Project No. 15-34A

PERFORMANCE-BASED ANALYSIS OF GEOMETRIC DESIGN OF HIGHWAYS AND STREETS

SUPPLEMENTAL RESEARCH MATERIALS REPORT

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Performance-Based Analysis of Geometric Design of Highways and Streets

Supplemental Research Materials Report

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SECTION 1
INTRODUCTION AND OVERVIEW

1.1 RESEARCH PROBLEM STATEMENT

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 desire 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 is needed to provide the designer with the tools to evaluate the performance of different design alternatives objectively.

1.2 RESEARCH OBJECTIVES

The objective of this project is to complete the work begun under NCHRP Project 15-34 by 1) archiving prior 15-34 work; 2) updating information from prior 15-34 documents and deliverables to include current performance-based analysis capabilities and tools; and 3) documenting a process for conducting performance-based analysis to inform geometric design decisions; and 4) using case studies to illustrate the process. Six distinct tasks have been identified to achieve the project objective. These include:

- Task 1. Review the material developed in NCHRP Project 15-34.

- Task 2. Conference call with the panel to review the planned research approach.
- Task 3. Develop a draft work plan to develop the guide.
- Task 4. Panel meeting to review and revise the draft work plan.
- Task 5. Execute the revised work plan.
- Task 6. Submit final project deliverables.

SECTION 2
PAST NCHRP 15-34 MATERIALS AND ARCHIVE

2.1 ORIGINAL PROJECT TEAM AND TRANSITION

The original project team for NCHRP 15-34 was The Pennsylvania State University as the prime consultant and Kittelson & Associates, Inc. as the sub-consultant. The original intent of NCHRP project 15-34, as outlined in its January 2007 Interim Report, was to facilitate the transference of research findings and performance-prediction technologies to application within highway and street decision-making processes. This would be achieved through the following specific actions:

- Establishing a lexicon of transportation performance terms and measures related to geometric design decisions,
- Developing a framework that efficiently conveys knowledge of relationships between transportation performance and geometric design decisions,
- Populating the framework with knowledge that is currently or imminently available,
- Creating a bridge between traditional geometric design practice and design-decision methods that explicitly consider performance through:
    - A guidebook for practitioners;
    - Recommended revisions to *A Policy on Geometric Design of Highways and Streets (Green Book)* (1) that will attain consistency and mutual reinforcement between the Green Book and guidebook; and
    - Articulating a vision for the future of performance-based geometric design analysis.

Four sequential research tasks aimed at meeting these objectives were executed in the latter half of 2006, culminating in a First Interim Report (January 2007). The information gathered as part of these tasks is still relevant and applicable to the project objectives. The Task 4 interim meeting was held on February 5, 2007.

After the meeting held in February 2007, significant project changes were made, including a change to the principal investigator, and then the original NCHRP 15-34 project was stopped in March 2010.

However, with the panels' desire to continue the project and advance the work that was already completed, NCHRP 15-34A was initiated in Summer 2012 with Kittelson & Associates, Inc. leading the project and University of Utah as a sub-consultant. Below is a timeline illustrating the history of the original NCHRP 15-34 project and the initiation of the new project as NCHRP 15-34A.

- July 2006 Project Initiated
- 2006 Conduct Work
- January 2007 Interim Report 1
- February 2007 Project Panel Meeting
- Fall 2007 Principal Investigator Change
- 2008/2009 Conduct Work
- June 2009 Project Panel Meeting
- March 2010 Project Stopped
- Late Summer 2012 Project NCHRP 15-34A Initiated

2.2 NCHRP 15-34 PROJECT MATERIALS

The initial task of NCHRP 15-34A was to assemble and review the materials previously developed within the original project. The following table summarizes the key documents obtained from the original project NCHRP 15-34.

Exhibit 2-1
Key Documents Obtained from NCHRP 15-34

Item No.	Document/File Name	Description
1	NCHRP 15-34 Proposal	The original winning proposal
2	Contractor Response.doc	Panel comments on the proposal
3	NCHRP 15-34 Working Plan	Amplified work plan
4	Phase I Working Files	A series of electronic 'working files' and workshop materials developed during the original Tasks 1 through 4 leading to the First Interim Report. Exact agreement between the electronic files and the official First Interim Report (in hardcopy) has not been checked.
5	NCHRP 15-34 First Interim Report (hard copy and electronic word files*)	The First Interim Report, prepared by Mahoney, Porter, Himes, and Wemple, submitted in January 2007. The report contained six chapters and an appendix corresponding to the first four tasks of the project.
6	'Framework Construction'	The series of files served as Appendix A and showed an example framework for organizing geometric design decisions and performance measures through a series of hyperlinked documents.
7	15-34 Panel Meeting Notes 2-5-2007.doc	Detailed notes prepared by the contractor from the first panel meeting. Overall (general) comments as well as chapter-by-chapter comments are provided. Reactions to the First Interim Report were positive. Overall, the priorities moving forward were to: 1) Ensure the hyperlinked framework was 'user-friendly; 2) include additional performance measures and performance estimating tools for pedestrians and bicyclists; 3) determine design decisions that apply to specific project types; and 4) identify case studies of performance-based analysis.
8	Update on Project Activities and Work Completed Since Interim Report	This document appears to be a summary of work that immediately followed the First Interim Report and panel meeting. Most of the document is made up of project decision trees and tables to link design decisions to specific project types (in response to comments during the panel meeting). Very preliminary work on input data needs, availability, and accuracy is also provided.
9	Draft Second Interim Report (partial hardcopy)	This is a partial draft (introductory chapter only) of a Draft Second Interim Report prepared by Shankar, Kwon, Chen, Park, and Oh. The report describes a need to conduct extensive case studies in the VISSIM microsimulation model. Details on methodology and results are not provided in the partial hardcopy that is currently available.

Exhibit 2-2 Continued
Key Documents Obtained from NCHRP 15-34

10	15-34 Panel Meeting Notes from 7-7-2009 (on Second Interim Report)	Notes prepared by the NCHRP project manager from the second panel meeting. At this point, the panel was recommending a 10 to 12 page outline of a "guide" that built on Chapter 6 of the First Interim Report. It was also noted that the feasibility of continuing the hyperlinked document provided as Appendix A of the First Interim Report should also be explored.
11	Panel Comments on Second Interim Report	Written panel comments on the Draft Second Interim Report.
12	Kwon_Final_Thesis.pdf	A Master of Science thesis by Daniel Kwon, the second author on the Draft Second Interim Report. The thesis provides insights into the work executed since 'Item No 8' in the absence of NCHRP documentation that has not been provided by the original contractor.
13	Supplemental PowerPoint files from TRB Performance Based Geometric Design Analysis Workshop at TRB 2007 Annual Meeting	A series of three PowerPoint files that summarize the work presented in the First Interim Report and were used to facilitate a workshop on performance-based geometric design analysis at the 2007 TRB Annual Meeting.

The NCHRP 15-34A project team assembled and reviewed the original project materials. From this process, the team identified the material to be archived and material that would be helpful as the remaining project tasks were approached.

The research team has organized and archived the relevant information into an accessible, web-based format. The archived materials on the website were drawn primarily the 15-34 First Interim Report (January 2007), including definitions and timing of design decisions, recommended performance measures, capabilities of performance prediction tools related to performance measures that are predicted, and the sensitivity of those measures to geometric design decisions. This material appeared to comprise the majority of the original research findings and products that were definitively supported and well received by Panel members.

The NCHRP 15-34 archived material is located at the following website link: **https://sites.google.com/site/nchrp1534archive/.**

SECTION 3
USABLE NCHRP 15-34 ELEMENTS AND MATERIALS

The team reviewed NCHRP 15-34 materials and was able to identify the elements and materials to be carried forward throughout the remainder of the project tasks.

The culmination of the original research project was intended to be a stand-alone guidance document for conducting performance-based analysis of geometric design decisions. A preliminary outline of the guidance document was provided in the January 2007 Interim Report. A number of case studies and example applications of performance-based analysis concepts were to be included in the guidebook.

The NCHRP 15-34A research team was able to use the following information from the prior NCHRP 15-34 research efforts to begin developing the draft project reports:

- Similar project development process considering environmental clearance activities;
- Tables and matrix summaries of design elements, design decisions, and resources/software/tools available to evaluate the performance effects of design decisions (with updates based on more recently completed research);
- Updated performance categories consistent with broader, national performance-based transportation decision making efforts; and
- Specific recommended performance measures that capture panel priorities during the previous 15-34 efforts with updates based on more recent completed research.

As the research team continued to develop the *NCHRP Report 785*, some of the elements from the previous NCHRP 15-34 material were useful to the chapter development. Exhibit 3-1 summarizes the previous research material relevant to each chapter of the current report.

Exhibit 3-1
Relevant NCHRP 15-34 Material by Report Chapter

NCHRP Report 785	Relevant Material From NCHRP 15-34
Chapter 1 Introduction	Introduction in the Amplified Work Plan and Chapter 1 of the First Interim Report.
Chapter 2 Overview	Chapter 2 of the First Interim Report : • 2.1.2 Decisions and information used to estimate performance • 2.2 Decisions related to geometric design and approximate timing
Chapter 3 Identify Project Outcomes	Chapter 3 of the First Interim Report: • 3.2 Performance measure categories and measures • 3.3 Phase I Evaluation and Recommendation of Performance Measures
Chapter 4 Geometric Design Elements	Chapter 2 of the First Interim Report : • 2.1.3 Defining specific, discrete geometric design decisions • 2.2 Decisions related to geometric design and approximate timing • 2.3 Summary of Information Pertinent to Design-Related Decisions 2.4 Information related to performance estimation
Chapter 5 Process Framework	Chapter 4 of the First Interim Report: • 4.2 Identify performance analysis procedures that account for geometric features and summarize predictive capabilities • 4.3 capabilities of tools to predict task 2 recommended performance measures.
Chapter 6 Case Studies	Case studies will reference guidance document chapters and appendices

3.1 SUMMARY:

The NCHRP 15-34 work served as a solid foundation for the information presented in NCHRP 15-34A project report. The research team archived materials from NCHRP 15-34. The NCHRP 15-34A team conducted a thorough review and was able to incorporate general ideas and principles from various elements of the past work into the current documents.

SECTION 4
UPDATES ON PERFORMANCE-BASED ANALYSIS

A key activity within the project approach was to update the information from prior NCHRP 15-34 efforts to include current performance-based analysis resources. There have been significant advancements in performance prediction tools and design guidelines since the project first began, including:

- Publication of the *Highway Safety Manual: First Edition* (2),
- Updates to the *Interactive Highway Safety Design Model* (3),
- Publication of the *2010 Highway Capacity Manual* (4),
- Release of SafetyAnalyst,
- Research on capacity, reliability, and safety under the *Strategic Highway Research Program (5)*, and
- New transportation legislation that transitions the Federal Aid program to a performance-based and outcome-based program

The 15-34A research team also had access to panel comments related to the First Interim Report identifying possible improvements to the performance measures proposed by the 15-34 research team. By pulling together these significant advancements with previous panel comments, the 15-34A team created an updated the framework for quantifying geometric design performance, defined as those aspects of performance influenced by the roadway and roadside geometrics. This updated framework proposes a set of performance measure categories and performance measures for quantifying the expected transportation outcomes of geometric design decisions (i.e., geometric design performance).

To explicitly link the new efforts to previous 15-34 results that were well received by the panel, each of the discussions in this section begins with the NCHRP 15-34 First Interim Report (cited as Mahoney et al., 2007) (6) as a starting point. Updates in performance-based analysis related to the topic of interest are then identified, along with panel comments on the respective 15-34 content. Recommendations for the direction of NCHRP 15-34A serve as a basis for the content in the stand-alone process document.

4.1 PERFORMANCE MEASURE CATEGORIES

Mahoney et al. (6) proposed the performance measure categories defined in Exhibit 4-1. The NCHRP 15-34 archived materials are located at the following website link: **https://sites.google.com/site/nchrp1534archive/**.

Exhibit 4-1
Performance Measure Categories for NCHRP 15-34

Performance Category	Definition
Accessibility	The ability to approach a desired destination or potential opportunity for activity using highways, streets or sidewalks as the primary modes of travel.
Mobility	The ability to move from one place to another using highway, street or sidewalk facilities.
Safety	The frequency and severity of highway and street related crashes, including those resulting in deaths, injuries and property damage.

The performance measure categories offered in their report were generally accepted by the project panel, with suggestions related to increasing the ability to capture multimodal performance outcomes. Since that time, several national initiatives related to performance-based decision-making have advanced. The categories offered by Mahoney et al. (6) were therefore revisited with these initiatives in mind. Consistency between 15-34A performance categories and these longer-term, national initiatives could result in products with longer lasting value.

The second Strategic Highway Research Program (SHRP 2) was authorized by Congress to addressing pressing needs in the areas of Capacity, Reliability, Renewal, and Safety. The focuses of these areas are summarized in Exhibit 4-2.

Exhibit 4-2
SHRP 2 Research Focus Areas

Area	Focus
Capacity	Integrate mobility, economic, environmental, and community needs in the planning and designing of transportation capacity
Reliability	Reduce congestion through incident reduction, management, response, and mitigation
Renewal	Address the aging infrastructure through rapid design and construction methods that cause minimal disruption and produce long-lived facilities
Safety	Prevent or reduce the severity of highway crashes by understanding driver behavior

The US DOT's Strategic Plan for 2012-2016 (7) includes six strategic goals: 1) Economic Competitiveness, 2) Environmental Sustainability, 3) Livable Communities, 4) Organizational Excellence, 5) Safety, and 6) State of Good Repair. These goals are briefly described in Exhibit 4-3.

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) (8). MAP-21 funds surface transportation programs at over $105 billion for fiscal years (FY) 2013 and 2014. Of significance to NCHRP 15-34A, MAP-21 transitions the Federal Aid program to a performance-based and outcome-based program. States and metropolitan areas will explicitly show how program and project selection will help achieve a set performance targets related to the following categories:

- Congestion Reduction;
- Infrastructure Condition;
- Environmental Sustainability;
- Freight Movement and Economic Vitality;
- Reduced Project Delivery Delays;
- Safety; and
- System Reliability.

Agencies have until March 2014 to formally establish performance measures in response to this requirement, but many agencies have incorporated performance outcomes and goals into their strategic planning for some time.

Exhibit 4-3
US DOT's Strategic Goals

Area	Focus
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.
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 by expanding opportunities for shifting freight from less fuel-efficient modes to more fuel-efficient modes
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.
Organizational Excellence	Make the US DOT a high-performance, outcome-driven agency.
Safety	Reduce transportation-related fatalities and injuries.
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.

4.2 ASSESSMENT OF PERFORMANCE MEASURE CATEGORIES

The categories proposed by Mahoney et al. (6) capture transportation functions at their core (i.e., access and mobility) as well as an important societal goal for transportation systems (i.e., safety). However, these categories by themselves may not be able to fully capture important aspects of user quality of service and the expected variation in performance over time (e.g., day-to-day, year-to-year). The SHRP 2 research focus areas of reliability and safety include research projects relating road geometrics to reliability- and safety-based performance measures (e.g., SHRP 2 S01 and S08 series, as well as SHRP 2 L07) (5). Capacity is impacted by various 'known' and 'unknown' characteristics of the road and surrounding environment. By itself, it does not necessarily quantify performance until it is combined with a measure of transportation demand (e.g., demand-to-capacity ratio). Renewal addresses the structural and materials-related longevity of the infrastructure as well as techniques to minimize traffic disruption during construction activities, both aspects of performance that are outside the scope of NCHRP project 15-34A.

The MAP-21 transportation categories of Congestion Reduction, Safety, and System Reliability are directly related to geometric design decisions. Freight Movement and Economic Vitality can be indirectly related to geometric design decisions through Congestion Reduction, Safety, and System Reliability, as well as through measures of accessibility. Policies and regulations related to environmental reviews, documentation, and clearance are in place as a result of societal goals related to environmental sustainability, a performance category explicitly identified in MAP-21 (8). The interaction between performance-based analysis and environmental evaluations is described in Chapter 2, Section 2. titled *Geometric Design and Environmental Evaluations and Clearance* of *NCHRP Report 785, Performance-Based Analysis of Geometric Design of Highways and Streets*. The procedures and challenges associated with estimating direct and indirect environmental effects as a result of geometric design decisions is outside of this project's scope. Infrastructure Condition is similar to the SHRP 2 renewal area, addressing structural and materials-related performance and longevity. Performance targets related to project delivery delays are intended to quantify the efficiency of the project development process. The link between performance-based analysis and project development is discussed in Chapter 2, Section 2.3 titled *Geometric Design Activities within the Project Development Process* of *NCHRP*

Report 785, Performance-Based Analysis of Geometric Design of Highways and Streets. But project delivery delays are not a direct measure of transportation performance and will not be covered by this effort.

An assessment of the USDOT's strategic goal categories results in similar findings to the MAP-21 transportation categories, with Safety the most directly related to geometric design decisions; Economic Competiveness and Livable Communities indirectly related to geometrics; Environmental Sustainability covering fuel economy standards, construction practices, and alternative energy sources outside of this project's scope; State of Good Repair quantifying infrastructure condition and maintenance; and Organizational Excellence more of an agency-specific goal.

4.2.1 Recommended Performance Measure Categories

Based on the assessment in the previous section, the following geometric design performance categories will be used throughout the NCHRP 15-34A project to discuss geometric design performance:

Exhibit 4-4
Performance Measure Categories for NCHRP 15-34A

Performance Category	Definition
Accessibility	The ability to approach a desired destination or potential opportunity for activity.
Mobility	The ability to move from one place to another and the efficiency of that movement.
Reliability	Consistency of performance over a series of time periods (e.g., hour-to-hour, day-to-day, year-to-year).
Safety	The frequency and severity of highway and street related crashes, including those resulting in deaths, injuries and property damage.
Quality of Service	Users' perceptions of transportation performance.

The categories in Exhibit 4-4 are an update to what was proposed by Mahoney et al. (6). Accessibility, mobility, and safety remain to capture fundamental transportation functions as well as important societal goals related to safety. The definition for mobility was expanded based on published research recommending operations performance monitoring capture the efficiency of movement in addition to the amount of movement (Margiotta et al., 9). For the purposes of this report, "mobility" is meant to be independent of any particular travel mode and could be interchanged with "mobility function." Reliability was added to address variation in performance as a result of known and unknown factors. Some have noted differences between the 'reliability' of transportation service and the 'variability' in operating conditions but have concluded, from a practical standpoint, that these terms can be used interchangeably (Cambridge & TTI, 10). Reliability measures may be impacted by events falling under the other performance categories (e.g., travel time reliability may be impacted by the expected frequency and severity of crashes).

Quality of service is added to capture users' perceptions of performance, often very important to government agencies. The most common measures include levels of service for motor vehicles, bicycles, and other modes as well as more quantitative measures that determine level of service (e.g., density, percent-time-spent-following). Quality of service may be affected by user perceptions of performance related to one or more other categories. For example, bicycle quality of service is likely to be influenced by bicyclists' perceptions of their safety. Quality of service may also vary independently of performance in other categories. For example, freeway density and level of service on freeways may change without any noticeable change in mobility. Quality of service may also include the perceived quality of travel by design vehicle users such as truck or bus drivers.

Considering measures of mobility, safety, and quality of service during geometric design activities is increasingly common. Broader measures of accessibility and their sensitivity to geometric design are emerging areas of research. To provide additional background, more detailed explanations of accessibility and reliability are provided in the following sections with references to selected literature.

4.2.2 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. Measures and impacts on the broader concept of accessibility 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. For example, cumulative or opportunity measures evaluate accessibility in terms of the number or proportion of opportunities that can be reached within specified travel distances or times from a reference location (*11-14*) As a function of both proximity and connectivity, accessibility can also be measured in terms of the number of destinations reachable within a specific travel time. These practical, choice-oriented cumulative accessibility measures are coming into greater use in transportation planning (*15*).

Gravity-based measures weight the activity locations by time, cost or distance needed to reach them. The accessibility measures are expected to increase with the increases in the opportunity measures. Accessibility is expected to decline the farther the opportunities are from the origin. These gravity-based measures require an impedance factor, and the appropriate weights for the destination (*16*). Utility-based measures reflect the utility of all choices and calculate final choice utility relative to the utility of all other choices. These measures incorporate individual traveler preferences as part of the accessibility measure (*17*).

In this research, we capture accessibility 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. However, we do provide a review of selected relevant research in the accessibility area to set the stage for future work and to provide additional resources for interested readers. No one best approach to measuring accessibility exists, and different situations and purposes demand different approaches. (*14*)

Additional research on the relationship between project-level design decisions and accessibility is needed. As the role of accessibility considerations in making geometric design decisions continues to be explored, some preliminary performance measures to assess includes:

- **Access to a facility by highway user type:** The ability to use a facility (e.g. access to state highway by bicyclists). The performance measure uses a yes/no determination and does not indicate a level of accessibility. Examples include facility access by:
    - Passenger car;
    - Truck;
    - Pedestrian;
    - Bicycle;
    - Transit.

- **Cumulative opportunity:** The number of destinations within a specified travel time or distance of a trip origin, population, facility, or design element or the percentage of population within a specific travel time or distance from a trip destination, population, facility, or design element. A very large number of cumulative opportunity variations is possible and dependent on the project setting. Examples include:
    - Number of intermodal connections within 5 miles of a state highway,
    - Percent of the population living within 1 mile of a bicycle facility,
    - Percent of the population living within 10 miles of an interchange, and
    - Employment within 15 miles of state highway.
- **Travel impedance:** A measure of user cost of making a trip to an opportunity or destination. Common measures include travel time and distance. Other related mobility measures may also be used including delay and travel cost.

4.2.3 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 evident by its role as a theme in the second Strategic Highway Research Program (SHRP 2) and in performance-based decision-making aspects of Moving Ahead for Progress in the 21st Century Act (MAP-21). 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 analysis also applies to safety-related topics, such as available versus required sight distance, probability of vehicle skidding, and rollover for the range of driver, vehicle, roadway, and environmental conditions experienced over a series of time periods at a road location (*18-33*). Reliability is sensitive to geometric design, because the geometric design may impact 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. As an example, Musunuru and Porter (2014) demonstrated a reliability-based geometric design approach to making decisions regarding the basic number of lanes on freeways. The uncertainty involved in design year projections of traffic-related characteristics that influence number of lanes decisions provides a logical application of a probabilistic framework (*34*). Reliability will also be indirectly related to geometry inasmuch as the geometry impacts the frequency of severity of random events that impact travel time (e.g., crashes).

4.3 PERFORMANCE MEASURES

Mahoney et al. (6) proposed the performance measures identified in Exhibit 4-5. Their recommendations were a result of a detailed review of research literature, state transportation agency documents, project documents, and performance estimating tools followed by multiple levels of screening and evaluation. These activities took place in the later part of 2006. The NCHRP 15-34 archived materials are located at the following website link: **https://sites.google.com/site/nchrp1534archive/**.

Exhibit 4-5
Performance Measures Proposed During NCHRP 15-34

Performance Category	Definition
Accessibility	Access to a facility by a highway user type; cumulative opportunity; structural and dimensional accessibility to trucks; travel impedance
Mobility	Capacity; congestion; user cost of travel; delay; density; level of service; percent-time spent following; queue characteristics; reliability; speed; stops; travel rate; travel time; volume-to-capacity ratio
Safety	Crash cost; crash frequency; crash rate; crash severity; safety index

The panel provided several comments related to these proposed measures during a meeting held February 5, 2007:

- Rank the importance of some performance measures over others, because data collection for all these measures may not be practical;
- Many of the performance measures are related or are the same;
- Discuss and illustrate the inter-relationships between performance measures;
- Include a measure of ease of modal transfer under accessibility;
- Do not include structural and dimensional accessibility to trucks;
- The performance measures should be selected, then near-term and future capabilities discussed (i.e., do not limit performance measures to those that can be estimated); and
- Subjective safety measures should be included for pedestrians and bicyclists until crash models are available.

In addition to these panel comments, the first edition of several performance prediction tools were only in development at the time of the 15-34 recommendations (e.g., *Highway Safety Manual, SafetyAnalyst*). Other tools have evolved significantly (e.g., Interactive Highway Safety Design Model (IHSDM) (3), 2010 Highway Capacity Manual (4)). The body of published literature on the operational and safety effects of geometric design has continued to grow (see, for example, Brewer 2012). Finally, new performance measure categories have been proposed for 15-34A to accommodate several national initiatives that have advanced related to performance-based decision-making. Therefore, the performance measures proposed by Mahoney et al. (6) were revisited and built upon with these points in mind.

Primary measures of geometric design performance for each performance measure category are identified in Exhibit 4-6. This table is not intended to convey a set of 'recommended' performance measures, or exclude other measures (discussed more below). These measures are instead considered to be fundamental representations of their respective categories, while at the same time are sensitive to geometric design. For example, average travel speed is provided as the primary measure of mobility. Average travel speed is sensitive to geometric design through the influence of geometric design on free-flow speed and on the shape of speed-flow curves. Other measures of mobility include delay and travel time, but these performance measures are indirectly related to geometric design through average travel speed. In other words, design decisions will impact delay and travel time by increasing or decreasing average travel speed, assuming the locations of the trip beginning and end point do not change. Therefore, mobility in this framework captures the rate of motion, irrespective of the trip length. Delay and travel time depend on the spatial distribution of origins and destinations, but these spatial characteristics are addressed by measures of accessibility.

Exhibit 4-6
Primary Measures of Geometric Design Performance by Category

Performance Category	Primary Measures of Geometric Design Performance[1]
Accessibility	Measures[1] that integrate travel distances and/or travel times between selected origins[2] and destinations[2] for different modes
Mobility[3]	Average travel speed
Reliability	Travel time variability (e.g., from hour-to-hour, day-to-day, week-to-week)
Safety	Expected crash frequency, by crash severity and crash type
Quality of Service	Levels of service

1 Unless specifically noted, the measures of geometric design performance are applicable to all travel modes (e.g., automobile, bicycle, pedestrian, transit).

2 Accessibility is an emerging concept recognizing that travel time is made up of both distance and speed. Its application is relatively limited in geometric design contexts.

3 Origins and destinations, as referred to here, are not necessarily trip ends (e.g., number of businesses within two miles of freeway access)

4 Measures of travel quantity (e.g., person throughput, vehicle throughput) are frequently used with measures of travel efficiency to fully quantify mobility. Measures of efficiency tend to be more relevant to geometric design performance. Measures of quantity are therefore excluded from this project. This same decision was made in the original 15-34 work (Mahoney et al., 2007) and was reassessed and confirmed as part of this effort.

As noted by Mahoney et al. (6), the list of performance measures used in practice and recommended in published literature is extensive. Performance measures selected on any given project will depend on context-specific project objectives and intended outcomes, community visions and plans, and on strategic performance targets of local and state agencies. Chapter 6 of the *NCHRP Report 785, Performance-Based Analysis of Geometric Design of Highways and Streets* provides several case studies that illustrate a process for conducting performance-based analysis to inform geometric design decisions. Additional performance measures, by category, are provided in Exhibit 4-7. Those proposed by Mahoney et al. (6) were used as a starting point. Redundant measures were removed and new measures added as a result of the updated framework and new performance prediction tools. The performance measures in Exhibit 4-6 and 4-7 are interrelated. Most measures in Exhibit 4-7 can be estimated by knowing one or more of the primary performance measures or other additional performance measures.

Exhibit 4-7
Additional Measures of Geometric Design

Performance Category	Additional Measures of Geometric Design Performance[1]
Accessibility	n/a
Mobility	Delay, queue characteristics (e.g., queue length, queue storage ratio), travel time, volume-to-capacity ratio
Reliability	Variability (e.g., standard deviation, variance) in average travel speed2, variability in delay[2]
Safety	Crash rate, Measures that combine crash frequencies and severities to a common unit (e.g., Crash Cost, Equivalent Property Damage Only, Relative Severity Index)
Quality of Service[3]	Average travel speed, Control delay, Density, Level of service score, Pedestrian space, Percent-time-spent-following, quality of travel by design vehicle

[1] Unless specifically noted, the measures of geometric design performance are applicable to all travel modes (e.g., automobile, bicycle, pedestrian, transit).

[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)

[3] These secondary measures of quality of service are those that are believed to influence users' perceptions of quality of service and therefore influence level of service based on Highway Capacity Manual methodologies.

The distinction between mobility and quality of service requires additional discussion. Margiotta et al. (9) recommended that mobility measures be based on measurements of travel time. Mobility measures in Exhibit 4-6 and 4-7 are therefore linked to travel time in some way. Qualities of service measures are intended to classify and/or quantify users' perceptions of performance. In some cases, quality of service may be sensitive to mobility measures on a one-to-one basis (e.g., control delay); in other cases, they may not. For example, users' perceptions of freeway performance are expected to change as density changes, as density has been found to represents users' perceptions of their freedom to maneuver. However, density values may change significantly without any change (or very little change) in average travel speed or travel time. 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. The Highway Capacity Manual (2010) served as the primary reference for both the primary and additional quality of service measures.

4.4 PERFORMANCE MEASURES AND PERFORMANCE PREDICTION TOOLS

Exhibit 4-8 links performance analysis procedures and tools to performance measures from Exhibit 4-6 and Exhibit 4-7. Three levels of prediction capabilities are noted:

- Performance measure is directly reported by prediction tool – the performance measure of interest is a direct output of the prediction tool; no further computational steps are needed.
- Output from prediction tool can be used to calculate performance measure – the performance measure of interest is not a direct output of the prediction tool; however, model output can be used to estimate the performance measure with additional computational steps by the analyst.
- The performance measure cannot be estimated with the prediction tool.

Summaries such as Exhibit 4-8 served as a starting point for the more detailed performance measure, geometric design links provided in Chapter 4 of the process framework.

Exhibit 4-8
Prediction Capabilities of Identified Tools and Knowledge

	Spatial Transportation Analysis Tools	Highway Capacity Manual	Microscopic Simulation	Highway Safety Manual	Crash Prediction Model of IHSDM	NCHRP 17-45/ISATe	L07, L08, L09 Products and Tools
Accessibility							
Measures that integrate travel distances and/or travel times between selected origins and destinations for different modes	●						
Mobility							
Average travel speed	●	●	●				
Delay	□	●	●				
Queue characteristics		●	●				
Travel time	●	●	●				
Volume to capacity ratio	●	●	●				
Quality of Service							
Level of Service		●	□				
Control delay		●	●				
Density		●	□				
Level of Service Score		●					
Pedestrian Space		●					
Percent-time-spent-following		●					
Reliability							
Travel time variability							●
Variability in other travel time-based metrics							□
Safety							
Crash frequency, by crash severity and type				●	●	●	
Crash rate				□	●	□	
Measures that combine crash frequencies and severities to a common unit				□	□	□	

● Performance measure is directly reported by prediction tool
□ Output from prediction tool can be used to calculate performance measure

Chapter 4 of the process framework mainly focuses on presenting high priority, well-established, and direct relationships between geometric design decisions and performance. An example summary that a user will find in Chapter 4 is shown in Exhibit 4-9 for mobility-related performance measures.

Exhibit 4-9
Example summary of direct relationships between geometric design decisions and mobility performance from process framework

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 roader 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. Degrade mobility for pedestrians and bicyclists. Higher vehicle speeds are associated with higher severity crashes.	HCM 2010
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
Two-Lane Segment	Average percent time spent following	The average percent 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.	Increase vehicle speeds, increase potential for higher severity crashes.	HSM, HCM 2010
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
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 between delay experienced by different modes depending on the type of traffic control present.	HCM 2010, NCHRP Report 672 *Roundabouts: An Informational Guide*
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. Degrade mobility for pedestrians and bicyclists.	HCM 2010

Chapter 4 also includes a higher level summary of "expected" or "likely" relationships between performance categories and geometric elements, even if they have not been uncovered by research or published findings. In other words, some of the expected relationships may not have been quantified yet by research on the operational and safety effects of geometric design. There is a probability that the relationship may not ultimately exist (i.e. that the performance measure category ultimately is not sensitive to geometric design decisions). An example of a higher level summary of "expected" or "likely" relationships between performance categories and geometric elements for intersections is shown in Exhibit 4-10. In these summaries, each characteristic/decision – performance measure category combination is classified as either 'expected direct effect,' 'expected indirect effect,' or 'no expected effect.' Expected direct effects are transportation performance effects caused by the geometric design decisions that occur at the same time and place (e.g., a given horizontal curve radii affects expected crash frequency at that location immediately).

Expected indirect effects are transportation performance effects caused by the geometric design decision, but later in time 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 impact quality of service for pedestrians and bicyclists. It may also influence businesses along the street that now have access to and increased exposure to potential patrons. There would obviously also be direct safety and operational effects due to the presence of the 'new' ramps terminals immediately at the terminal locations.

No expected effect expresses that the characteristic/decision is not intended to impact the respective aspect of performance, either directly or indirectly.

A second set of notations then indicates whether or not 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; or
- Not applicable (i.e., the relationship does not exist).

Both sets of notations were determined using information that was readily available to the research team, or using the research team's best judgment. Future evolutions of these tables would ideally include specific research or performance prediction tool citations for each noted characteristic/decision – performance measure relationship, along with the following characteristics of the prediction technique:

- Scope of prediction technique (e.g. facility type, environmental and traffic conditions),
- Characteristics of data used to build model,
- Model fit,
- Validation, accuracy, and reliability of predictions,
- Sensitivity to geometric design decisions,
- Elasticity of geometric design decisions, and
- Data requirements.

Exhibit 4-10
Example summary of expected relationships between intersection elements and performance from process framework

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

● = direct effect
□ = indirect effect
-- = no 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

SECTION 5
NCHRP REPORT 785 DOCUMENT SUMMARY

NCHRP Report 785, Performance-Based Analysis of Geometric Design of Highways and Streets presents a performance based approach of meeting broader project outcomes based on a process for understanding intended project outcomes and then considering and selecting geometric design elements or features to best meet a project's unique context. The approach accounts for the respective stage of the project development process, and focuses on the performance effects of geometric design decisions. The report summarizes the performance factors for various geometric design elements and presents examples of how, depending intended outcomes of a project, the geometric designer has choices on design elements and consider design values or features based on their impact and the role and relationship resultant geometric design performance has on intended outcomes. Such documentation can support aid in risk management efforts and design variance reviews.

Within *Report 785*, the following principles will guide users in creating usable, practical, and long-lasting products:

- **Intended Outcomes:** Fundamentally, the intent is to document the importance and need of establishing each project's "intended outcomes" and then focusing on performance-based analysis of geometric design to assess if intended outcomes had been achieved.
- **Connect to Project Development Process: Users** benefit from considering the project development process and of the discrete activities (such as environmental evaluation and documentation).
- **Performance Measures of Design Decisions:** The primary focus is the performance effects of geometric design decisions.

The following provides an overview of each chapter within *Report 785*:

Chapter 1: Introduction - The first chapter of The Report provides and introduction to the role of performance-based analysis within transportation activities and value within geometric design of highways and streets. The guiding principles are discussed and an overall framework of the approach is provided.

Chapter 2: Overview – This chapter provides an overview of geometric design decisions within the project development process and the relationship between project-level and design performance measures. In addition, the geometric design activities within each project stage, environmental evaluations and context sensitive design approaches are discussed.

Chapter 3: Identify Project Outcomes - This chapter provides an overview of the project outcomes and defines the project performance and geometric design performance.

Chapter 4: Geometric Design Elements – This chapter presents information regarding the relationships between geometric design elements and performance measures related to the performance categories, design controls and influences, and geometric design elements for segments and nodes discussed in Chapter 3. The information in Chapter 4 focuses on presenting the established and known relationships between geometric design elements and performance.

Chapter 5: Process Framework - The process framework for conducting performance-based analysis informs geometric design decisions. When considering how performance outcomes relate to the investment needed to achieve various outcomes, one can consider the potential benefits compared to the associated investment. The performance-based approach can support project documentation needs and can, overall, inform and guide project decision making while supporting risk management objectives.

Chapter 6: Case Studies/Project Examples – The case studies within this chapter provide real project examples applying the performance-based analysis principles described in the previous chapters. The case studies cover multiple facility types within various stages of the project development process.

SECTION 6
NOTES FROM 2013 TRB MID-YEAR MEETING DISCUSSION

On July 30, 2013, Brian L. Ray and R.J. Porter presented information on NCHRP 15-34A at the 2013 TRB Mid-Year Meeting for the following TRB standing committees:

- Highway Safety Performance;
- Geometric Design;
- Safety Data, Analysis and Evaluation;
- Access Management; and
- Operational Effects of Geometric Design.

The AASHTO Technical Committee on Geometric Design was also present at the mid-year meeting. The following section summarizes the discussion that took place following the NCHRP 15-34A presentation.

6.1 SUMMARY OF DISCUSSION

At the close of the presentation, the presenters asked the audience for input regarding two specific questions, which led to additional discussion. The notes below are organized first as responses to the initial questions followed by notes from the general discussion.

6.1.1 What do you think will be the most applicable project types for performance-based analysis?

- 3R Projects
- Reconstruction in a constrained urban environment
- Traffic control during construction
- Interim improvements leading to an ultimate configuration
- Improvements to state highways through small towns (i.e., when the main street is the state highway)
- Design exceptions

6.1.2 What do you think are key performance measurements to include?

- Reduction or impact on crash frequency and severity
- Design choices and the associated tradeoffs
- Challenge of who gets to select the performance measures and targets
- Should consider the potential for negative impacts or tradeoffs of design choices even if the design choices are making positive progress toward the desired performance outcome
- How will users know what performance measure and what performance target to select?
- The key value of analysis seems to come from the comparison of multiple alternatives, solution options, or design decisions
- Consider including life cycle costs and financial sustainability or feasibility of decisions
- Request that accessibility be defined and applied to non-motorized modes as well as motorized modes
- Request that mobility clearly include consideration of non-motorized modes as well as motorized

6.1.3 General Comments

- Process seen as beneficial for risk management because it will provide a process or framework for evaluating, documenting and making decisions
- Ideal is to have a process that leads to the best answer and then as a profession, in theory it would not be necessary to have design exceptions
- Hope to see process help users understand if the decisions they are making are good or not – rather than if the decisions they are making align with a specific criteria

SECTION 7
SUGGESTED FUTURE RESEARCH

Throughout the course of this research effort, the research team identified areas of further research that would provide additional benefit to this topic area, but could not be included within the scope of the NCHRP 15-34A research project.

Therefore, the following list provides a summary of suggested future research related to performance-based analysis of geometric design of highways and streets:

- A set of performance measures was provided in chapter 4 of the process framework document. These measures are based on the current state of practice as well as the capabilities of existing performance-prediction tools. Future research should identify and recommend the most effective performance measures for performance-based geometric design analysis. Possible evaluation criteria include:
    - Useful for a range of applications (project scope, project development phase, facility type),
    - Meaningful to a variety of stakeholders,
    - Simple, understandable, logical, and repeatable,
    - Unambiguously defined,
    - Sensitive to geometric design decisions,
    - Availability of analytic-based estimation technique at various project development phases currently and in the future,
    - Feasibility of conducting performance estimation in project development context (e.g., data requirements, data availability and accuracy, required level of human expertise and effort), and
    - Accuracy and reliability of the prediction technique(s).
- Chapter 4 summarized current prediction capabilities of various performance estimating tools. There is a need to bring additional information about the reliability of available

performance prediction algorithms to the fingertips of designers so they might better assess the level of confidence in the performance estimates. Such information would include:

  - Scope of prediction technique (e.g. facility type, environmental and traffic conditions),
  - Characteristics of data used to build model,
  - Model fit,
  - Validation, accuracy, and reliability of predictions,
  - Sensitivity to geometric design decisions,
  - Elasticity of geometric design decisions, and
  - Data requirements.

- Assess the availability and accuracy of the required data to conduct performance-based analysis of geometric design decisions at different project development stages. Where required data are not available or accurate, the impact of incomplete or missing data and the use of default values for different elements will be addressed.

- Examine the use of historical data and performance analysis into reconstruction project decisions on National Highway System (NHS) and non-NHS facilities. This would include possible procedures for implementing quantitative operational and safety analysis using historical data along the corridor to prioritize design deficiencies and needs for a reconstruction project with limited budget and right of way.

- Develop a generalized approach to managing the collection, use and presentation of data for performance-based analysis of geometric design throughout project development.

- Further assess the potential role of measures of accessibility in performance based geometric design analysis. Accessibility measures are powerful in that they incorporate both the required trip distance and mobility components of transportation into a single set of measures. However, their use by designers is relatively limited. Tools that are not traditional used for project-level analysis, including spatial modeling tools (e.g., GIS) with transportation analysis capabilities will be needed for fully analyzing the accessibility effects of geometric design decisions.

- Further assess the potential role of measures of reliability in performance based geometric design analysis. Work in this area is ongoing as part of SHRP 2 research efforts, but significant gaps in the relationship between geometric design decisions and travel time reliability remain.
- Develop tools that quantify the maintenance performance effects of geometric design decisions. Important considerations include the frequency and intensity of routine maintenance activities associated with highway and street features as well as the selection of physical highway and street dimensions to support future maintenance activities and associated temporary traffic control (e.g., allocation of lane and shoulder widths to support use of shoulder during future maintenance work). Maintenance costs and considerations may be particularly relevant to innovative physical operational and safety improvements including roundabouts, curbing, indirect left-turn treatments and a number of traffic calming measures.
- Explore incorporating the uncertainty (e.g., the standard error) of performance measure estimates into geometric design decisions in addition to the magnitude of performance measures. This could allow design decision makers to better understand the relative likelihoods (or probabilities) that design alternatives will meet transportation performance goals throughout their life cycles.

SECTION 8
DRAFT AASHTO GREEN BOOKTEXT

As part of this research effort, the research team has reviewed the 6th edition (2011) of the American Association of State Highway and Transportation Officials' (AASHTO's) *A Policy on Geometric Design of Highways and Streets* (the Green Book) to consider potential ways that future editions of the Green Book might incorporate material related to performance-based analysis of geometric design. This section includes notations on where the AASHTO Technical Committee on Geometric Design may consider possible revisions to future Green Book updates.

8.1.1 Overview

Integrating performance-based analysis of geometric design of highways and streets has the potential to make profound changes in our profession. In theory, if all design decisions were established based on the results of performance-based approaches, there could be fundamental changes in how design criteria are developed and applied. If design decisions are based on whether a geometric design meeting a project's performance objectives, established from the overall intended project outcomes, design information might be presented in completely new ways. Our current AASHTO policies stem from aggregating a series of individual policies to help address the emerging needs of roadway providers and roadway builders. Over time, the compilation of various policies in the "Red", "Blue", and "Green" Books has become viewed as an emulsified product encompassing geometric design practice needs. Clearly no single resource document can be deemed the singular resource for such a complex activity as geometric design. The AASTHO Technical Committee on Design is responsible for maintaining and advancing the Green Book and continues to consider ways to best meet the needs of state highway agencies in designing, operating, and managing roadway facilities. In doing so, Green Book updates often incorporate the findings of applied research or other changes in the evolution and practice of geometric design.

A purely performance-based design approach has the potential to support whole sale changes and revisions to future editions of the Green Book. This would likely arise with fundamental ideas of how to adapt a geometric design process to the changing needs of transportation and roadway facilities. For the purposes of NCHRP Project 15-34A, the research team recognizes the opportunities and likely evolution of future issues of the Green Book. For maximum value in what may be an incremental approach to eventual changes, we have identified the specific areas of the 6th edition that could potentially accommodate new discussion based on the findings and organization of the 15-34A research and process framework.

8.1.2 Potential changes to the 6th edition (2011)

Location: Foreword, Page xli, following paragraph 5

Action: Add paragraph (4 to 5 sentences) to summarize the value and ability to use performance-based analysis of geometric designs. Use material from the following two paragraphs.

Example: "Design involves weighing and balancing a variety of considerations in the pursuit of a choice. In highway design, construction cost, durability, esthetics, maintenance, operations, negative impacts, non-motorized user impacts, traffic flow, and safety are principal considerations. Performance-based analysis of geometric design of highways and streets is a method by which various tradeoffs can be quantified and conveyed to a broad audience in meaningful terms and ultimately considered by decision makers. Performance-based analysis of geometric design will allow agencies to make informed judgments on the probable (rather than assumed) tradeoffs that are likely to result for specific circumstances. The body of knowledge related to impacts of geometric design decisions on user accessibility, mobility, quality of service, reliability, and safety continues to evolve to support performance-based analysis of geometric design decisions."

Location: Chapter 1, Section 1.2.3, Page 1-7

Action: Add paragraph (4 to 5 sentences) to provide performance-based analysis considerations to the Access Needs and Control sections. Text additions are likely to come from information presented in NCHRP 15-34A, Chapters 3 and 4.

Example: "Direct land access impacts a broader measure of 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. Designer decisions have the potential to directly and indirectly impact these broader measures of accessibility."

Location: Chapter 2, Section 2.8.4, Page 2-86

Action: Add 1 to 2 paragraphs that provide geometric design performance considerations for safety for segments and nodes. Text additions are likely to come from information presented in NCHRP 15-34A Chapter 4.

Example: "The final report for NCHRP 15-34A, *Performance-Based Analysis of Geometric Design of Highways and Streets* (reference published report) demonstrates how the HSM predictive methods 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 final report also summarizes the existing state of knowledge regarding the relationships between geometric design elements and safety for segments, at-grade intersections, and interchanges on different facility types."

Location: Chapter 2, After Section 2.8, Page 2-86

Action: Add a new section on Performance-Based Analysis of Geometric Design that briefly describes the performance-based analysis concept and refers to the NCHRP 15-34A report.

Example: "2.9 Performance-Based Analysis of Geometric Design of Highways and Streets Performance-based analysis of geometric design of highways and streets is a method by which various tradeoffs can be quantified and conveyed to a broad audience in meaningful terms and ultimately considered by decision makers. By employing techniques that predict the performance effects of geometric design decisions, stronger linkages between design alternatives and their probable outcomes will be established. These linkages will be of benefit to decision makers, stakeholders and the public, by allowing increasingly transparent decisions. A framework for conducting performance-based analysis of geometric design decisions was developed as part of NCHRP 15-34A, *Performance-Based Analysis of Geometric Design of Highways and Streets* (NCHRP Report 785). The framework 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."

SECTION 9
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