiple performance characteristics and produce a financially feasible solution. The transportation profession's research regarding crash prediction for rural two-lane roadways indicates longer horizontal curves with larger radii tend to result in fewer roadway departure crashes. Such horizontal curves also enable motorists to drive at higher speeds. In mountainous or rolling terrain, this can result in more cut or fill and therefore higher project costs. Research indicates horizontal curves that are shorter in length and have smaller curve radii tend to result in more roadway departure crashes (*5*). Such horizontal curves also result in slower motorist speeds, which is desirable in this context for Richter Pass Road. In mountainous and rolling terrain, shorter horizontal curves with smaller radii tend to require less cut or fill and therefore tend to be lower in cost.

To help further inform the county and DOT's selection of an alternative, the project team estimated the cost for each alternative.

Exhibit 6-13. Evaluation results of each alternative.

Alternative	Safety Performance (crashes/year[a])	Mobility Performance (inferred speed[b])	Average Cut or Fill Required per Station (yd^3)
No Project	13	15 to 55 mph	0
1 – Minimal	11	15 to 55 mph	100
2 – Ultimate	4	60 to 80 mph	700
3 – Practical	7	35 to 40 mph	200
4 – Subultimate	6	60 to 80 mph	450

[a]Expected (average) annual total crashes per year.
[b]Inferred speed of horizontal curves within study area.

Exhibit 6-14. Cost estimates for evaluation results.

Alternative	Safety Performance (crashes/year[a])	Mobility Performance (inferred speed[b])	Cost per Mile
No Project	13	15 to 55 mph	$0
1 – Minimal	11	15 to 55 mph	$633,600
2 – Ultimate	4	60 to 80 mph	$5.0 million
3 – Practical	7	35 to 40 mph	$1.5 million
4 – Subultimate	6	60 to 80 mph	$4.3 million

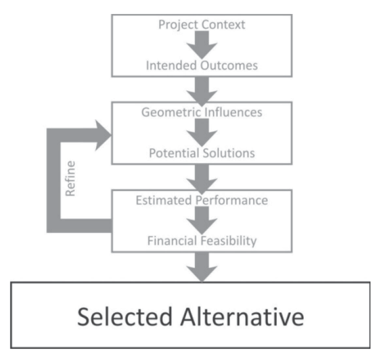
[a]Expected (average) annual total crashes per year.
[b]Inferred speed of horizontal curves within study area.

Incorporating Financial Feasibility. The project team developed cost estimates for each alternative. The cost estimates took into consideration key cost drivers such as cut, fill, retaining walls, and right-of-way acquisition. Exhibit 6-14 summarizes the cost estimates with the evaluation results shown previously.

The project team decided not to estimate a benefit/cost ratio or calculate a cost-effectiveness factor for each alternative. The county, DOT, and project team believed that would oversimplify some of the considerations that cannot be monetized or quantified for a cost-effectiveness assessment. For example, the value and benefit of establishing a consistent and predictable roadway alignment for motorists (i.e., low variability in inferred speed) is not something that can be directly captured by a benefit/cost ratio or cost-effectiveness evaluation. The county and DOT used the cost estimate information in combination with the performance results and understanding of the project context to select the preferred alternative.

6.3.3.2 Selected Alternative

Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., radius of a horizontal curve). This information helped inform the following discussion and decision.



The county and DOT decided to implement Alternative 3. Alternative 3 achieves the desired crash reduction relative to existing conditions. It also creates a uniform driving experience for motorists; the alignment is consistently designed for 35 mph. The county, DOT, and community collectively agreed Richter Pass Road's purpose and function are more aligned with serving a local mobility and access function. They agreed 35 mph is a more reasonable posted speed for motorists, and creating an alignment that inherently reinforces the posted speed of 35 mph is appropriate for the corridor. The county, DOT, and community recognize a lower speed for the roadway may slightly degrade mobility. However, they are willing to accommodate lower mobility for a more affordable safety improvement.

Authors' Note: Upon further discussion regarding Alternative 3, the county and DOT chose to explore further refining Alternative 3 by including the 6-ft-wide shoulders. The subsequent safety and cost evaluation indicated the 6-ft-wide shoulders reduced crashes to approximately six crashes per year and raised the total project cost to approximately $3 million per mile. Based on the limited additional reduction in crashes (one additional crash reduced per year with an increase in cost of $1.5 million per mile) and corresponding relatively significant increase in cost, the county and DOT decided to move forward with their original selection of Alternative 3 with 4-ft-wide shoulders.

The performance-based analysis to inform the solution development and project decisions within this project example enabled the county and DOT to identify a solution that balanced their safety *and mobility performance goals at a financially feasible level of investment. The agencies were able to look beyond the traditional approach (i.e., Alternative 2) of fully building out a roadway to meet a pre-defined standard that, in this instance, no longer coincided with the function the roadway was playing or was going to play in the future. The performance-based analysis framework gave the agencies the tools they needed to identify the critical elements of project context, intended project outcomes, key performance categories and measures influencing geometric considerations, and methods for evaluating each alternative's anticipated performance.*

6.4 Project Example 3: Cascade Avenue

Authors' Note: Project Example 3 illustrates how performance-based analysis can be integrated into reconstructing an existing auto-oriented urban arterial to incorporate complete street attributes with a focus on alternative street cross sections. In this project example, the project is initiated and championed by local business owners (i.e., local business improvement district) who would like to see the corridor revitalized in terms of the local economy and broader community livability.

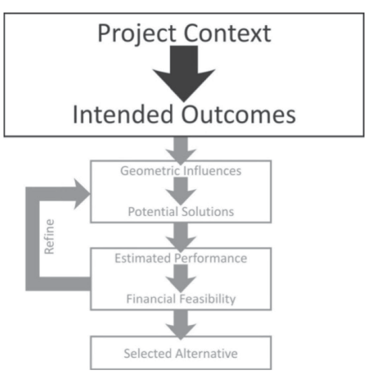
The learning objectives of this project example include the following:

- *Incorporate performance measures and decisions related to accommodating multiple modes*
- *Illustrate tradeoffs between modes considering measures beyond mobility*
- *Capture considerations and tradeoffs within a constrained physical environment*

The broader project objectives (i.e., increase economic vitality and community livability) are connected to geometric design performance categories of quality of service for multiple modes, safety, access, reliability, and mobility. Section 3.1.2 discusses how the intended project outcomes correspond to the performance categories. Sections 3.2 and 3.3 were used to help differentiate between and link together the project performance and geometric design performance. Section 4.4 helped inform the selection of specific performance measures within each performance category.

6.4.1 Project Initiation

6.4.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context that are likely to help inform the intended project outcomes and the performance category and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. An important factor in the context of this project example is that the motivation for the project is being driven by members of the local business community who would like to see the corridor revitalized from an economic standpoint and also from a long-term livability perspective for the surrounding community.

The local business community lobbied city staff and decision makers to study and implement design solutions to Cascade Avenue. The intended project outcome is to make it a more comfortable, safe, and attractive urban street for transit riders, pedestrians, and bicyclists. Cascade Avenue is an urban arterial providing a north-south connection between the downtown district and a university campus approximately 2 mi north of downtown. It is currently a four-lane undivided arterial with on-street parallel parking and intermittent transit stops. Under the existing condition, there are no bicycle lanes and sidewalks are curb-tight (i.e., no landscape buffer between the sidewalk and roadway).

The AADT volume for Cascade Avenue is 22,000 vpd. It is a key arterial for three different fixed transit routes serving approximately 45% of the transit riders traveling within the city.

Despite the lack of bicycle facilities on Cascade Avenue, it is already a frequently used route by bicyclists traveling between downtown and the university campus as it is the most direct route between those two origins-destinations. The posted speed on Cascade Avenue is 35 mph. Local law enforcement has a difficult time enforcing the posted speed during off-peak periods when traffic is relatively low. The higher speeds in off-peak travel periods make Cascade Avenue less attractive to pedestrians an d bicyclists.

The local business community would like Cascade Avenue to become a more well-rounded city street. They would like people in the surrounding communities to see and use it as a place to spend time, visit shops, linger at cafes and restaurants, as well as use it to travel within the city. The business community's overarching motivation for the project is to revitalize Cascade Avenue and the surrounding area economically. They see improvements to Cascade Avenue from an urban design and transportation perspective as critical to their mission. The city agreed to study the street and identify and evaluate a range of potential configurations to better serve multiple modes and create a more complete urban street environment.

The local business community would like Cascade Avenue to become a more well-rounded city street.

This project example documents the preliminary design development and evaluation of alternative street cross sections. The primary condition requested by local business owners was to keep the potential solutions on Cascade Avenue within the existing 82-ft-wide right-of-way. The business community is open to removing the existing on-street parking as a means to provide more space for other modes or uses. They are also in the process of gaining support from a broad base of local business owners to form a local improvement district (LID) to help fund the project.

6.4.1.2 Intended Project Outcomes

Authors' Note: The following subsection summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, the project purpose is to enhance the multimodal characteristics of Cascade Avenue in support of the local business improvement district that would like to have more pedestrian activity along the corridor as a means for revitalizing the surrounding community. There are no direct geometric performance measures for evaluating how well a project alternative will revitalize or facilitate economic or community growth. However, there are indirect geometric performance measures contributing to characteristics that would support economic and/or community revitalization (e.g., quality of service for pedestrians, bicyclists, and transit riders).

We used the information in Chapter 3 to help differentiate between the project performance and geometric performance. We also used Section 5.2.2 to inform the following summary of the intended project outcomes, including the applicable performance categories. In this project example, safety, mobility, quality of service, accessibility, and reliability are the geometric performance categories contributing to the broader goal of improving economic vitality along the corridor. We used Section 4.4.1 (Accessibility) through 4.4.5 (Safety) to select the performance measures.

The local business community is the champion for the project. They are the catalyst for identifying and implementing a project on Cascade Avenue with the purpose of revitalizing the street and surrounding areas from an economic and livability perspective. The primary target audience is the business community stakeholders who would like to see transit riders, pedestrians, and bicyclists better served by Cascade Avenue. As a result, transit riders, pedestrians, and bicyclists are key road users served by the project. Secondary target audiences include local residents and existing motorists. The project will need to balance the impacts on existing automobile and transit service. The key agency stakeholders are the city and local transit agency. The city has jurisdictional responsibility over Cascade Avenue. Therefore, it will be responsible for capital improvements, maintenance, and operations of the street. The local transit agency currently has three of its major fixed-route bus routes using Cascade Avenue to serve a large portion of its ridership.

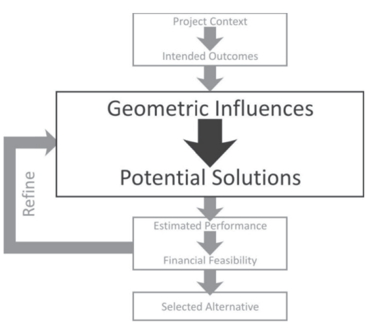
The intent of the study is to improve the road user experience, provide access for road users not previously served, while enhancing the economic vitality and activity of the street. The performance categories selected are quality of service, safety, accessibility, reliability, and mobility. The performance measures to be used to evaluate alternative roadway cross sections are as follows:

- Quality of service—MMLOS from HCM2010
- Safety—Crash frequency and number and management of conflict points
- Accessibility—Type and presence of facilities and transit service characteristics
- Mobility—Average travel time
- Reliability—Consistency in travel time

These performance measures do not directly measure economic vitality for an area or the potential for economic vitality. However, they are connected to geometric characteristics and reflect characteristics influencing different road users' quality of experience. For example, a better MMLOS grade for the pedestrian mode corresponds to roadway geometric characteristics more likely to create an attractive environment in which pedestrians feel safe and comfortable. This helps achieve the business community's goal of transforming Cascade Avenue into a city street where people want to shop, dine, and generally spend time. Similar parallels can be drawn for the other performance measures listed.

6.4.2 Concept Development

6.4.2.1 Geometric Influences



Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics that are likely related to the key project performance measures.

Roadway cross-sectional elements were selected as the primary geometric elements likely to influence the performance measures noted in Section 6.4.1.2. These cross-sectional elements include the following:

- Lane width
- Number of automobile through lanes
- Bicycle facility presence and type (e.g., bicycle lanes, buffered bicycle lanes)
- Sidewalk width
- Presence and width of landscaped buffer between sidewalk and travel lanes
- Presence and type of on-street parking (e.g., parallel parking, angled parking)
- Bus-only lanes
- Central roadway median

The potential solutions discussed in the following section explore different combinations of cross-section characteristics and create a range of alternatives reflecting the tradeoffs inherent in trying to serve different travel modes within a constrained right-of-way. Additional guidance for identifying the design elements that influence or are influenced by a given performance measure can be found in Section 4.4.

6.4.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended project outcomes, performance measures, and influential geometric elements.

The primary constraint and challenge in developing solutions for Cascade Avenue is serving the range of existing and desired road users within the existing right-of-way. Automobiles are currently given the majority of space on Cascade Avenue; therefore, additional alternatives developed for Cascade Avenue are oriented toward one or more combinations of better serving transit riders, pedestrians, and bicyclists. The four basic alternatives (including the existing condition) are:

- Basic Alternative 1—Existing cross section oriented toward serving automobiles
- Basic Alternative 2—Transit-oriented cross section
- Basic Alternative 3—Bicycle- and pedestrian-oriented cross section
- Basic Alternative 4—Hybrid of transit, bicycle, and pedestrian features

Alternative 1 will serve as a common baseline for comparison across alternatives; it is the existing roadway that prioritizes space for automobiles. Alternative 2 focuses on serving transit vehicles and riders. The roadway features within Alternative 2 include elements such as transit-only lanes. Alternative 3 is oriented toward bicycle and pedestrian modes and includes features such as buffered bicycle lanes. Alternative 4 is a hybrid of Alternatives 2 and 3. It strives to balance the needs of transit riders, bicyclists, and pedestrians. The following sections discuss the resources used to develop the solutions, the process, and the primary alternatives evaluated.

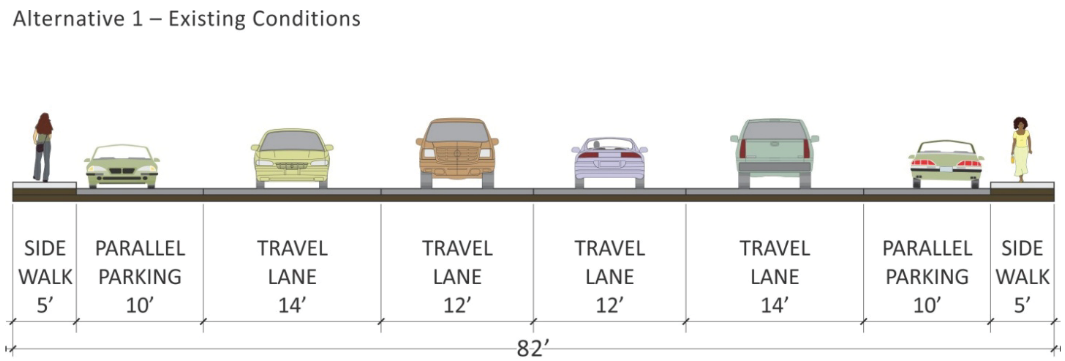
Resources Used to Develop Solutions. The project team used the *Urban Streets Design Guide* published by the National Association of City Transportation Officials (NACTO) (*7*) as a resource for developing alternative cross sections. The team also used NACTO's *Urban Bikeway Design Guide* (*8*) and AASHTO's *Guide for the Development of Bicycle Facilities*, Fourth Edition (*9*), in identifying and developing alternatives. They used these guidance documents in combination with the city's local design guides and standards. The resources were particularly helpful in providing visuals, examples, and alternative approaches for addressing the challenge of serving multiple travel modes. This project example focuses on documenting the development, analysis, and selection of a new, basic cross section for Cascade Avenue. There is valuable information in these reference materials regarding design and operational strategies for managing conflicts between modes at intersections and within the transition areas influencing how well an overall street corridor serves road users.

Solution Development. Each alternative cross section has a modal emphasis in contrast to the existing auto-oriented cross section. The cross-section alternatives were developed to be reasonable representations of a type of alternative. This means some design details (such as curb type) will be determined in later stages of project development.

A common element among the alternatives is the lack of on-street parking. The local business community expressed interest in increasing pedestrian activity on the street and therefore the desire to focus on solutions providing more space for that activity. This approach is consistent with the broader city's goals and policies to focus on projects serving person-trips rather than auto-only trips. This translates to creating more space for modes other than autos. The primary concern related to eliminating on-street parking on Cascade Avenue was that vehicles would use on-street parking in adjacent residential areas. The city is addressing this concern as part of a broader city-wide parking management plan encompassing the Cascade Avenue area as well as the downtown district and the area surrounding the university.

Other tradeoffs considered by the project team while developing and identifying the specific characteristics within each cross section included allocating lanes for specific modes. For

Exhibit 6-15. Cross section of existing roadway.



example, providing a transit-only lane has the ability to improve mobility and reliability for transit riders by reducing the average travel time along the corridor for transit riders. It also provides more predictable operating conditions for transit vehicles in peak traffic conditions. However, allocating space to transit vehicles negatively impacts mobility (and potentially reliability) for automobiles because they are reduced to one lane in each direction of travel instead of the existing two lanes. Similar tradeoffs were considered related to providing bicycle lanes and wider sidewalks for pedestrians. Another characteristic reflected in two of the alternatives is adding a central landscaped median that would transform Cascade Avenue to a divided facility. There are documented safety benefits for autos and pedestrians in having a median. A median also provides space to implement landscaping to help improve the aesthetics of the corridor. As will be seen in Alternative 3, the project team also considered changes that would provide additional designated space for pedestrians and bicyclists and create a buffer between pedestrians and bicyclists and moving vehicles. The intent of these features is to decrease the likelihood of crashes and improve the overall experience of traveling and spending time on Cascade Avenue.

Primary Alternatives for Evaluation. Using the resources and considerations previously described in brief, the project team arrived at the following alternatives for evaluation:

- **Alternative 1—Existing (Auto-Oriented):** Four-lane undivided roadway with on-street parallel parking on both sides of the street. Alternative 1 is shown in Exhibit 6-15.
- **Alternative 2—Transit Oriented:** Four-lane divided roadway with transit-only lanes and increased sidewalk widths. Alternative 2 is shown in Exhibit 6-16.
- **Alternative 3—Bicycle and Pedestrian Oriented:** Two-lane divided roadway with a buffered bicycle lane, landscaped buffer, wider sidewalks, and shared auto-transit lane. Alternative 3 is shown in Exhibit 6-17.

Exhibit 6-16. Transit-oriented roadway cross section.

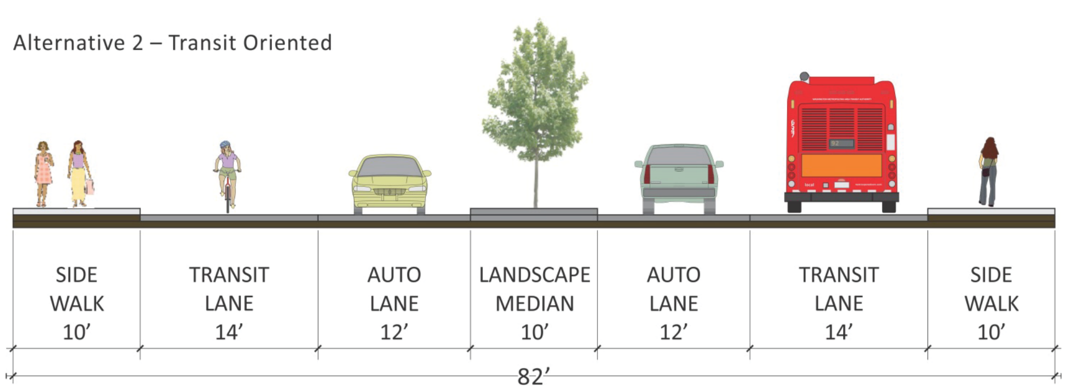
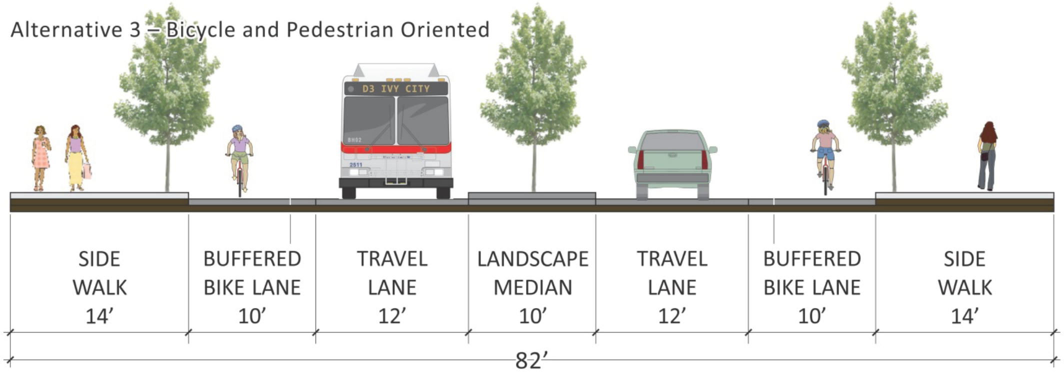


Exhibit 6-17. Bicycle- and pedestrian-oriented roadway cross section.



- **Alternative 4—Hybrid of Transit, Bicycle, and Pedestrian Alternatives:** Four-lane undivided roadway with transit-only lanes, bicycle lanes, and a wider sidewalk. Alternative 4 is shown in Exhibit 6-18.

The exhibits demonstrate that the alternatives have the following elements in common:

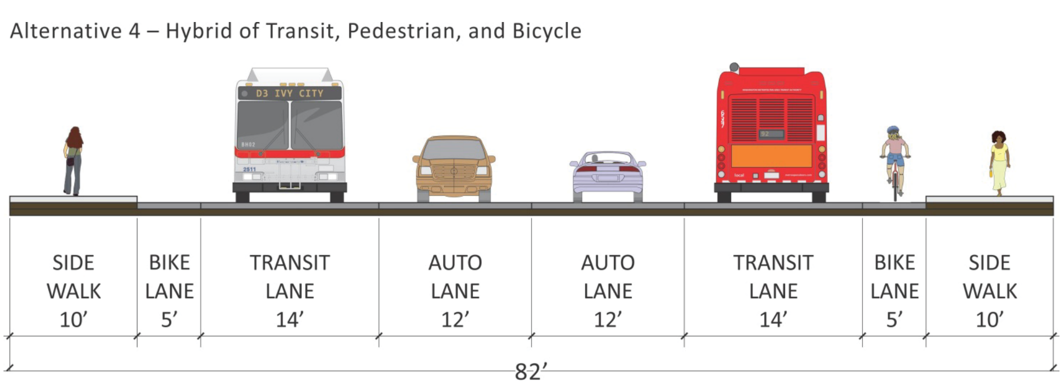
- Fall within the existing 82 ft of right-of-way width and, therefore, does not require additional right-of-way
- Require changing the existing curb locations and, therefore, revising stormwater management and drainage along the corridor
- Reduce the capacity for automobiles from two lanes in each direction to one lane in each direction
- Remove on-street parking (as discussed previously)
- Increase sidewalk width for pedestrians

The differentiating factors across the alternatives influencing their performance include the amount of space designated for bicyclists, presence of a central median, the presence of a physical buffer for pedestrians and bicyclists from motor vehicles, and the type of space allocated for transit vehicles.

Additional critical issues that are not directly captured in the exhibits but that will need to be considered prior to selecting an alternative for implementation include the following:

- Logistics (e.g., allocating designated zones) of truck loading and unloading for the businesses along Cascade Avenue

Exhibit 6-18. Hybrid of transit, bicycle, and pedestrian alternatives.

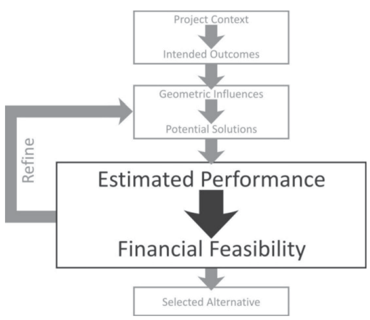


- Definition of transition areas on approach to intersections or major driveways where vehicle turning movements will occur; these conflict areas will need to be managed particularly within alternatives providing transit-only and/or bicycle lanes
- Revisiting, confirmation, and possibly modification of intersection control, lane configurations, and/or signal timing (if a signal is present) to better align with the selected cross section

For example, if Alternative 2, the transit-oriented cross section, is selected, the city may want to implement transit signal priority to help maintain consistent and reliable transit service along the corridor. These additional considerations are not addressed within this project example but were considered in the broader context of implementing the selected cross-sectional alternative.

6.4.3 Evaluation and Selection

6.4.3.1 Estimated Performance and Financial Feasibility



Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 3.3.2 presents information on the broader performance categories applicable to geometric design performance. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.

The performance categories evaluated for this project focused on the following:

- Safety as defined by crash frequency, crash severity, and conflict points
- Mobility as defined by average travel time
- Reliability as defined by variation in travel time
- Accessibility as defined by type and facility presence and transit service characteristics
- Quality of service as defined by MMLOS

The following paragraphs discuss how the performance was estimated for each alternative, results of the performance evaluation, results of the financial feasibility, and effectiveness of each alternative.

Estimating Performance. To the extent feasible, the project team estimated the performance of each alternative quantitatively. However, in some cases, due to the state of the research and practice, a qualitative assessment was necessary. Exhibit 6-19 summarizes the resources used to calculate the performance of each alternative.

Exhibit 6-19. Summary of resources for performance evaluation.

Alternative	Safety	Mobility	Reliability	Accessibility	Quality of Service
1 – Existing Condition	HSM, Chapter 12	HCM2010	HCM2010	Qualitative Assessment	HCM2010
2 – Transit Oriented	HSM, Chapter 12 Principles	HCM2010	HCM2010	Qualitative Assessment	HCM2010
3 – Bicycle and Pedestrian Oriented	HSM, Chapter 12 Principles	HCM2010	HCM2010	Qualitative Assessment	HCM2010
4 – Hybrid of Transit, Bicycle, and Pedestrian	HSM, Chapter 12 Principles	HCM2010	HCM2010	Qualitative Assessment	HCM2010

Resource references: HSM (*5*), HCM2010 (*10*).

The project team faced several challenges in being able to quantitatively assess each alternative across the range of selected categories and associated performance measures. The primary challenge was the gap in existing research findings. For example, research is not able to reflect the quantitative performance of the innovative street cross sections being considered for Cascade Avenue. The following list provides a more detailed description of how each resource can be used to estimate the performance measures identified above, including the instances when a qualitative assessment was necessary because of the lack of available research.

- **Safety.** AASHTO's HSM has methodologies (5) and information within it to be able to estimate the predicted safety performance for roadway cross sections of urban/suburban arterials. The HSM addresses cross sections ranging from two-lane undivided to five lanes (a five-lane cross section has two lanes in each direction with a two-way center turn lane). Therefore, the HSM can be used to estimate the long-term annual safety performance of Cascade Avenue under existing conditions.

  However, the remaining alternatives include cross-sectional features that cannot be evaluated using the HSM or other known resource:

  – The transit lanes present in Alternatives 2 and 4
  – The buffered bicycle lane present in Alternative 3
  – The traditional bicycle lane in Alternative 4

  Therefore, the relative safety performance of these alternatives was considered qualitatively based on their abilities to separate conflicting modes and provide additional and/or protected space for vulnerable users (i.e., pedestrians and bicyclists).

- **Mobility.** The project team used a software program to implement HCM2010 methodologies (*10*) and estimate the average travel time from one end of Cascade Avenue to the other. The average travel time was estimated for the morning, midday, and evening weekday periods, as well as the Saturday midday peak period. The intent of including the multiple periods was to obtain a sense of the range of travel time during low-, mid-, and high-traffic volume periods. The analysis focused on average travel time for motorists and transit vehicles (and, therefore, transit riders).
- **Reliability.** As discussed in Section 4.4.4, research is ongoing within the transportation profession to develop performance measures and a means to strengthen the connection between reliability and geometric design decisions. In the context of urban arterials, measuring the variation in travel time is the best means for estimating relative consistency for motorists and transit riders on Cascade Avenue. To estimate the potential variation in travel time, the project team simulated traffic operations along the corridor for different periods of the day to reflect different traffic volume demands and introduced different unanticipated events (e.g., partial or full lane closure due to a crash or truck loading/unloading) to estimate the relative consistency in travel time for each alternative. The analysis focused on the variation in travel time for auto and transit vehicles. As will be seen in the results discussed later, providing a transit-only lane can notably help improve reliability for transit vehicles and riders. Results only speak to the reliability of the transit routes while they are traveling on Cascade Avenue; events may occur prior to or after the routes depart Cascade Avenue that negatively impact their overall reliability.
- **Accessibility.** The project team evaluated access qualitatively, giving it an assessment of low, moderate, or high depending on the presence of facilities for specific modes and the transit service characteristics reflected in each alternative. Within this project context, additional access to the corridor for pedestrians, bicyclists, and transit riders was considered a positive performance characteristic given the overarching goal of the project to increase economic vitality of the corridor through increased pedestrian activity or person-trips.
- **Quality of Service.** MMLOS was calculated using the methodology presented in the HCM2010 (*10*). The methodology produces a letter grade A through F to indicate the quality of the travel

experience from specific road users' perspectives. Therefore, it is possible for the same alternative to produce a LOS C for bicyclists and LOS B for pedestrians. In other words, the methodology reflects that one street cross section can result in different qualities of experience depending on whether a person is walking, biking, taking transit, or driving an automobile. It is a useful methodology, particularly in combination with the HSM, because MMLOS captures some of the benefits from project elements the HSM cannot, such as bicycle lanes.

The results of the performance analysis are summarized in Exhibit 6-20. The results for the safety and access evaluations are categorized as low, moderate, or high. In the context of this project, high performance in those two categories is desirable. High safety performance means, in a qualitative assessment, there is a lower likelihood of crashes and/or severe crashes due to attributes such as separate designated space for vulnerable modes, physical separation of vulnerable modes from motor vehicles, and other similar attributes.

Exhibit 6-20 demonstrates it can be a complicated exercise to evaluate and interpret results from the evaluation of several alternatives across multiple modes using a variety of performance measures. Key themes the project team identified from the performance evaluation results included the following:

- **Safety.** Alternatives 2 and 3 are expected to have better safety performance compared to other alternatives. This is attributable to the presence of the central median. The median separates

Exhibit 6-20. Performance evaluation results[a].

Alternative	Safety	Mobility: Average Travel Time (min)	Reliability: Variation in Travel Time (min)	Accessibility	Quality of Service: MMLOS
1 – Existing Condition					
Pedestrian	Low	—	—	Low	D
Bicycle	Low	—	—	Low	F
Transit	Low	4.43	3.68 to 5.26	Moderate	D
Auto	Low	2.67	2.42 to 3.17	High	A
2 – Transit Oriented					
Pedestrian	High	—	—	Moderate	C
Bicycle	Moderate	—	—	Moderate	E
Transit	High	4.40	3.68 to 4.76	High	B
Auto	High	3.43	3.35 to 3.60	Low	C
3 – Bicycle and Pedestrian Oriented					
Pedestrian	High	—	—	High	B
Bicycle	High	—	—	High	C
Transit	High	4.80	3.97 to 6.00	Moderate	D
Auto	High	4.80	3.80 to 6.10	Low	D
4 – Hybrid of Transit, Bicycle and Pedestrian					
Pedestrian	Low	—	—	Moderate	C
Bicycle	Moderate	—	—	Moderate	D
Transit	Moderate	4.38	3.65 to 4.78	High	B
Auto	Low	3.45	3.32 to 3.56	Low	C

[a]The exhibit summarizes results for the Saturday midday peak period. Similar summaries were prepared for the weekday evening and morning periods.
— indicates not applicable.

vehicles moving in the opposite direction and provides a pedestrian refuge for pedestrian crossings at intersections and mid-block. These alternatives also include separate facilities designated for auto, transit, and bicycles. Furthermore, Alternative 3 includes additional buffering for pedestrians and bicyclists from motorized traffic. As noted previously, if Alternatives 2 or 3 is selected (or if Alternative 4 is selected), the project team will need to spend time designing transition areas to transition from the street cross section to intersections where vehicle turn movements will need to occur. Within Alternative 3, the team will also need to consider and develop an approach for managing conflicts between transit vehicles and bicyclists on approach to transit stops. This may include strategies such as moving the transit stop to a platform away from the sidewalk and having the bicycle lane pass between the platform and the sidewalk. Alternatives 1 and 4 have the lowest expected safety performance. This is attributed to the lack of a central median and, in the case of Alternative 1, the lack of separate facilities for bicyclists and transit vehicles.

- **Mobility.** Alternative 1 is expected to have the highest mobility (lowest average travel time) for motorists on Cascade Avenue, which is attributed to the four-lane cross section. Alternatives 2 and 4 are the next two alternatives with higher mobility for motorists and transit vehicles. Each of these alternatives includes a transit and auto lane in each direction and, therefore, has similar mobility results for those modes. The average travel time reflected in Alternatives 2 and 4 is closer to the posted speed limit on Cascade Avenue of 35 mph, which is desirable with respect to safety (i.e., provides more time for motorists to react to roadway conditions and is more likely to result in less severe crashes in the event one occurs) and creating a more comfortable environment for pedestrians and bicyclists.
- **Reliability.** Alternatives 2 and 4 have the highest reliability (i.e., lowest variation in travel time) for transit riders and motorists. While these two alternatives do not have the highest mobility for motorists, they do create moderately more consistent travel times. Increased reliability is achieved primarily by the transit lanes included within the alternatives. Transit lanes prevent motorists from being stuck behind a transit vehicle loading and unloading passengers. The increased reliability is also attributable to removing the on-street parking present in Alternative 1. Alternative 3 has the lowest reliability for transit riders and motorists. This is because transit vehicles and motorists are sharing a single travel lane in each direction; therefore, transit stops, truck loading and unloading maneuvers, and incidents (and incident management) directly affect the space both modes need for travel. This creates the greater variation in travel time.
- **Accessibility.** Alternatives 2, 3, and 4 provide similar levels of access for pedestrians, transit riders, bicyclists, and motorists. Within Alternatives 2, 3, and 4, access (with respect to being able to travel on Cascade Avenue and gain access to the businesses along it) range from moderate to high for pedestrians, transit riders, and bicyclists because of the presence of facilities for those modes. Within those same alternatives, access for motorists is evaluated as low. This is primarily because on-street parking is not included in Alternatives 2, 3 or 4.
- **Quality of Service.** Alternative 3 provides the highest quality of service for pedestrian and bicycle modes. The high quality of service for pedestrians is attributable to the wider sidewalks, landscaping buffer, and additional separation from motor vehicles gained from the adjacent buffered bicycle lane. For bicyclists, the higher quality of service is attributable to eliminating on-street parking, providing a designated bicycle lane, and including wider width for the buffered bicycle lane. Alternatives 2 and 4 provide the best quality of service for transit riders, which is primarily attributed to the operational benefits of the transit lanes (e.g., better service characteristics). This is in combination with the pedestrian improvements included in those alternatives. Motorists' quality of service is highest in Alternative 1 because of the higher mobility and relatively few times motorists would need to stop. Motorists are expected to experience moderate quality of service within Alternatives 2 and 4. This is likely attributed to separating automobiles and transit vehicles to help manage the number of times motorists would need to stop while traveling the corridor.

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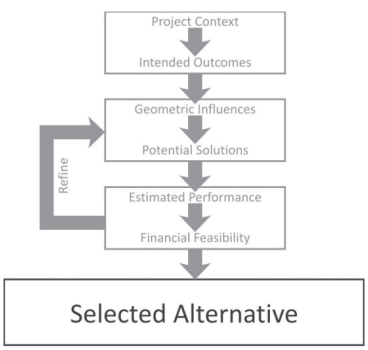
Given these considerations purely based on performance evaluation results, the project team and broader stakeholders felt Alternatives 2 and 3 had performance characteristics best reflecting the attributes they desired for Cascade Avenue. The following section discusses the financial feasibility considerations.

Incorporating Financial Feasibility. The project team developed cost estimates for each alternative. The cost estimates considered critical characteristics such as the costs of curb relocations, modifications needed to stormwater drainage and management, new pavement markings, revisions to signing, modifications to transit stop locations and configurations, improved illumination, and landscaping and other similar costs associated with the unique characteristics of each alternative. Exhibit 6-21 summarizes the cost estimates for the alternatives.

The significant elements influencing cost included modifying the stormwater drainage, adding a median, landscaping, changing transit stop locations and configurations, and pavement rehabilitation. Many of these attributes are present within Alternatives 2, 3, and 4 to varying degrees. Alternatives 2 and 3 are higher in cost than Alternative 4 because of the median and additional landscaping that they include.

The project team did not estimate a benefit/cost ratio or calculate a cost-effectiveness factor for the alternatives. To be able to calculate a benefit/cost ratio or cost-effectiveness factor, simplifying assumptions would be needed and some performance metrics omitted due to the lack of research and inability to quantify them. As a result, the city and project stakeholders did not want to oversimplify or omit performance measures they felt to be critical in selecting an alternative for Cascade Avenue. The city used the project cost information in combination with the performance evaluation results and understanding of the project context to reach consensus with project stakeholders on a preferred alternative.

6.4.3.2 Selected Alternative



Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., presence of a median). This information helped inform the following discussion and decision.

The city and project stakeholders selected Alternative 2 as the preferred alternative. Alternative 2 provides improved safety, reliability, access, and quality of service for transit riders, pedestrians, and bicyclists. Within this alternative, the bicycle quality of service is the least improved relative to transit riders and pedestrians' anticipated experience. Within Alternative 2, bicyclists will need to share the transit lane with transit vehicles. This is an improvement over existing conditions because of the lower number of transit vehicles relative to automobiles and the width of the transit vehicle lane. The city felt most comfortable with the performance of Alternative 2. This is primarily because of the improvement in safety across modes and the preservation of reasonable mobility and reliability for motorists and transit vehicles. Cascade Avenue is a critical corridor for transit service within the city. There are limited parallel alternative routes for motorists to use in place of Cascade

Exhibit 6-21. Cost estimates.

Alternative	Cost per Mile
1 – Existing Condition	$0
2 – Transit Oriented	$1.4 million
3 – Bicycle and Pedestrian Oriented	$1.6 million
4 – Hybrid of Transit, Bicycle, and Pedestrian	$1.0 million

Avenue that are not through residential areas. For those reasons, it was of high importance to the city to maintain a reasonable degree of mobility and reliability for motorists and transit, while better serving other modes.

The local business community that initiated the Cascade Avenue improvements preferred Alternative 3 and Alternative 2 as their secondary selection. Attributes from Alternative 3 that the city plans to integrate into Alternative 2 to address the business community's interests include adding landscaping along the sidewalks by using tree wells or other landscaping areas spaced at regular intervals. Attributes and characteristics to better serve bicyclists included elements such as bicycle corrals for easy parking in front of businesses; wayfinding signs for bicyclists; and signs and pavement markings to communicate to bicyclists and transit riders that bicyclists are permitted and encouraged to use the transit lane for travel.

6.5 Project Example 4: SR-4

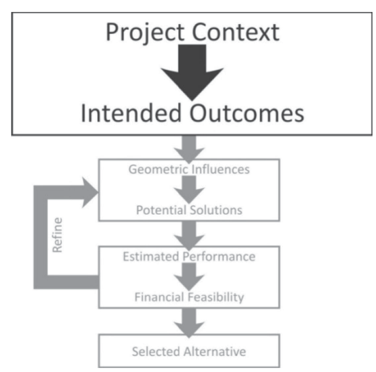
Authors' Note: Project Example 4 considers alternative shoulder widths and sideslopes along a rural collector roadway to improve safety while minimizing impacts to the adjacent environmentally sensitive area. The learning objectives for this project example are as follows:

- *Illustrate how performance-based analysis can be incorporated into an environmental review process*
- *Discuss and explore tradeoffs between desired project performance and environmental impact*

In this project example, SR-4 is being improved to serve as an alternate route for a parallel highway undergoing reconstruction. The performance categories considered within the project example are safety, reliability, and quality of service. Section 4.4 helped inform the selection of the specific performance measures used to evaluate the alternative solutions.

6.5.1 Project Initiation

6.5.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context likely to help inform the intended project outcomes, performance categories, and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. In this project example, the motivation for the project is to improve SR-4 as an alternate route while a parallel highway undergoes substantial reconstruction.

SR-4 is an east-west, two-lane rural highway passing through a biologically diverse and sensitive wetland. It runs roughly parallel to US-9, which borders the wetland area to the north. The two routes connect an established metropolitan area to the east and a growing suburban community to the west. The suburban area is transitioning from an established rural community to suburban development as growth in the urban metropolitan area pushes farther out from the urban core. SR-4 is frequently used by recreational cyclists in addition to motorists looking for a more direct and/or scenic route than is provided by US-9.

SR-4 historically has had AADT of 9,500 to 10,100 vpd over the last 5 years. The additional traffic from the increased development west of the wetlands has tended to use US-9. US-9 AADT has increased from 15,000 to 18,750 vpd with similar growth trends anticipated for the next 5 to 10 years as development continues. The state DOT forecasts AADT on US-9 to grow to 23,500 vpd within a 5-year horizon. This is expected to increase to nearly 30,000 vpd within a 10-year horizon. The DOT prefers to continue to emphasize US-9 as the primary route to the metropolitan area to help preserve and limit the impact to the wetlands surrounding SR-4. The agency does recognize SR-4 is a critical alternate route to US-9 that should be maintained so it is able to continue to safely and reliably serve motorists and cyclists.

The DOT has planned projects for SR-4 and US-9 to proactively improve their performance. This project focuses on identifying changes to SR-4 to proactively improve safety, reliability, and quality of service (as it relates to bicycle traffic), while minimizing negative impacts to the wetlands through which it travels. The existing cross section for SR-4 is two lanes, undivided, with 2-ft shoulders. The sideslopes are a relatively steep 2H:1V. The current roadway prism has a relatively narrow and limited footprint within the wetlands.

6.5.1.2 Intended Project Outcomes

Authors' Note: The following summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, the project purpose is to improve the safety and reliability of SR-4, in preparation for higher traffic volumes and additional use while the parallel state facility (US-9) undergoes substantial reconstruction. The governing agency also expects a relatively high number of recreational bicyclists to use SR-4. Therefore, quality of service for bicyclists is also an obvious performance characteristic to consider. Generally, similar to Project Examples 1 and 2, the project performance and geometric performance are relatively closely aligned.

We used Section 5.2.2 to inform the following summary of the intended project outcomes. This includes the applicable performance categories. In this project example, reliability and safety are the geometric performance categories of interest. We used Sections 4.4.4 (Reliability), 4.4.3 (Quality of Service), and 4.4.5 (Safety) to select the performance measures.

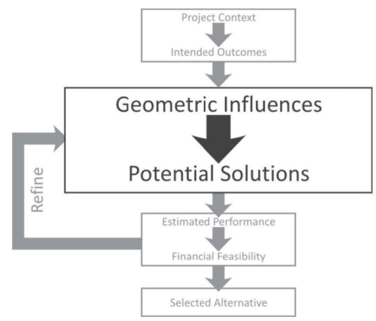
The DOT has planned large capital projects to expand US-9 from its existing two- and four-lane undivided cross sections to a consistent four-lane divided highway. To save money on construction costs and expedite completion of the project, the DOT has decided to close US-9 to traffic during the reconstruction and divert traffic to SR-4. In preparation for the additional traffic demand on SR-4 during construction, the DOT is considering alternatives to improve SR-4's expected safety performance (for motorists and cyclists) and reliability. The DOT also sees long-term value in such projects on SR-4 because its long-term plan for managing the overall impact to the environmentally sensitive area is to limit roadway connectivity to the single route through the wetlands (SR-4) and a roughly parallel route to the north (US-9).

The DOT would like to identify and implement treatments to SR-4 without the project escalating to a level of significant impact and requiring an EIS. Recently, the DOT conducted an EA for SR-4 that considered a wide range of alternative design solutions. From the EA, the DOT learned improving SR-4 to meet its roadway standards would result in a significant impact to the wetlands. The DOT also identified, from preliminary design work associated with the EA, an acceptable roadway footprint. This footprint would allow the DOT to reconstruct the roadway without having a significant environmental impact. Therefore, it could complete the project without an EIS.

The purpose of this project is to identify the most effective cross section for SR-4 to improve safety, reliability, and quality of service for cyclists within the physical footprint defined from the EA. The primary audience is the motorists (including truck drivers) who will be diverted to use SR-4 while US-9 undergoes reconstruction and the bicyclists who currently use and will continue to use SR-4. The DOT is the primary agency stakeholder as it has jurisdiction over the roadway; the local FHWA environmental office is also a key governmental stakeholder within the project. Community members of the developing area west of the wetlands and a community group focused on protecting the wetland are key broader public stakeholders. Safety will be measured as the frequency and severity of crashes. Reliability will be measured by the variation in travel time and will also be considered in the context of incident management. Incident management is of particular concern to the DOT because SR-4 will be the only route regionally available for east-west travel while US-9 is undergoing reconstruction. Quality of service for bicyclists will be evaluated based on the amount of space available for bicyclists on SR-4.

6.5.2 Concept Development

6.5.2.1 Geometric Influences



Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics that are likely related to the key project performance measures.

The roadway shoulder width and sideslopes were selected as the primary geometric characteristics on which to focus in developing alternative cross sections for SR-4. These were selected because they are known to substantively influence safety performance with respect to the occurrence and severity of run-off-the-road crashes. Run-off-the-road crashes are among the most prevalent crash types on rural roadways. Shoulder width and sideslopes also have a direct impact on reliability with respect to providing space for incident management, snow management, and/or disabled vehicles. Finally, shoulder width also has a direct impact on the amount of space, and therefore quality of service, for bicyclists. Centerline rumble strips and shoulder rumble strips were also considered as potential treatments to augment different combinations of shoulder width and sideslopes, with the intent of further reducing the likelihood of run-off-the-road and lane departure crashes.

Additional guidance for identifying the design elements that influence or are influenced by a given performance measure can be found in Section 4.4.

6.5.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended outcomes, performance measures, and influential geometric elements.

A key challenge in developing potential solutions for SR-4 is balancing the impact of an alternative and the performance measures. The EA conducted by the DOT determined that as long as the design changes to SR-4 increased the total width of the roadway footprint (including the sideslopes) to no greater than 110 ft, then there would be no significant impact to the surrounding environmentally sensitive area. Therefore, each of the alternatives developed and evaluated have a total width of no greater than 110 ft. The DOT would like to determine the most effective alternative to proactively address performance categories of safety, reliability, and quality of service for bicyclists while minimizing the impact to the surrounding environment. Community project stakeholders would also like to see as little impact as possible to the wetlands.

Based on these considerations, the project team developed three basic alternatives in addition to the no-build alternative:

- **Basic Alternative 1—No-Build Condition:** Maintains the existing roadway cross section and corresponding roadway prism. This serves as a consistent basis for comparison for each alternative and enables the DOT to address the basic question of whether investing in any of the alternatives provides sufficient value relative to how the existing condition is expected to perform.

- **Basic Alternative 2—Wide Shoulders:** Increases shoulder widths to standard width for roadway functional classification and maintains similar sideslopes to the existing condition. This alternative represents the approach of substantially widening the shoulders to provide space for vehicles to recover if they drift from the travel lane, disabled vehicles, and incident management in the event of a crash. This alternative also provides sufficient space to accommodate recreational cyclists and install shoulder rumble strips. The sideslopes are similar to the existing condition; they are non-recoverable and not traversable (steeper than 3H:1V). They are relatively steep to minimize the physical impact to the surrounding area. If motorists were to leave the paved shoulder, they could lose control of their vehicle and face a higher probability of the vehicle rolling down the sideslope to the bottom of the embankment. As a result, the likelihood of higher severity crashes for motorists that depart the paved shoulder is greater for this alternative relative to Alternative 3 or 4.
- **Basic Alternative 3—Moderate Shoulders and Sideslopes:** Increases shoulder width, but to less than standard width, and adjusts sideslopes to be non-recoverable and traversable (3H:1V to 4H:1V). This represents an approximate hybrid of widening shoulders and softening the sideslopes of the roadway. The increased shoulder width is sufficient to provide clear safety benefits and some additional space for incident management, disabled vehicles, and bicyclists. However, the shoulder width is not as wide as Alternative 2. The shoulder is not able to accommodate bicycle traffic and shoulder rumble strips. The sideslopes are considered traversable although not recoverable. This means motorists who depart the roadway and begin down the sideslope will be able to continue down the sideslope to the bottom without having their vehicle roll. However, they will not be able to regain sufficient control to re-enter the roadway or stop prior to the bottom of the slope.
- **Basic Alternative 4—Narrow Shoulders and Gradual Sideslopes:** Maintains narrow shoulders and adjusts sideslopes to be recoverable. This represents the approach of maintaining the existing shoulder widths and focusing adjustments on the sideslope. Under this alternative, the sideslopes are modified to be a recoverable (4H:1V or greater) slope. This means motorists who depart the shoulder may possibly regain control of their vehicle and either bring it fully back onto the shoulder or bring it to a stop before it reaches the bottom of the embankment. Roadway departure crashes within this alternative have a lower probability of resulting in severe injury or injury crashes relative to the other alternatives. However, the narrow shoulders make it more difficult to accommodate incident management, disabled vehicles, and bicyclists on SR-4.

The previous alternatives were identified to explore the relative effectiveness of, and relationship between, shoulder width and sideslopes at addressing the performance measures. Each has a different level of impact to the roadway prism and, therefore, evaluating the full range enables a better understanding of what is likely to produce the desired performance with minimal negative impacts.

The following describes the resources used to develop the alternatives above into specific alternatives for evaluation.

Resources Used to Develop Solutions. The project team used AASHTO's *A Policy on Geometric Design of Highways and Streets* (*1*), the DOT's roadway design manual, and AASHTO's *Roadside Design Guide* (*11*) as the primary resources to develop and define Alternatives 2, 3, and 4.

Solution Development. The project team worked from the basic alternatives and the resources noted above to identify the specific shoulder width dimensions and sideslope characteristics defining each of the alternatives.

The key considerations influencing the selection of specific shoulder widths was the standard shoulder width dimension for a rural two-lane highway within the state. Another consideration was the approximate incremental safety effectiveness of wider shoulders, as documented in AASHTO's HSM (*5*). The DOT's roadway design manual identified 8 ft as the standard shoulder width for rural two-lane highways. The HSM documents that, to date, the profession has not seen a definitive incremental safety improvement from shoulder widths greater than 8 ft. Therefore, 8 ft is used as the upper bound for the shoulder-width dimension. And within the alternatives, 4 ft is used as a moderate increase to evaluate the combination of a moderate improvement in shoulder width and sideslope.

The selection of sideslope dimensions was based on the concepts of what is considered a recoverable, non-recoverable but traversable, and non-recoverable and non-traversable sideslope. These are described as follows:

- **Recoverable sideslopes** have a slope of 4H:1V or greater. Recoverable sideslopes enable drivers to maintain control of their vehicle and either bring it to a stop or return to the paved roadway section. These sideslopes result in a relatively large roadway footprint. This is why the recoverable sideslope incorporated into the alternatives was paired with a narrow shoulder width in an effort to minimize the impact on the surrounding area.
- **Non-recoverable but traversable sideslopes** are those in the range of 3H:1V to 4H:1V. These sideslopes allow motorists to maintain sufficient control to reach the bottom of the embankment without their vehicle rolling or flipping, which helps reduce the potential for severe crashes. Traversable sideslopes have smaller footprints than recoverable sideslopes, but not as small as relatively steep sideslopes. Therefore, the traversable sideslope was combined with the moderate increase in shoulder width to understand if there is a middle ground between increasing the shoulder width and modifying sideslopes to minimize the roadway footprint.
- **Non-recoverable and non-traversable sideslopes** are those steeper than 3H:1V. The footprints for these roadways are relatively small, but the risk for a severe crash is relatively high if a vehicle leaves the roadway. Therefore, the non-recoverable, non-traversable sideslope was combined with the relatively wide shoulders to provide motorists with additional space to maneuver without departing the roadway.

In total, the combination of shoulder width and sideslope dimensions was identified to provide the greatest opportunity to improve expected performance relative to safety, reliability, and quality of service for bicyclists, while also minimizing the impacts to the surrounding area.

Primary Alternatives for Evaluation. Based on the project context, the primary alternatives the project team identified for evaluation, using the resources previously noted, are as follows:

- **Alternative 1—Existing Conditions:** Two-lane undivided cross section with 2-ft-wide shoulders in each direction and roadside sideslopes of 2H:1V. Exhibit 6-22 illustrates the basic cross section.
- **Alternative 2—Wide Shoulders:** Two-lane undivided cross section with 8-ft-wide shoulders in each direction and roadside sideslopes of 2H:1V. Exhibit 6-23 illustrates the basic cross section.
- **Alternative 3—Moderate Shoulders and Sideslopes:** Two-lane undivided cross section with 4-ft-wide shoulders in each direction and roadside sideslopes of 3H:1V. Exhibit 6-24 illustrates the basic cross section.
- **Alternative 4—Narrow Shoulders and Gradual Sideslopes:** Two-lane undivided cross section with 2-ft-wide shoulders in each direction and roadside sideslopes of 4H:1V. Exhibit 6-25 illustrates the basic cross section.

The project team evaluated the relative performance of each alternative and calculated the environmental impacts for each. The environmental impacts were quantified based on the

Exhibit 6-22. Cross section of existing roadway.

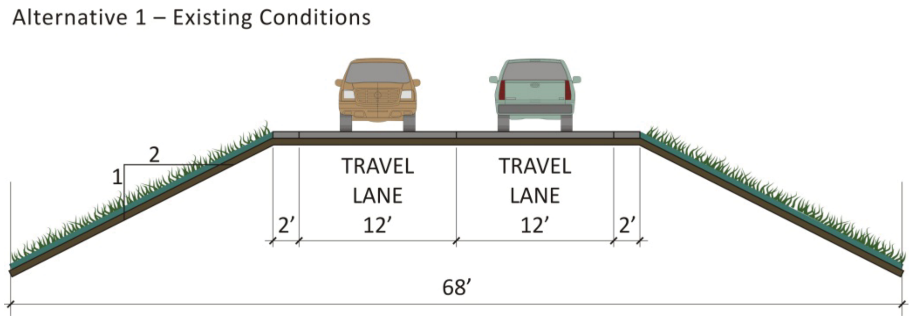


Exhibit 6-23. Cross section of wide shoulders.

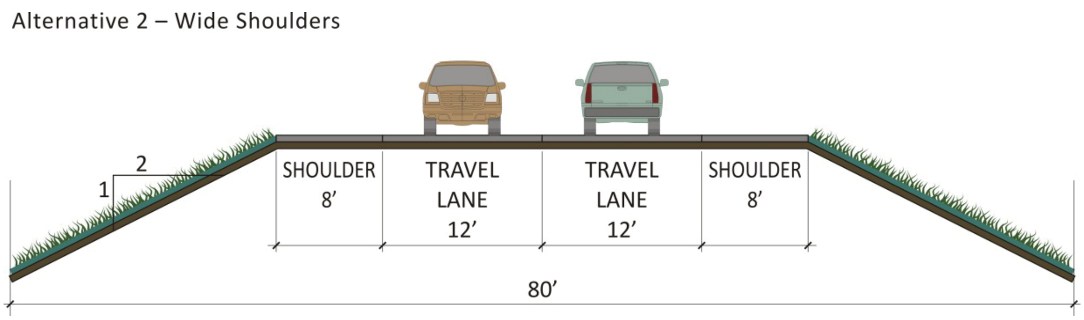


Exhibit 6-24. Cross section of moderate shoulders and sideslopes.

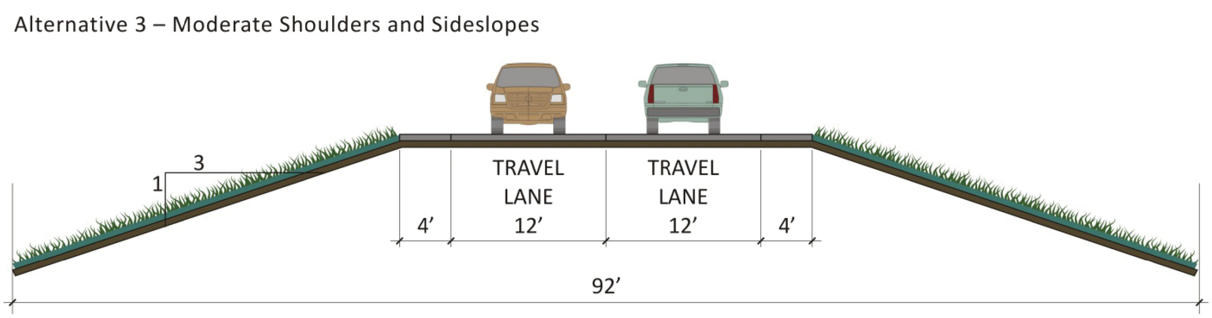
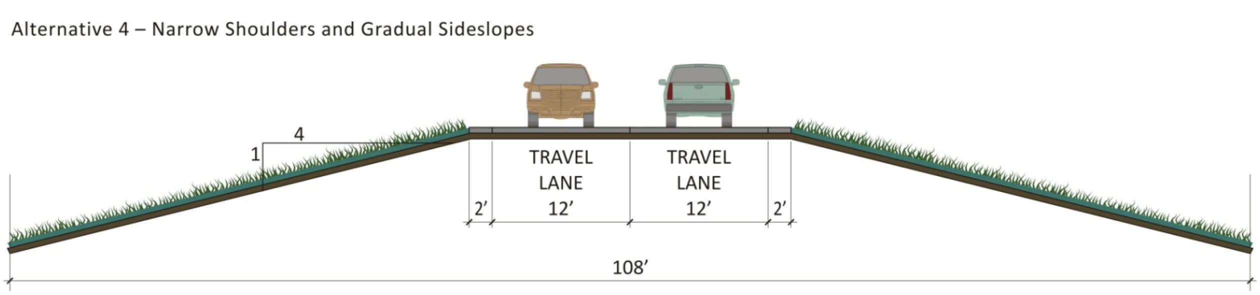


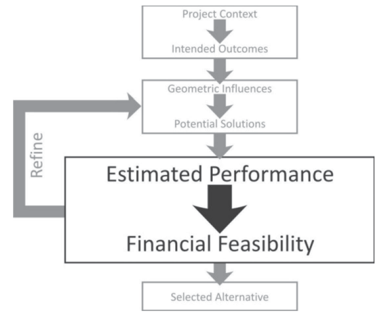
Exhibit 6-25. Cross section of narrow shoulders and gradual sideslopes.



physical size of the roadway prism footprint and the additional impervious area the alternative would add to account for the potentially negative impact of additional stormwater runoff into the adjacent wetlands.

6.5.3 Evaluation and Selection

6.5.3.1 Estimated Performance and Financial Feasibility



Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 3.3.2 presents information on the broader performance categories applicable to geometric design performance. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.

The performance evaluation focused on the following performance categories and associated measures:

- Safety as defined by crash frequency and severity
- Reliability as defined by the variation in travel time
- Quality of service as defined by the space available for bicyclists

Estimating Performance. Chapter 10 of AASHTO's HSM (*5*) was used to estimate the expected safety performance for the alternatives. Methodologies from the HCM2010 (*10*) and a software program implementing those methodologies were used to estimate the variation in travel time to determine the reliability of each alternative. More specifically, reliability was measured by simulating peak and off-peak traffic volume conditions and randomly incorporating incidents resulting in partial or full lane closures to determine the impact of unforeseen events such as crashes along the corridor. A similar approach was applied and discussed in Project Example 3. Principles from the HCM2010's MMLOS methodology (*10*) were the basis for using shoulder width as a surrogate measure for the quality of service for bicyclists. The HCM2010 MMLOS methodology (*10*) is only directly applicable to urban and suburban contexts; however, the project team identified some principles that also seemed transferable to this rural context. The primary principle related to quality of service for bicycles was the amount of space allocated for their use separate from motor vehicles.

In addition to the previous performance metrics, the project team also calculated two metrics to use as surrogates for gauging each alternative's relative impact to the surrounding environment: (1) the cross-sectional area of each alternative and (2) the impervious area of each alternative. Both of these metrics were calculated relative to existing conditions. Exhibit 6-26 summarizes the evaluation results for the alternatives.

As reflected in the performance evaluation results, there is no single, clear alternative consistently performing better across each performance measure while also resulting in the lowest impact to the surrounding area. The project team identified the following trends in the analysis results:

- **Alternative 4** results in the most improvement with respect to safety and is the only alternative to not increase the impervious surface area. It has the lowest reliability and quality of service for bicyclists. It also has the largest increase in roadway cross-sectional area.
- **Alternative 2** is expected to provide the most reliability and highest quality of service for bicyclists. It has a slightly higher estimated annual crash frequency than Alternative 4. It also has the largest increase in impervious area among the alternatives but the lowest increase in roadway cross section.

Exhibit 6-26. Summary performance evaluation results.

Alternative	Safety (crashes/ year)[a]	Reliability (minutes)[b]	Quality of Service[c]	Increase Relative to Alternative 1	
				Roadway Prism Cross-Sectional Area (ft^2/ft)	Impervious Surface Area (ft^2/ft)
1 – Existing Conditions	6.0	16.5 to 11.0	Low	0	0
2 – Wide Shoulders	4.9	13.8 to 11.0	High	120	12
3 – Moderate Shoulders and Sideslopes	4.6	18.9 to 11.0	Moderate	140	4
4 – Narrow Shoulders and Gradual Sideslopes	4.3	20.6 to 11.0	Low	200	0

[a] The safety analysis applies the methodology from Chapter 10 of the HSM to calculate expected annual average crash frequency. Within that methodology, roadside sideslopes are captured within the roadside hazard rating crash modification factor.
[b] Reliability was measured by simulating peak and off-peak traffic volume conditions and randomly incorporating incidents resulting in partial or full lane closures to determine the impact of unforeseen events such as crashes along the corridor. A similar approach was applied and discussed in Project Example 3.
[c] Quality of service for bicyclists is noted as low, moderate, or high based on the shoulder width within the alternative (high indicates a more desirable quality of service for bicyclists).

- **Alternative 3** performs consistently in between Alternatives 2 and 3 with moderate results across the performance measures.

Based on the performance results and assessment of the impact to the adjacent environmentally sensitive area, the DOT is considering Alternative 4 because of its safety performance, recoverable sideslopes to mitigate the probability of severe roadway departure crashes, and the no net gain in impervious area. The following section discusses the financial feasibility considerations.

Incorporating Financial Feasibility. The project team developed cost estimates for each alternative. The cost estimates took into consideration costs associated with earthwork for adjusting the roadway sideslopes and new and rehabilitated pavement, and other similar costs. Exhibit 6-27 summarizes the cost estimates for the alternatives.

The significant elements influencing cost included adding new pavement and needing to rehabilitate existing pavement. Earthwork for modifying the sideslopes was the other significant factor for cost. As a result, Alternative 2 was estimated to be the most expensive alternative given that it includes both fill to widen the roadway and additional pavement work. Alternative 3 was also on the higher side for similar reasons, and Alternative 4 was the least expensive due to the lack of pavement work.

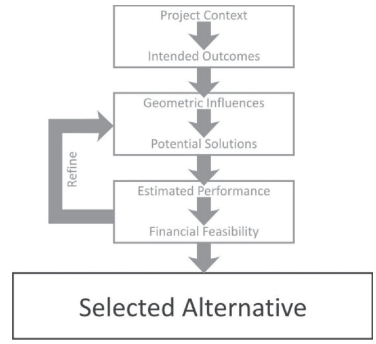
The project team did not estimate a benefit/cost ratio or calculate a cost-effectiveness factor for the alternatives. To be able to calculate either a benefit/cost ratio or cost-effectiveness factor, simplifying assumptions would need to be made to associate monetary values with metrics such as quality of service for bicyclists, increase in roadway cross-sectional area, and increase

Exhibit 6-27. Cost estimates for Project Example 4

Alternative	Cost per Mile
1 – Existing Conditions	$0
2 – Wide Shoulders	$1.8 million
3 – Moderate Shoulders and Sideslopes	$1.1 million
4 – Narrow Shoulders and Gradual Sideslope	$900,000

in impervious surface area. As a result, the DOT and project stakeholders did not want to oversimplify or omit performance measures they felt to be critical in selecting an alternative for SR-4. The DOT used the project cost information in combination with the performance evaluation results and understanding of the project context to reach consensus with project stakeholders on a preferred alternative.

6.5.3.2 Selected Alternative



Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., should width). This information helped inform the following discussion and decision.

The DOT and project stakeholders selected Alternative 4 as the preferred alternative. Alternative 4 improves the expected safety performance the greatest and has the lowest impact with respect to an increase in the impervious area. It also stays within the footprint defined by the EA to avoid a significant environmental impact to the surrounding area. Given these performance attributes, the DOT felt it was the most cost-effective improvement for SR-4. It addressed the agency's primary concern of proactively improving safety along SR-4 and helping to continue to preserve the surrounding wetlands. The lack of additional impervious surface for the roadway was particularly attractive to the DOT because it would help the DOT manage the potentially negative impacts that runoff from roadways can have to wetland water quality. When wetland water quality is compromised, it creates issues for the plants, animals, and insects that have habitats in the wetlands. Selecting an alternative with more potential to compromise wetland water quality would put the project at risk of having an elevated environmental document (EIS).

Alternative 4 does not provide a particularly high level of reliability or quality of service for bicyclists. The DOT addressed these potential performance issues through two different programs. To address reliability, the DOT developed an incident response and management protocol and process. It made use of an existing team of response vehicles to help disabled vehicles and respond to crashes. The existing team was expanded and a specific subgroup was assigned to SR-4 during the period of time when US-9 was closed for reconstruction. The response team was also expanded to include local tow truck companies placed on a special on-call list to promptly respond to incidents. To address quality of service for bicyclists, the DOT chose to manage bicycle traffic by disseminating information about alternative cycling routes (i.e., alternatives to SR-4) that bicyclists could use for recreational purposes while US-9 was closed for reconstruction and SR-4 was serving the re-routed motor vehicle traffic.

6.6 Project Example 5: 27th Avenue

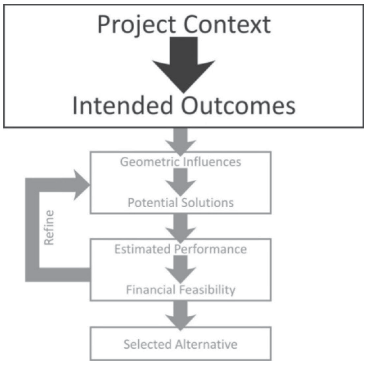
Authors' Note: Project Example 5 considers alternative alignments and cross sections for a new urban collector roadway. A new urban collector, 27th Avenue, is being designed to provide additional connectivity within and access to an industrial area. The overarching intended project outcome is to entice and encourage new employers to the newly zoned industrial area. The city, within which the industrial area is located, would like to increase its industrial employment base. The new urban collector would connect to the broader roadway network by way of existing US-33. The learning objectives for this project example are as follows:

- *Illustrate how to consider the broader context before beginning the details of design*
- *Demonstrate how the needs of different modes can be balanced*
- *Apply the performance-based analysis process within an EA*

The performance categories considered within the project example are access, quality of service, and safety. Section 4.4 helped inform the selection of the specific performance measures used to *evaluate the alternative solutions. This project example is first introduced within Sections 3.1.1 and 3.1.2 in the discussion regarding how to identify whom a project is serving and what is trying to be achieved.*

6.6.1 Project Initiation

6.6.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context likely to help inform the intended project outcomes, performance categories, and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. The key motivator for this project is to make improvements to the roadway network to encourage and draw additional employers to the industrial area adjacent to US-33.

The city is trying to increase the number of industrial employment opportunities to create a more well-rounded local economy. The city council approved expanding the industrial zone adjacent to the existing heart of the city's industrial land uses. To draw in larger industrial-type employers and supporting services, the city is going to construct some of the necessary street infrastructure to make the new area viable for employers. The area is bounded by a steep hillside to the west, the downtown core to the south, and existing industrial uses to the north and east. An existing highway, US-33, runs along the newly zoned area's northeasterly border. Exhibit 6-28 illustrates the location of the expanded industrial zone.

Despite the proximity to rail, other industrial uses, and US-33 (a regional highway), there are some inhibitors for industrial employers. There is not sufficient connectivity within the newly zoned area to facilitate its use without heavy reliance on US-33. US-33 has relatively stringent access spacing standards, making it difficult to obtain access permits from the state DOT. Also, there are limited access points to the area and those that do exist are not consistently conducive to heavy-vehicle traffic. US-33 serves the existing industrial uses in the area while being a critical connection between the downtown and a regional park located to the north. As a result, US-33 is heavily traveled by recreational bicyclists traveling between downtown and the regional park. This high demand occurs despite the lack of bicycle lanes on US-33 and the variation in the paved shoulder width from 2 to 4 ft along the corridor.

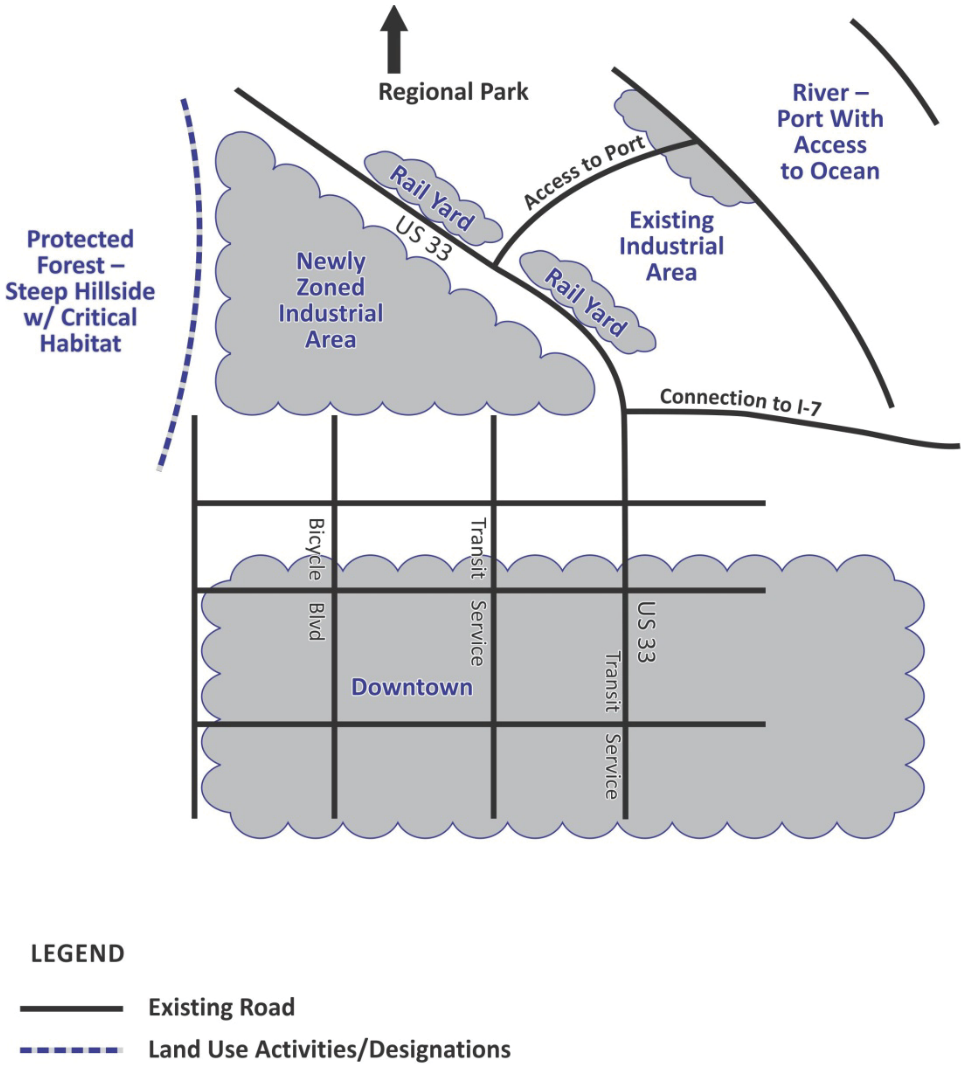
6.6.1.2 Intended Project Outcomes

Authors' Note: The following summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, the project purpose is to make improvements to the roadway network to encourage and entice employers to the existing industrial area. There are no direct geometric performance measures for evaluating how well a project alternative will encourage or entice employers to the industrial area. However, there are indirect geometric performance measures contributing to characteristics that would support encouraging employers within an industrial area (e.g., quality of service for large vehicles, access to regional highways or freeways).

We used the information in Chapter 3 to help differentiate between the project performance and geometric performance. We also used Section 5.2.2 to inform the following summary of the intended project outcomes, including the applicable performance categories. In this project example,

Exhibit 6-28. Existing conditions of new industrial area.



accessibility, quality of service, and safety are the geometric performance categories of interest. We used Sections 4.4.1 (Accessibility), 4.4.3 (Quality of Service), and 4.4.5 (Safety) to select the performance measures.

City planners would like to address some of the inhibitors for industrial employers, while also addressing some of the issues related to mixed bicycle and heavy-vehicle traffic on US-33 within an area that does not have sufficient space for both modes. The city has decided to focus their investment on improving connectivity within the newly zoned area. In doing so, it hopes to address some of the deterrents for employers and explore ways to improve bicycle accommodations from the downtown area to the regional park. The city's basic approach for achieving this goal is to plan, design, and construct a new urban collector, 27th Avenue, within the newly zoned industrial area.

The city plans to seek federal funding for part of the 27th Avenue project. Enough work has been done to know the project does not qualify for a categorical exclusion, and so the city needs to perform an EA to determine if the project could result in significant environmental impacts. The project did not qualify for a categorical exclusion due to its proximity to the hillside (previously shown in Exhibit 6-28), which is a federally listed critical habitat. Considering the new

27th Avenue, the city will need to avoid, and demonstrate there is no, significant impact to the hillside from the 27th Avenue construction. If it is unable to demonstrate no significant impact, the city will need to produce an EIS. The city would prefer to avoid significant environmental impact and, therefore, plans to adapt the 27th Avenue project design accordingly.

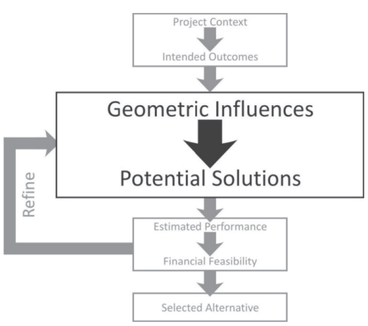
With respect to funding, a LID has also been formed to generate funds for ongoing maintenance and improvements within the newly zoned industrial area. The city will operate and maintain the roadway when it is constructed.

The primary audience to be served by this project is heavy-vehicle operators who will need to be able to easily access and circulate within the industrial area. The city knows this is a critical factor industrial businesses consider in selecting their location. The secondary audience or users who also need to be considered in developing 27th Avenue are bicyclists and motorists traveling between the regional park and downtown districts. The other participating stakeholders are the business owners in the area participating in the LID that will help with funding 27th Avenue.

The overarching intended outcome of the project, from the city's perspective, is to entice industrial employers to the newly zoned industrial area. The city wishes to generate employment opportunities for an employment group that is currently an under-employed segment of the city's population. There are no clear direct performance measures connecting design decisions to generating additional industrial-based jobs within an area. There are surrogate transportation performance categories and associated measures reflecting the type of roadway system industrial-based businesses value. The project team identified those key performance categories as accessibility, quality of service, and safety. The performance measure to be used for access is the ease with which heavy vehicles will be able to navigate the industrial area and the quality of access to US-33 and the downtown. The performance measure selected to measure quality of service is MMLOS performance for bicyclists (to access the regional park) and transit riders (to serve employees accessing jobs within the industrial area). The expected frequency and severity of crashes will be used to measure safety.

6.6.2 Concept Development

6.6.2.1 Geometric Influences



Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics likely related to the key project performance measures.

The project team decided to focus the initial alternative development and analysis on two elements: (1) obtaining a finding of no significant environmental impact and (2) creating design attributes and parameters supporting the transportation performance measures previously identified.

Roadway alignment is the primary factor influencing whether the 27th Avenue project can avoid a significant environmental impact. The critical habitat is part of the hillside and at the base of the hillside along the western border of the newly industrially zoned area. Therefore, horizontal alignment of 27th Avenue was one area of focus and consideration with respect to geometric design decisions.

In addition to the roadway alignment, the project team also elected to focus on defining a set of cross-section design parameters that can be used to develop 27th Avenue. The cross sections must balance some of the performance tradeoffs between access for heavy vehicles, quality of service for bicyclists and transit riders, and safety across modes. The project team selected the following design parameters to explore because of their direct relationship to the previously mentioned performance measures:

- Intersection geometry as it relates to being able to accommodate large vehicles (e.g., radius of curb returns)
- Lane width
- Bicycle facility presence and type (e.g., bicycle lanes)
- Ability to accommodate transit
- Sidewalk presence and width for pedestrians and transit riders

See Section 4.4 for additional guidance for identifying the design elements that influence or are influenced by a given performance measure.

6.6.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended outcomes, performance measures, and influential geometric elements.

The project team's initial effort focused on defining the alignment for 27th Avenue. Three alignment options were developed and assessed based on their ability to avoid a significant environmental impact, provide access to US-33 and downtown, and facilitate circulation within the industrial zoned area. In addition, the alignments ideally should not preclude reasonably sized parcels for large and smaller supporting employers. A brief description of each of the alignment options follows:

- **Alignment 1—US-33 and Interstate Access:** Provides connection to US-33 and to I-7. Divides the newly zoned area into four quadrants.
- **Alignment 2—Rail Yard and Port Access:** Provides a direct connection to US-33, rail yard and port. Divides the newly zoned area into two large parcels.
- **Alignment 3—US-33, Interstate, and Downtown Access:** Provides a connection to US-33, I-7, and three minor arterials in the northern downtown core. Maintains the most contiguous amount of industrial land.

Exhibit 6-29 illustrates the alignment options. Each of the alignment options can be paired with a set of design parameters helping to define the 27th Avenue cross section.

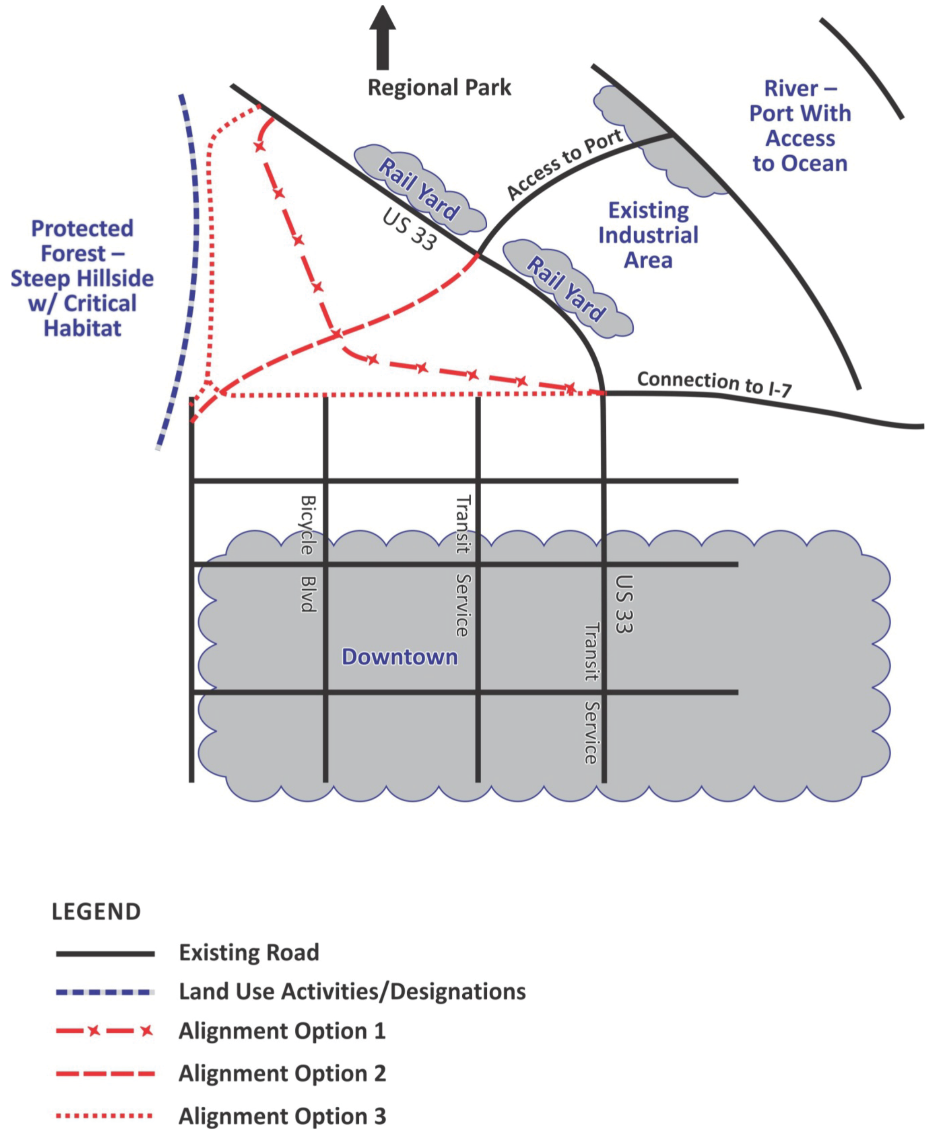
The project team developed three sets of alternative design parameters considering the different road users to be served by 27th Avenue:

- **Alternative 1—Freight Oriented:** A set of design parameters focused on characteristics facilitating the movement of large vehicles.
- **Alternative 2—Freight with Bicycle Accommodations:** A set of design parameters incorporating characteristics for large vehicles and bicyclists.
- **Alternative 3—Complete Street:** A set of design parameters considering characteristics of large vehicles, bicyclists, and transit riders.

The following subsections discuss the resources used to develop the potential solutions, considerations in developing the solutions, and the more refined alternatives the project team evaluated for 27th Avenue.

Resources Used to Develop Solutions. The project team used AASHTO's *A Policy on Geometric Design of Highways and Streets* (*1*), the city's roadway design standards, the state's highway design manual, and NACTO's *Urban Streets Design Guide* (*7*) as references and guidance materials to develop specific alternatives for evaluation.

Exhibit 6-29. Alignment options for 27th Avenue.



Solution Development. In this project, the project team was challenged to consider a range of options for an alignment as well as cross-section characteristics to try to achieve the varied performance measures previously discussed. To keep the solution development within a reasonable scope of effort, the project team focused the alignment options on avoiding significant environmental impacts, providing access to the broader transportation network, and enabling onsite circulation. The options identified for the roadway cross-section design parameters are focused on elements that provide sufficient space for heavy vehicles (as a form of accessibility), quality of service for bicyclists and transit riders, and safety. In developing the alignment options, some consideration also was given to how to augment the options to better serve (1) bicyclists currently using US-33 to access the regional park and (2) safety with respect to speed management.

Alignment Options for 27th Avenue. Alignment options for 27th Avenue were developed considering the connections to regional transportation facilities and the need to avoid a significant environmental impact. The potential connections to regional transportation facilities include the following:

- **US-33**—A highway serving as a key transportation freight corridor reaching from coastal communities west of the industrial area to urban, suburban, and rural mountain communities east of the industrial area.
- **I-7**—An Interstate freeway passing north-south through the state, connecting the majority of the major coastal cities and ports.
- **Rail Yard**—The rail yard is served by two major freight rail lines traversing east-west across the state, ultimately connecting to a major interstate rail hub.
- **Port (River)**—Provides access to large merchant and freight-carrying ships with access to the ocean and, therefore, access to a wide range of global ports.
- **Downtown—**Connection to areas where employees will be traveling to and from their places of residence. It is also a connection to existing transit service and bicycle boulevards.

The project team explored different options and degrees of direct connections to these regional transportation facilities. There are advantages and disadvantages to directly connecting to any one of these regional facilities. The direct access can be attractive to industrial employers; however, depending on the existing operations of that facility, it may result in operational delays or limited capacities by adding industrial traffic directly to an already well-used facility. Directly connecting to the downtown also presents potential considerations with respect to cut-through traffic and the general advantages and disadvantages of expanding the downtown street grid. One key advantage the city wanted to capture in one of the options was the ability to provide an alternate route and better quality route for bicyclists traveling to the regional park so bicyclists would not be forced to use US-33.

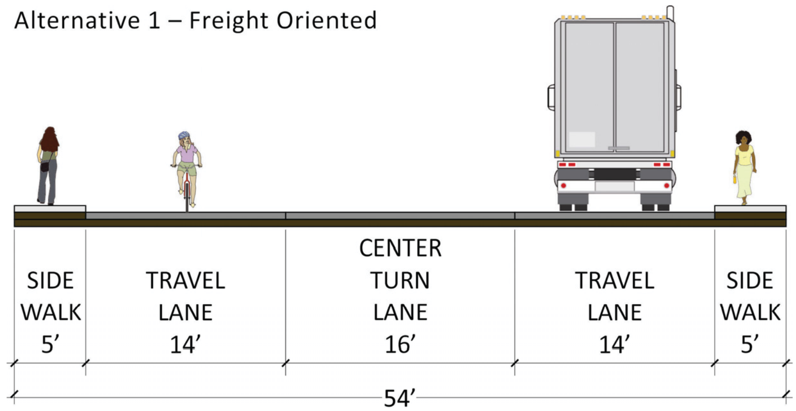
Design Parameters for 27th Avenue Cross Section. Design parameters for the 27th Avenue cross section were identified based on the road users that 27th Avenue is intended to serve. Any of the alternative cross sections can be paired with any one of the alignment options previously discussed.

A common element between the cross sections is the consideration given to accommodating large vehicles needing to routinely access the industrial uses. As additional road user design elements are incorporated into the cross section, the project team tried to balance the ultimate roadway width with providing sufficient space for different road users. This was an ongoing tradeoff in developing and evaluating the different cross sections. The city would like to keep the total cross-section width as narrow as possible while still meeting road users' needs. A narrower cross-section footprint will allow more space for the industrial uses and employers that the city would like to attract to the area. The clear tradeoff in keeping the roadway cross-section footprint narrow is having less space to serve the large vehicles, bicyclists, and transit riders who are anticipated to use 27th Avenue. The city made one overarching design decision applied to each alternative cross section. The city decided 27th Avenue will be an undivided roadway facility; therefore, none of the alternatives include a center median. The primary reason for this is to keep the roadway cross section open and free of physical obstacles, providing more space and options for drivers of heavy vehicles to navigate the industrial area.

Primary Alternatives for Evaluation. Using the resources and considerations briefly described previously, the project team arrived at the alignment options shown in Exhibit 6-29 and the following alternative cross sections for evaluation:

- **Alternative 1—Freight-Oriented:** Two-lane roadway with 14-ft-wide travel lanes and a 16-ft-wide, two-way center left-turn lane (total three-lane cross section). Cross section includes curb-tight 5-ft-wide sidewalks on both sides of the street. Shown in Exhibit 6-30.

Exhibit 6-30. Cross section of Alternative 1—Freight Oriented.



- **Alternative 2—Freight with Bicycle Accommodations:** Two-lane roadway with 12-ft-wide travel lanes and a 14-ft-wide two-way center left-turn lane (total three-lane cross section). Cross section includes 6-ft-wide bicycle lanes and curb-tight 5-ft-wide sidewalks on both sides of the street. Shown in Exhibit 6-31.
- **Alternative 3—Complete Street:** Two-lane roadway with 12-ft-wide travel lanes and a 14-ft-wide two-way center left-turn lane (total three-lane cross section). Cross section includes 5-ft-wide bicycle lanes and 10-ft-wide pedestrian space on both sides of the street. Shown in Exhibit 6-32.

Exhibit 6-31. Cross section of Alternative 2—Freight with Bicycle Accommodations.

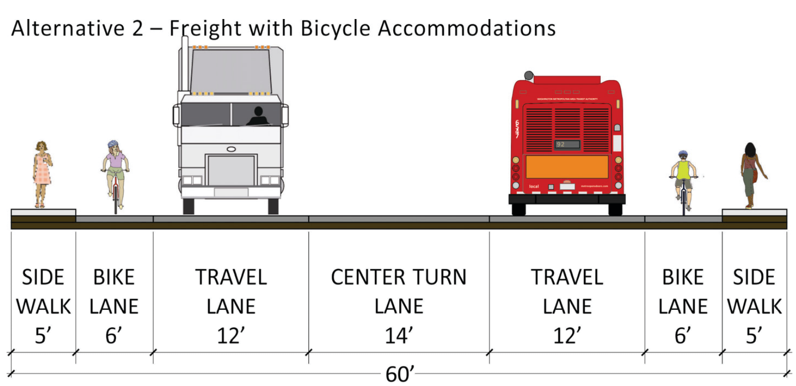
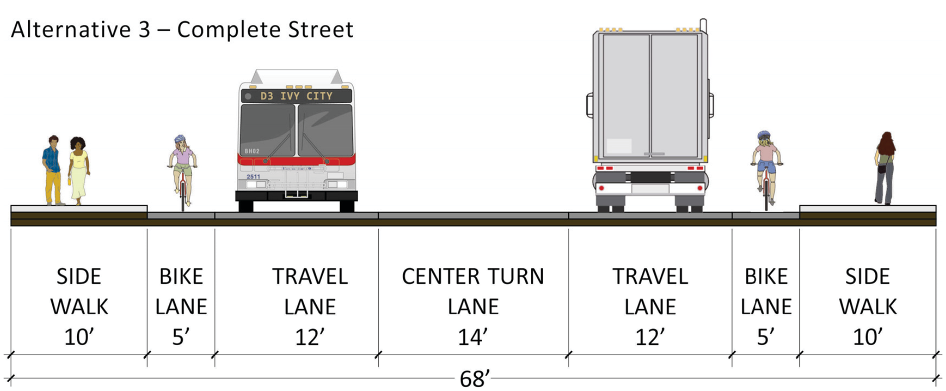


Exhibit 6-32. Cross section of Alternative 3—Complete Street.



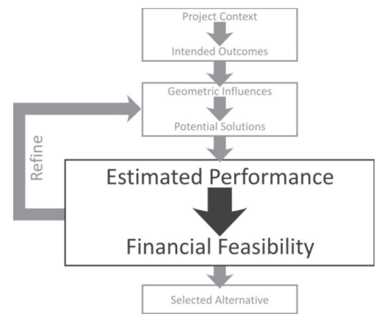
The exhibits show there are a few common elements across the alternative cross sections:

- A two-way center turn lane to facilitate access to future industrial uses fronting 27th Avenue
- Sidewalks to separate pedestrian activity and vehicle movement
- One through travel lane in each direction, which was deemed sufficient given 27th Avenue will be primarily facilitating internal circulation

6.6.3 Evaluation and Selection

6.6.3.1 Estimated Performance and Financial Feasibility

Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.



The performance evaluation for the alternative alignment options was based on each alignment's ability to:

- Avoid significant environmental impacts
- Facilitate circulation and connections to regional transportation facilities
- Maintain contiguous parcels of land for industrial uses
- Create an improved alternative route to the regional park

The performance evaluation for the alternative cross sections focused on the following performance categories and associated measures:

- Safety as defined by crash frequency
- Accessibility as defined by connectivity within the industrial area, connection to the regional park, connection to regional highways; and ability to accommodate large vehicles
- Quality of service as defined by accommodations for bicyclists and transit riders

Estimating Performance

Alignment Options. The alignment options were evaluated qualitatively across the previously listed attributes. The project team used geographic information system (GIS) software, aerial imagery, initial surveys, and preliminary engineering of the horizontal alignments to assess how each option performed relative to the attributes. The GIS mapping enabled the team to identify and determine the location of environmentally sensitive areas along and at the base of the hillside that need to be avoided. The identification of sensitive areas considered the physical impact of the roadway and industrial development as well as where and how stormwater runoff from 27th Avenue and the newly zoned industrial area is managed. The aerial imagery, initial survey of the industrial area, and preliminary engineering of the horizontal alignments, paired with the GIS information, enabled the project team to complete informed assessments of the alignment options.

Exhibit 6-33 summarizes the qualitative assessment results for the alignment options. Each alignment option was assessed using a scale of zero to three to rate how each scored for the criteria above. A zero indicates the option did not meet the criteria and a three indicates the option fulfills the criteria.

Alignment 3 scored the highest based on the criteria outlined previously for the following reasons:

- Avoids significant environmental impacts and establishes a western border for the newly zoned area. This means incoming industrial uses and employers will only be able to develop east of 27th Avenue. This guarantees no negative impacts to the hillside and will save interested

Exhibit 6-33. Assessment of alignment options.

Alignment Options	Avoid Env. Significant Impact	Connection to Regional Facilities	Circulation within Area	Contiguous Parcels of Land	Improved Alternate Route to Regional Park	Total Score
1 – US-33 and I-7 Access	3	2	2	1	1	9
2 – Rail Yard and Port Access	3	2	2	2	0	9
3 – US-33, I-7 and Downtown Access	3	3	3	3	3	15

employers from having to evaluate and/or seek environmental clearance to move into the newly zoned area.

- Provides a connection to US-33 in two different locations. It also provides a direct connection to I-7 on- and off-ramps. Finally, it connects with three minor arterials in the northern downtown core. One arterial is an existing bicycle boulevard and one has an existing transit line.
- Provides circulation within the newly zoned area along the western and southern border.
- Maintains the largest amount of contiguous parcels of land, providing potential employers with flexibility in their site development.
- Provides a more direct connection and an alternate parallel route to US-33 for bicyclists to reach the regional park.

Alignments 1 and 2 performed well for some of the evaluation criteria but were weakest in maintaining contiguous parcels of land for development and providing an alternate route to the regional park.

Alternative Cross Sections. The performance measures associated with the performance categories identified for the alternative cross sections were estimated using the following resources:

- **Safety**—Chapter 12 of AASHTO's HSM (*5*) was used to estimate the expected safety performance.
- **Accessibility**—Access was evaluated qualitatively based on the physical space allocated to heavy vehicles. Access with respect to connectivity within the area and to regional transportation facilities was captured in the assessment of the alignment options.
- **Quality of Service**—HCM2010 MMLOS methodology (*10*) was used to evaluate the quality of service (i.e., quality of the travel experience perceived by the road user) anticipated for bicyclists and transit riders.

Exhibit 6-34 summarizes the evaluation results for each of the alternatives. The qualitative scale used to evaluate access was a rating of poor, fair, or good based on the degree to which the cross section is anticipated to accommodate heavy vehicles.

Exhibit 6-34. Evaluation of alternative cross sections.

Alternative Cross Sections	Safety (crashes/ year)	Quality of Service		Access for Heavy Vehicles
		Bicycle MMLOS	Transit Riders MMLOS	
1 – Freight Oriented	2.3	E	E	Good
2 – Freight with Bicycle Accommodations	2.3	C	C	Fair
3 – Complete Street	2.3	C	B	Fair

As shown in Exhibit 6-34, each of the cross sections is estimated to have the same number of crashes per year even though across the alternatives there are changes in lane width, bicycle lane presence and width, and sidewalk width. The reason the expected crashes per year do not change across the alternatives is because the methodology in Chapter 12 of the HSM applicable to urban and suburban facilities is not able to quantify the safety effects of changes in lane width, presence or width of bicycle lanes, or the presence or width of sidewalks (*5*). This is, in part, why the project team also evaluated the quality of service for bicyclists and transit riders using the HCM2010 MMLOS methodology (*10*). That methodology is sensitive to the presence and width of bicycle lanes and sidewalks. Looking across the performance results of the alternative cross sections, Alternatives 2 and 3 seem to offer the more balanced options for multiple road users, while Alternative 1 clearly favors heavy-vehicle traffic. The following section discusses the financial feasibility considerations for the alternatives.

Incorporating Financial Feasibility. The project team developed cost estimates for each alignment option and alternative cross section to help determine which combination to select for 27th Avenue. The cost estimates for the alignment took into consideration the length of the proposed alignment and the cost per linear foot of the alternative cross sections. The costs include considerations such as stormwater management, full-depth pavement given the anticipated high volume of heavy vehicles, signing, pavement markings, lighting, and a contingency cost for unforeseen expenses or fluctuations in material costs. Exhibit 6-35 summarizes the cost estimates.

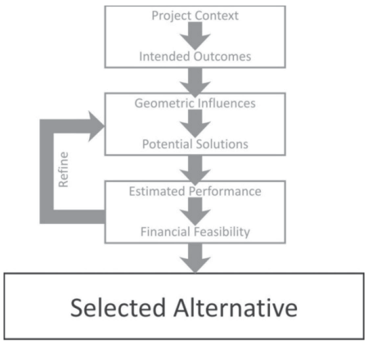
The significant drivers of cost were the length of the alignment and width of the cross section. Alignment 3 is the longest alignment option; the cost estimates for the different cross sections for that option are greater than for Alignments 1 and 2. Similarly, Alternative 3 is the widest cross section and, therefore, across each of the alignment options has the highest associated cost.

The project team did not estimate a benefit/cost ratio or calculate a cost-effectiveness factor for the different alignment options and alternative cross sections. To be able to calculate a benefit/cost ratio or cost-effectiveness factor, simplifying assumptions would be needed to convert the assessment of alignment options into monetary benefits. Additional assumptions would be needed to quantify the degree of access provided to heavy vehicles for each alternative. The project team determined such assumptions would be vulnerable to subjectivity and may convolute the assessments previously performed in the project. Therefore, the city used the cost estimates in combination with the performance evaluations to build internal consensus and solicit input from external stakeholders to work toward a selected alternative.

Exhibit 6-35. Cost estimates for 27th Avenue.

Alignment Option	Alternative Cross Section	Estimated Cost
1 – US-33 and I-7 Access	1 – Freight Oriented	$1.1 million
	2 – Freight with Bicycle Accommodations	$1.3 million
	3 – Complete Street	$1.5 million
2 – Rail Yard and Port Access	1 – Freight Oriented	$700,000
	2 – Freight with Bicycle Accommodations	$850,000
	3 – Complete Street	$1.0 million
3 – US-33, I-7, and Downtown Access	1 – Freight Oriented	$1.3 million
	2 – Freight with Bicycle Accommodations	$1.4 million
	3 – Complete Street	$1.6 million

6.6.3.2 Selected Alternative



Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., radius of a horizontal curve). This information helped inform the following discussion and decision.

The city and project stakeholders selected Alignment 3 paired with cross-section Alternative 2. Alignment 3 performed the best in the performance evaluation and especially well with respect to providing access to regional facilities and an alternate route for bicyclists to access the regional park. Alternative 2 was selected because it provided the most balanced means for serving heavy vehicles and bicyclists while managing cost and overall footprint of the roadway. Transit riders and pedestrians can also be served with Alternative 2 and, therefore, the city felt it was the most balanced overall solution.

6.7 Project Example 6: US-6/Stonebrook Road

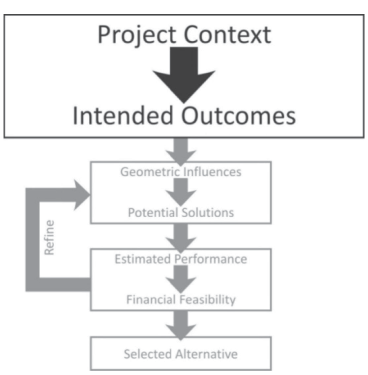
Authors' Note: Project Example 6 illustrates how performance-based analysis can be integrated into the alternatives identification and evaluation stage of an interchange improvement project located in a rural area that is evolving into a suburban environment. The project example addresses considerations within a project to convert an at-grade rural intersection to an interchange. The project team initially considered potential at-grade solutions; however, as is discussed below, it ruled out at-grade options due to the desired form and function of US-6. The project team then focused on selecting the appropriate interchange form, ramp terminal intersection control type, and interchange location (e.g., spacing considerations). The learning objectives for this project example are as follows:

- *Demonstrate how to incorporate performance analysis into interchange-related design decisions*
- *Illustrate the use of design resources beyond traditional design manuals [e.g.,* NCHRP Report 687: Guidelines for Ramp and Interchange Spacing *(12)]*

The performance categories considered within the project example are safety and mobility. Section 4.4 helped inform the selection of the specific performance measures used to evaluate the alternative solutions.

6.7.1 Project Initiation

6.7.1.1 Project Context



Authors' Note: Using the considerations noted in Section 5.2.1, we are able to identify key characteristics of the project context that are likely to help inform the intended project outcomes, performance category, and performance measures we will use to develop and evaluate potential solutions. The following summary of the project context sets the foundation for the remaining activities within the performance-based analysis framework. An important motivation for this project is to proactively improve the at-grade US-6/Stonebrook intersection from a safety perspective to reduce the likelihood of severe crashes by reducing conflicts and eliminating the type of conflicts contributing to severe crashes. The interchange would create new roadway capacity as the surrounding area evolves from rural to suburban land uses.

US-6 is an east-west four-lane divided highway serving urban communities to the west and providing a connection to recreational mountainous areas to the east and rural agricultural areas further east. The state DOT is responsible for planning, implementing, and maintaining improvements to US-6. US-6 is the primary highway access to reach the mountain recreational areas and carries relatively high volumes of weekend traffic throughout the year. It also serves a relatively high percentage of heavy vehicles carrying goods to and from the developed areas in the western part of the state and agricultural areas in the eastern part of the state.

Over the last two decades, development from the urban and suburban communities in the west has gradually pushed further east. As a result, there has been a higher volume of cross-street traffic at several locations along US-6 in what was once a rural and remote area. Within the last 2 years, five fatal crashes have occurred at the existing at-grade intersection at Stonebrook Road. Field observations and traffic analysis by DOT and county transportation engineers indicate high delay for traffic on Stonebrook Road; an increasing demand for crossing US-6 at Stonebrook Road; and high-risk movements by drivers on Stonebrook Road attempting to turn onto, turn across, or travel across US-6 (e.g., attempting to use smaller gaps in traffic on US-6).

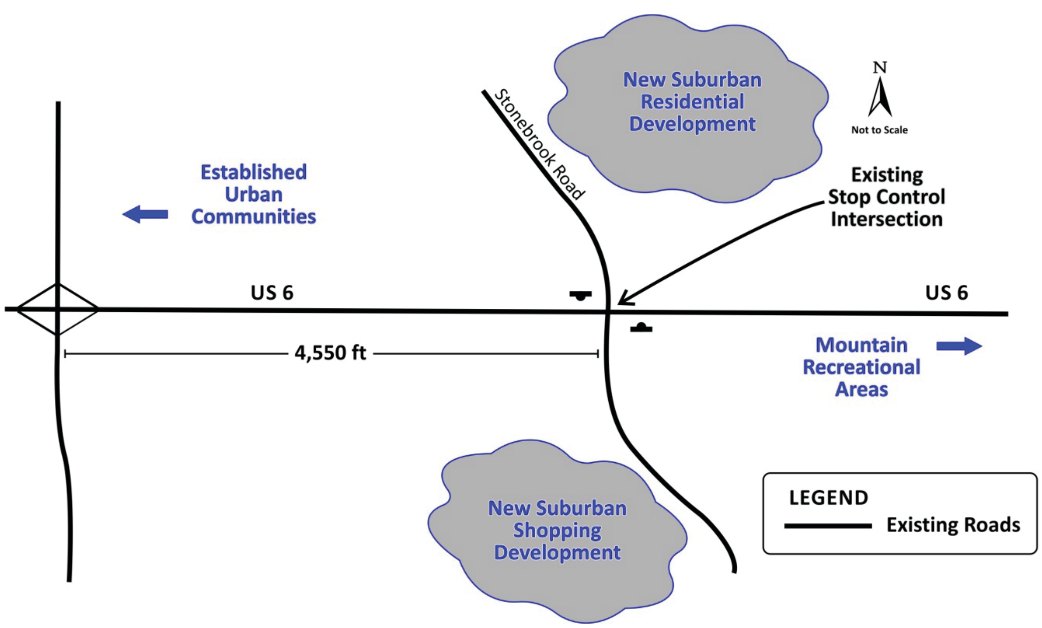
Stonebrook Road is currently a two-lane rural road with minimal paved shoulders and up to 4-ft-wide gravel shoulders in some locations. Historically, Stonebrook Road served primarily rural residents and agricultural land uses. With recent development trends, it also serves more suburban-type land uses (e.g., small strip malls, suburban residential developments) and is one of few north-south roadways that cross US-6. The US-6/Stonebrook Road intersection is within the heart of the area transitioning from rural to suburban uses. The area is experiencing the highest growth in population, employment, and traffic volumes within the county. The study area falls within an unincorporated area of the county. The county is forecasting additional growth in the years to come as agricultural land uses transition to suburban development. The county and DOT also expect higher traffic volumes traveling to and from the recreational mountain areas as additional facilities for skiing, hiking, and other activities continue to increase. Exhibit 6-36 illustrates the existing intersection location and surrounding land use considerations.

As shown in the exhibit, there is an existing interchange on US-6 west of the Stonebrook Road intersection. This is the US-6/Highway 248 (Hwy 248) interchange that currently informally indicates the approximate western extent of the denser urban and suburban development. The distance between Highway 248 and Stonebrook Road is approximately 4,550 ft.

6.7.1.2 Intended Project Outcomes

Authors' Note: The following summarizes the key information related to whom the project is intended to serve, what the project is intended to achieve (i.e., intended project outcome), the applicable project performance category (or categories), and the applicable performance measures.

Exhibit 6-36. Existing conditions of US-6 and Stonebrook Road.



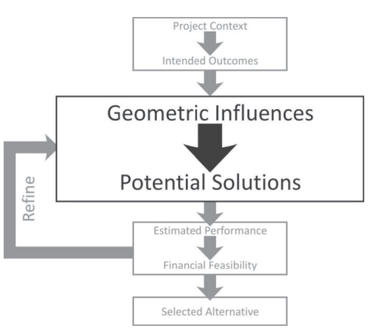
Section 3.1 provides guidance and anecdotal examples of how to identify whom the project is intended to serve and what the project is intended to achieve. Sections 3.2 and 3.3 describe the overarching relationship and differences between defining project performance and geometric design performance. In this project example, the project purpose is to proactively improve the safety and mobility of the US-6/Stonebrook Road at-grade intersection in anticipation of continued evolution from surrounding rural uses to suburban land uses (and the corresponding increase in motor vehicle traffic). Similar to Project Examples 1 and 2, the project performance and geometric performance are relatively closely aligned.

We also used Section 5.2.2 to inform the following summary of the intended project outcomes, including the applicable performance categories. In this project example, safety and mobility are the geometric performance categories of interest. We used Sections 4.4.2 (Mobility) and 4.4.5 (Safety) to select the performance measures.

Given the recent growth along US-6 and continued forecasted growth in the area, the DOT would like to implement a project at the US-6/Stonebrook Road intersection that reduces the risk of serious injury and fatal crashes, improves mobility for road users on Stonebrook Road, improves connectivity from one side of US-6 to the other, and preserves the operational integrity of US-6 (i.e., minimize delay introduced for road users traveling east-west on US-6). The DOT is the primary agency stakeholder within this project because it has jurisdiction over US-6. The county is an agency stakeholder with jurisdiction over Stonebrook Road. It has the best understanding of the forecasted growth in the area.

The target audience for this project includes existing road users along Stonebrook Road and future road users within the area who desire access to both sides of US-6 as well as US-6 itself. The secondary target audience for the project is existing and future road users traveling on US-6. Road users on US-6 are primarily autos and heavy vehicles with some recreational cycling. US-6 is a state-designated bicycle route with shoulders 8 to 10 ft in width to accommodate bicyclists. Road users on Stonebrook Road include autos, heavy vehicles, agricultural vehicles, bicyclists, and pedestrians; transit service is expected to be expanded to serve the area and circulate using Stonebrook Road within a 10-year planning horizon.

The purpose of this project is to identify the appropriate solutions for the US-6/Stonebrook Road intersection to serve existing and anticipated future road users. The project team identified and evaluated a range of concepts and associated performance based on (1) alternatives for at-grade intersection control and grade-separated options; (2) ramp terminal intersection control, if a grade-separated interchange is selected; and (3) ramp spacing considerations on US-6 (as part of grade-separated interchange considerations). The performance categories the DOT selected are to improve intersection safety and mobility (specific to road users on Stonebrook Road). The performance measures selected for safety are crash frequency and severity. The performance measure selected for mobility is the delay experienced by traffic on Stonebrook Road. Critical qualitative considerations the DOT wanted the project team to consider included maintaining the operational integrity of US-6 (i.e., minimizing delay for road users on US-6) and improving connectivity across US-6 to facilitate access for anticipated land uses.



6.7.2 Concept Development

6.7.2.1 Geometric Influences

Authors' Note: We used the information presented in Section 5.3 and specifically Section 5.3.1 for guidance on how to approach identifying the geometric influences for the project. We used Section 4.4 to help inform, at a more detailed level, the specific geometric characteristics likely related to the key project performance measures.

The project team initially identified three potential improvements to the US-6/Stonebrook Road intersection to improve safety and mobility. The three options were to convert the existing two-way stop-controlled intersection to (1) traffic signal control, (2) roundabout control, or (3) an interchange. While there are some operational and potential safety benefits to the traffic signal and roundabout control options, the project team decided not to pursue those improvements further due to the delay each of those options would introduce for road users on US-6. The DOT's ultimate plan for US-6 is to create a grade-separated facility; therefore, investing in at-grade intersection improvements was not of interest to the DOT.

Authors' Note: If there will be a significant delay before the interchange is constructed, there could be value, based on safety performance, in considering at-grade changes for the 8 to 10 years of benefits they might provide until the grade separation alternative could be constructed. In this project, the DOT was prepared to invest and construct grade-separated improvements within the near future; therefore, the at-grade options were not carried further in the solution development.

Based on this preliminary screening, the project team focused on the following roadway attributes for US-6/Stonebrook Road:

- **Interchange Form**—What type of interchange is most appropriate for the US-6/Stonebrook Road intersection? What are the safety and operational tradeoffs?
- **Ramp Terminal Intersection Control**—What type of intersection control at the ramp terminal intersections on Stonebrook Road are most appropriate given safety, operational, and road user considerations?
- **Interchange Location/Spacing**—Given interchange spacing considerations, where is the most appropriate location for the new interchange?

The following presents the project team's approach for identifying and developing solutions to address these roadway considerations. Section 4.4 provides additional guidance in identifying the design elements that influence or are influenced by a given performance measure.

6.7.2.2 Potential Solutions

Authors' Note: Section 5.3.2 provides useful information and considerations for how to develop potential solutions given the specific project context, intended outcomes, performance measures, and influential geometric elements.

The project team identified a set of alternatives to address each of the three broad areas of consideration. These alternatives are as follows:

- **Interchange Form**—Diamond, two-quadrant partial cloverleaf ramps (parclo) in advance of the cross street (Parclo A), or two-quadrant partial cloverleaf ramps beyond the cross street (Parclo B)
- **Ramp Terminal Intersection Control—**Two-way stop, traffic signal, or roundabout
- **Interchange Location/Spacing**—Locating the Stonebrook Road cross street and ramps in such a way as to support constructing the interchange while maintaining existing access to the areas north and south of US-6.

The following subsections highlight the resources used to develop alternative solutions and the key considerations from the solution development.

Resources Used to Develop Solutions. The project team used the AASHTO Green Book (*1*), the DOT's roadway design manual, *NCHRP Report 687* (*12*), the Institute of Transportation Engineers' (ITE) *Freeways and Interchanges Geometric Design Handbook* (*13*), and *NCHRP Report 672* (*2*).

Solution Development. Using these resources and considering the project performance measures, the project team developed a set of alternatives for evaluation. The following paragraphs describe key considerations in developing solutions for each of the areas of consideration.

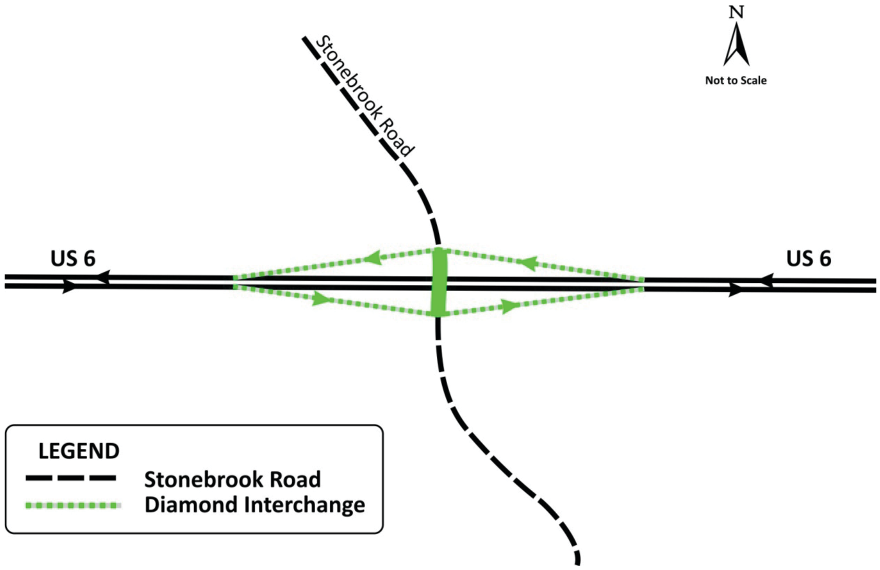
Interchange Form. The range of potential interchange forms appropriate for a given location are initially governed based on the type and function of the roadway facilities being connected by the interchange. In the case of US-6 and Stonebrook Road, US-6 is a highway and Stonebrook Road is a rural collector that will likely evolve into more of an urban arterial over time. US-6 is the regional facility and Stonebrook Road is a local facility providing access to US-6. Based on these functions, the interchange will be a service interchange. Using Exhibit 10-44 from the AASHTO Green Book, the project team identified potential service interchanges including diamond, split diamond, Parclo A, Parclo B, and cloverleaf. For the US-6/Stonebrook Road interchange, the project team decided to focus on the Diamond, Parclo A, and Parclo B interchanges as potential forms. The diamond interchange is the most intuitive for road users. Two-quadrant Parclo A and Parclo B interchanges provide flexibility to avoid right-of-way impacts to one or two quadrants of the interchange. They also have the ability to eliminate some left-turn movements at the ramp terminal intersections. Depending on the ultimate location of the interchange, this may be useful to avoid impacts to existing land uses near the US-6/Stonebrook Road intersection. As will be discussed later, interchange forms are also influenced by the proximity and form of adjacent interchanges.

Ramp Terminal Intersection Control. With each of the previously noted interchange forms, there will be two ramp terminal intersections on Stonebrook Road. The ramp terminal intersection control alternatives were initially identified as two-way stop, traffic signal, and roundabout. The current traffic volumes on Stonebrook Road do not meet volume warrants for traffic signals. Traffic volume forecasts estimate that traffic volumes will warrant a traffic signal in approximately 15 to 20 years, depending on the rate of growth of surrounding development. The DOT plans to construct the improvements at the US-6/Stonebrook Road intersection within 5 years. Therefore, the project team focused on the two-way stop control (TWSC) and roundabout control alternatives and compared the design life of those control forms to the estimated timeline of when the traffic signal would be warranted. The project team recognizes the TWSC would be the lowest cost control type to implement; however, it may not have the design life or anticipated safety performance associated with a roundabout. The shorter design life would require the DOT in the future to implement either a traffic signal or roundabout. If a roundabout is able to operate well for near-term and long-term traffic volumes, it may be more cost effective for the DOT to invest in the roundabout ramp terminal intersections upon initial interchange construction to preclude the need to revisit the interchange 10 years after construction.

Interchange Location/Spacing. *NCHRP Report 687* (*12*) notes planners and designers focus on ramp spacing dimensions versus interchange spacing. This emphasizes the operations and safety focus on the highway mainline and ramp terminals versus the somewhat arbitrary dimension between two interchanging cross streets. The project team considered various locations to construct the Stonebrook Road overcrossing. The natural location to consider is keeping Stonebrook Road on its current alignment and replacing the at-grade intersection with an interchange. However, constructing the interchange in that location creates complex traffic maintenance during construction or requires closing Stonebrook Road until the interchange can be completed. Given the importance of Stonebrook Road, closure was considered undesirable and, therefore, the team considered alternatives for relocating Stonebrook Road to create the interchange while keeping the existing intersection open during interchange construction. Locating the interchange east or west of Stonebrook Road requires considering the traffic operations, geometric design, safety performance, and signing locations. Traffic operation and safety performance is especially sensitive to ramp spacing dimensions and, therefore, the Stonebrook interchange location must be considered in the context of existing and future adjacent interchange locations on US-6.

Primary Alternatives for Evaluation. Based on the project context and considerations, the primary alternatives the project team identified for evaluation are described in the following subsections.

Exhibit 6-37. Diamond interchange.



Interchange Form Alternatives. This subsection presents schematics of the three alternative interchange forms:

- **Diamond Interchange:** Diamond interchange providing access to and from Stonebrook Road and US-6. Shown in Exhibit 6-37.
- **Two-Quadrant Parclo A Interchange:** Prevents right-of-way impacts in the northwest and southeast quadrants of the interchange. At the ramp terminal intersections, the Parclo A form eliminates the southbound left-turn movement to access eastbound US-6 and eliminates the northbound left-turn movement to access westbound US-6. Shown in Exhibit 6-38.
- **Two-Quadrant Parclo B Interchange:** Prevents right-of-way impacts to the northeast and southwest quadrants of the interchange. At the ramp terminal intersections, the Parclo B form eliminates the eastbound left-turn movement from eastbound US-6 onto northbound

Exhibit 6-38. Two-quadrant Parclo A interchange.

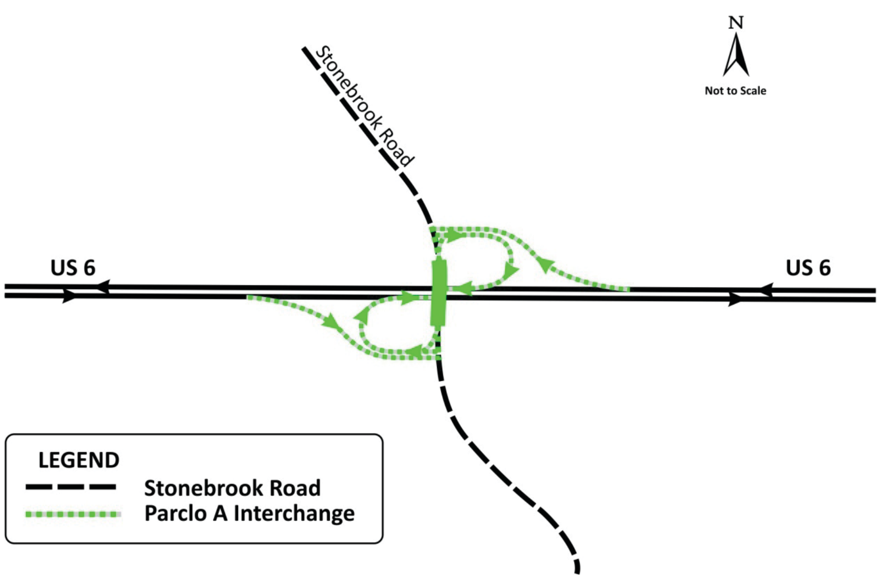
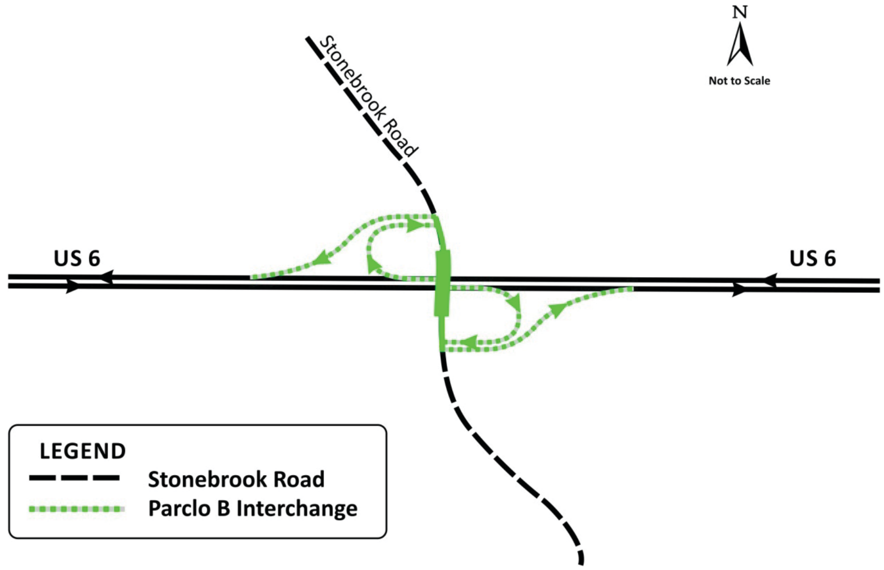


Exhibit 6-39. Two-quadrant Parclo B interchange.



Stonebrook Road and eliminates the westbound left-turn movement from westbound US-6 onto southbound Stonebrook Road. Shown in Exhibit 6-39.

The subsection on interchange location/spacing presents where each interchange form may be most appropriate given the proximity of the Hwy 248 interchange, adjacent land uses, and desire to keep Stonebrook Road open during construction of the interchange.

Ramp Terminal Intersection Control Alternatives. These three control alternatives differ in cost and longevity:

- **Two-Way Stop Control:** The lowest cost alternative to meeting near-term traffic volume demands expected at the ramp terminal intersections.
- **Roundabout Control:** Higher cost alternative that is able to handle near- and longer-term traffic volumes expected at the ramp terminal intersections.
- **Traffic Signal Control:** Higher cost alternative, not warranted with current traffic volumes. Forecasted volumes estimate it will be warranted approximately 10 years after initial interchange construction.

Interchange Location/Spacing Alternatives. There are three possible alignment alternatives for the US-6/Stonebrook Road intersection:

- **West of Existing Stonebrook Road Intersection:** This alternative locates the interchange west of the existing Stonebrook Road intersection. A key consideration for this location is that the adjacent Hwy 248 interchange is 4,550 ft from the current Stonebrook Road alignment. Based on guidance that considers conflict management and crash frequency between interchanges, this alternative would limit the potential interchange forms to a diamond interchange [see Exhibit 5-2 in *NCHRP Report 687* (*12*)]. The minimum spacing at which a diamond interchange form would be feasible would be approximately 4,000 ft between the Hwy 248 cross street and the new Stonebrook Road cross street. Therefore, the ramp spacing would be 1,300 ft between the US-6/Hwy 248 and new US-6/Stonebrook Road interchange ramps. The project team estimated the ramp spacing using guidance in Section 3.3.5 of *NCHRP Report 687* (*12*). Relative to the existing Stonebrook Road cross-street location, that would provide only approximately 550 ft between the new interchange and existing Stonebrook

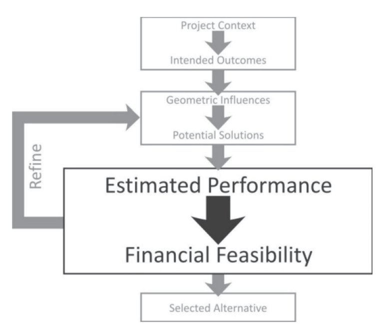
Road for constructing the on-/off-ramps for the new interchange. From a constructability perspective, that may not be sufficient space to keep the existing Stonebrook Road open to traffic throughout construction. The realignment of Stonebrook Road south of US-6 would also have the potential to negatively affect the new suburban shopping development.

- **Existing Stonebrook Road Interchange:** This alternative locates the interchange at the existing US-6/Stonebrook Road intersection. Based on guidance from *NCHRP Report 687*, this alternative would potentially allow for the parclo or diamond interchange forms [see Exhibit 5-2 in *NCHRP Report 687* (*12*)]. Constructing the interchange at this location would not have right-of-way impacts to the new suburban shopping center southwest of US-6/Stonebrook Road or the new suburban residential development northeast of US-6/Stonebrook Road. It would be necessary to close the existing US-6/Stonebrook Road intersection during interchange construction, which would negatively affect access to US-6 in the vicinity as well as the new land uses north and south of US-6. The drivers would need to use the US-6/Hwy 248 interchange farther west. The ramp spacing with the diamond form would be approximately 1,850 ft between the US-6/Hwy 248 and new US-6/Stonebrook Road interchange ramps. The ramp spacing with one of the parclo forms would be approximately 1,350 ft. The project team estimated the ramp spacing using guidance in Section 3.3.5 of *NCHRP Report 687* (*12*).
- **East of Stonebrook Road Intersection:** This alternative locates the interchange east of the existing US-6/Stonebrook Road intersection. Locating the interchange farther east enables any of the three interchange forms to be considered. It also makes it possible to maintain traffic on Stonebrook Road throughout the new interchange construction. To avoid right-of-way impacts to the new suburban residential development northeast of the US-6/Stonebrook Road intersection, this alternative would locate the new interchange approximately 2,700 ft east of the current intersection location. Therefore, the new Stonebrook Road would border the development on its eastern side. Using this alternative would require moving the main access to the residential development or constructing a local street connection from the existing main entrance to the new Stonebrook Road alignment. Shoppers or employees traveling to/from the new suburban shopping development would need to travel approximately a half mile east to access US-6 or cross US-6 to access land uses to the north. The ramp spacing would be approximately 4,550 ft between the US-6/Hwy 248 and new diamond US-6/Stonebrook Road interchange ramps. The ramp spacing would be approximately 4,050 ft if one of the parclo forms is used. The project team estimated the ramp spacing using guidance in Section 3.3.5 of *NCHRP Report 687* (*12*).

6.7.3 Evaluation and Selection

6.7.3.1 Estimated Performance and Financial Feasibility

Authors' Note: Sections 5.4 and 5.4.1 provide information and considerations regarding (1) how to estimate the performance of project alternatives or specific geometric design decisions and (2) how to assess the financial feasibility of those project alternatives or design decisions. Section 4.4 presents information regarding what resources are available within the profession to help conduct the performance analysis for each project alternative or geometric design decision.



The performance evaluation focused on the following performance measures:

- Safety as defined by crash frequency and severity
- Mobility as defined by delay for road users on Stonebrook Road

Estimating Performance. At the time the project team initially developed and evaluated the interchange alternatives, the HSM did not include safety prediction for freeways or interchanges. Since this project was completed, the final report for NCHRP Project 17-45, "Enhanced Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges" (*14*), has been made available and can be used to predict crash frequency and severity for different interchange and ramp terminal configurations. However, the final report for NCHRP Project 17-45 (*14*) does not include a method for predicting crashes at roundabout-controlled ramp terminal intersections. To understand the potential safety performance of the roundabout control intersection relative to the expected performance of TWSC and traffic signal control intersections, the project teamed used the results from before-after research studies published in Tables 14-3 and 14-4 of the HSM and related information published in Exhibit 5-9 within *NCHRP Report 672* (*2*). *NCHRP Report 687* (*12*) was used to evaluate the tradeoffs of potential interchange locations and ramp spacing considerations. HCM2010 (*10*) was used to evaluate the mobility tradeoffs to road users on Stonebrook Road.

Additional guidance on resources for safety and mobility performance categories can be found in Section 4.4. Exhibit 6-40 summarizes the evaluation results for each of the alternatives previously presented.

For each of the interchange forms, the crash estimates reflect those expected for the movements onto, off of, and along the ramps; the estimate does not include crashes expected at the ramp terminal intersections. Those are captured for each ramp terminal intersection type. The diamond interchange form is expected have the lowest number of crashes per year. The lower number of expected crashes per year relative to the two-quadrant Parclo A and Parclo B forms is most likely due to the lack of horizontal ramp curvature. The horizontal curvature for the

Exhibit 6-40. Alternatives evaluation of the US-6/Stonebrook Road intersection.

Alternatives	Safety (crashes/year)	Mobility (avg. delay for Stonebrook Road movements)	
		Current Year (s)	Future[a] (s)
Interchange Forms			
Diamond	11.2	—	—
Two-Quadrant Parclo A	15.3	—	—
Two-Quadrant Parclo B	16.2	—	—
Ramp Terminal Intersections			
Two-Way Stop Control	5.2	12.2	>50.0
Single-Lane Roundabout	2.4	8.2	18.8
Traffic Signal	3.2	—	20.1
Interchange Location/Spacing[b]			
West of Existing Intersection[c]			
Diamond w/ramp spacing =1,300 ft	10% to 25% more	—	—
At Existing Intersection			
Diamond w/ramp spacing = 1,850 ft	0% to 10% fewer	—	—
Parclo w/ramp spacing = 1,350 ft	10% to 25% more	—	—
East of Existing Intersection			
Diamond w/ramp spacing = 4,550 ft	0% to 10% fewer	—	—
Parclo w/ramp spacing = 4,050 ft	0% to 10% fewer	—	—

— indicates not applicable.
[a] 20 years after construction
[b] Presents relative crash risk based on ramp spacing and information from Exhibit 5-5 in *NCHRP Report 687*. Relative crash risk is measured by the percent difference in total crashes at a given ramp spacing compared to a ramp spacing of 1,600 ft, which is the minimum ramp spacing value from the AASHTO Green Book.
[c] Assumes a diamond interchange form given limited distance to US-6/Hwy 248 interchange.

ramps within the two-quadrant Parclo A and Parclo B forms is associated with higher expected crashes. Delay for Stonebrook Road was not estimated for each of the interchange forms because that performance metric is directly related to the ramp terminal intersection control. The project team decided that for initial solution development and evaluation all movements occurring at the ramp terminal intersections would be subject to the control present (i.e., no free movements onto or off of US-6 on- and off-ramps). The intent is to keep vehicle speeds for vehicles departing from and entering onto Stonebrook Road in the range of 25 mph because of the expected pedestrians and bicyclists on Stonebrook Road.

Roundabout control at the ramp terminals is expected to perform the best with respect to the expected number of crashes per year, and it is estimated to perform relatively well with regards to existing and future mobility for road users on Stonebrook Road. Based on forecasted traffic volumes, a single-lane roundabout is expected to operate well for near- and long-term traffic volumes. The TWSC alternative performs moderately well with respect to expected number of crashes per year and existing delay for movements onto and off of Stonebrook Road. In the future years, the delay for Stonebrook Road movements with the TWSC form is notably higher than the roundabout or traffic signal control. The traffic signal control performs moderately well with respect to long-term expected crashes; this assumes it is installed after volume warrants are met. Existing operations with a signal were not estimated because, as noted previously, with existing volumes, a signal is not warranted. Future operations with a traffic signal indicate moderate delay similar to the roundabout control.

The best performing interchange location/spacing alternatives relative to crash risk are the options to locate a diamond interchange at the existing US-6/Stonebrook Road intersection and locating a diamond or two-quadrant parclo interchange east of the existing intersection. These two fundamental spacing alternatives are at the existing intersection or east of the intersection. Given the similar anticipated crash risk associated with these options, the ultimate decision will be influenced by right-of-way and access considerations for the new suburban developments in the area and the degree to which the project team determines it is critical to keep Stonebrook Road open to traffic during construction of the new interchange.

Incorporating Financial Feasibility. The project team developed separate cost estimates for each interchange form, ramp terminal intersection, and interchange location/spacing configuration alternative. Because the detailed cost of each element is influenced by the others, the project team began by developing initial planning cost estimates for each and, in subsequent work, prepared more detailed cost estimates for the alternatives selected for development. The cost estimates shown in Exhibit 6-41 assumed that Stonebrook Road would be raised to pass over US-6, requiring a bridge to support Stonebrook Road, fill to raise Stonebrook Road approaches, and fill on which to construct the interchange ramps. The cost estimates also took into consideration items such as stormwater management needs, additional lighting, right-of-way, potential for retaining walls, and a contingency for unforeseen expenses or fluctuations in material costs. Each cost estimate assumes US-6 will maintain its current alignment and the segment of US-6 within the construction area of the interchange will be rehabilitated, repaved, and restriped as part of the overall interchange construction. The costs shown for the interchange spacing alternatives represent additional cost associated with the need to acquire right-of-way, construct additional local road connections (e.g., if the interchange is located east or west of the current Stonebrook alignment), and constructability issues (e.g., constructing temporary Stonebrook Road accesses and maintaining traffic during construction).

The significant drivers of cost across the alternatives were the bridge structure, fill, and earthwork to raise Stonebrook Road above US-6. The two-quadrant Parclo A and Parclo B interchange forms are estimated to be less than the diamond interchange form primarily because

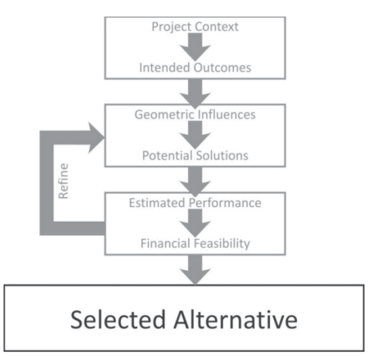
Exhibit 6-41. Cost estimates for US-6/Stonebrook Road.

Alternatives	Cost[a]
Interchange Forms	
Diamond	$24.3 million
Two-Quadrant Parclo A	$22.8 million
Two-Quadrant Parclo B	$21.2 million
Ramp Terminal Intersections	
Two-Way Stop Control	$250,000 per intersection
Roundabout	$600,000 per intersection
Traffic Signal	$350,000 per intersection
Interchange Location/Spacing	
West of Existing Intersection	$5 million
Existing Intersection	$3 million
East of Existing Intersection	$10 million

[a] Costs shown are additive. For example, to estimate the total planning-level cost for a diamond interchange with roundabout ramp terminal control intersections located east of the existing intersection location, one would add together $24.3 million; $600,000; $600,000; and $10 million to arrive at a total planning-level cost estimate of $35.5 million.

their right-of-way impacts would be constrained to fewer quadrants of the interchange. The circular ramps for the two-quadrant Parclo A and Parclo B ramps also create some opportunities for on-site stormwater management treatments that are reflected as potential cost savings relative to the diamond interchange. The TWSC is the least costly intersection control in the near term. The traffic signal control has the highest cost because it requires additional roadway width on Stonebrook Road for side-by-side turn-lane storage; this requires a wider bridge across US-6. In comparison, the roundabout has a higher near-term cost relative to the TWSC intersection, but overall appears to be the more cost-effective treatment given it performs well in the near and long term for the expected growth in traffic volumes. The additional costs associated with the alternative interchange locations are primarily influenced by right-of-way acquisition needs, maintaining traffic during construction, and reconstructing the alignment of Stonebrook Road. As a result, moving the interchange west or east of the existing intersection location has higher associated costs as they have additional right-of-way, traffic maintenance, and traffic management needs and require a greater degree of reconstructing Stonebrook Road alignment.

6.7.3.2 Selected Alternative



Authors' Note: Section 5.4.2 presents considerations with respect to selecting a preferred project alternative or determining the appropriate specific geometric design decisions (e.g., radius of a horizontal curve). This information helped inform the following discussion and decision.

The DOT and county selected the diamond interchange form primarily because it has the lowest expected number of crashes associated with it, is a relatively intuitive interchange form for motorists, and has the least impact to motorists traveling through on US-6. The adjacent interchange on US-6 is also a diamond form. Among the project team there was extensive discussion as to whether to locate the diamond interchange at the existing intersection location or east of the existing intersection. Due to the higher crash risk associated with the interchange located west of the existing intersection, that option was dropped from further consideration. The primary concerns holding back selecting the interchange for construction east of the existing intersection were the access and circulation impacts to the new suburban residential development and shopping center. The DOT and county held several meetings with the new residents within the development, the developer in the process of selling the remaining homes, and the businesses within the new shopping center. Given the potentially negative impacts to the residents, developer, and shopping center businesses associated with closing Stonebrook Road during the new interchange construction, the agencies and stakeholders agreed to locate the new interchange east of the existing intersection and invest in additional local road connections and realigning Stonebrook Road to facilitate access to the new residential development and shopping center with the new interchange in place.

With respect to the ramp terminal intersection control, the DOT and county selected the roundabout as the preferred ramp terminal intersection control form. The roundabout's safety and mobility performance (near and longer term), paired with its being the most cost-effective, long-term intersection form, were the primary reasons the DOT and county selected that alternative. They also see potential for using the roundabout and landscaping to create a sense of place for and gateway to the developing area. The county, especially, sees a great opportunity for using the landscaping opportunities at the roundabouts as means for establishing a community identity that blends the rural history of the surrounding area with the forecasted growth.

6.8 References

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
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	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
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
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