FACILITY – LEVEL QUALITY OF SERVICE ANALYSIS
METHODOLOGY FOR RURAL HIGHWAYS

by

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ABSTRACT

Rural highways constitute a significant portion of the national highway system, serving vital mobility and freight movement functions while connecting towns and small cities separated by rural areas. As urban areas expand further from central cities, rural highways are experiencing increased traffic demand, posing challenges to maintaining an acceptable level of operational performance and quality of service. To evaluate the operational performance and quality of service of highways, the Highway Capacity Manual (HCM) offers a comprehensive set of tools and methodologies. It incorporates analytical methodologies to perform operational analyses for individual highway components (segments and intersections). It also offers facility-level analysis methodologies for freeways and urban streets only. In this context, a facility is defined as a stretch of highway consisting of multiple components. However, the current HCM lacks a facility-level analysis methodology for rural highways which is essential for evaluating extended lengths of rural highways. A rural highway facility consists of any combination of two-lane highway segments, multilane highway segments, and intersections (signal, stop control, or roundabout intersections).

To address this limitation within the HCM framework, this research aims to develop a methodology for facility-level analysis of the quality of service for rural highways, thus adding to the existing tools and capabilities of the HCM. The proposed methodology, intended for inclusion in the next HCM edition, focuses on the interaction between contiguous segments and the operational impact of intersections on connected segments.

In the course of developing the analysis methodology for rural highway facilities, this research needed to develop procedures for facility segmentation, which is a critical step in developing and applying the proposed methodology. To this end, the research used extensive vehicle trajectory data from multiple sites in estimating the upstream and downstream influence areas for three different types of intersections: signalized intersections, stop-controlled intersections, and roundabouts. Specifically, quantile regression models were developed to estimate the influence areas for the three different types of rural intersections.

The proposed analysis methodology significantly enhances the ability of transportation analysts to assess operations along extended lengths of rural routes, allowing more effective planning and management of these important highway facilities.

CHAPTER ONE

INTRODUCTION

Background

Transportation systems, encompassing air, water, rail, highway, and pipeline transportation, constitute a vital component of a nation's economy and play a crucial role in driving economic growth and development. The importance of transportation is highlighted by its significant contribution to a country's gross domestic product (GDP). For instance, in 2021, the transportation sector contributed $1.3 trillion (5.6%) to the United States' GDP of $23.7 trillion (Bureau of Transportation Statistics, 2021).

Among the various forms of transportation systems, highway transportation has historically been considered the critical backbone of land-based transportation network, significantly contributing to the sustainable development of countries. In today’s world, highway transportation dominates the overall transportation system, serving as the primary infrastructure for the mobility of people and goods, as well as providing critical access for the acquisition of natural resources, industrial production, and retail marketing.

According to the Federal Highway Administration (FHWA), the total length of the US roadway network is approximately 4.3 million miles. This includes all public roads, such as rural and urban roads, highways, and interstates (ASCE, 2021; Federal Highway Administration (FHWA), 2021). This extensive network of roadways facilitates the movement of people and goods to their destinations daily. However, these roadways face the challenge of accommodating an ever-increasing volume of traffic each year. For instance, vehicle miles traveled reached over

3.3 trillion in 2019, marking an 18% increase from 2000 (Federal Highway Administration, 2021). This surge in travel demands has significant implications for traffic operations, leading to congestion, delays for drivers, and increased air pollution.

To assess the traffic operations and quality of service of the highway system, the Transportation Research Board (TRB) has developed a main reference and guidebook called the Highway Capacity Manual (HCM) (TRB, 2022). The HCM provides a comprehensive set of analytical tools and techniques that enable transportation professionals to estimate and predict the capacity and quality of service of various components of the highway system, such as highway segments, intersections, and interchanges. The HCM is widely regarded as the most authoritative guide for the operational analysis of highway systems.

The HCM defines six main types of roadway system elements based on spatial coverage, ranging from the smallest to the largest. These elements are points, segments, facilities, corridors, areas, and systems (TRB, 2022). However, the HCM primarily focuses on the first three elements: points, segments, and facilities. **Figure 1** illustrates the spatial relationship of these elements within the roadway system.

A point on a roadway is defined as a location where (a) conflicting traffic streams cross, merge, or diverge; (b) a single traffic stream is regulated by a traffic control device; or (c) there is a significant change in the segment capacity, such as a lane drop, lane addition, or narrow bridge. In contrast, a segment refers to the length of roadway between two points. Traffic volumes and physical characteristics generally remain uniform throughout a segment, although minor variations may occur (e.g., changes in traffic volumes due to a low-volume driveway). Examples of segments include basic freeway segments, multilane highway segments, rural two-lane highway segments, and urban street segments. A highway facility, on the other hand, comprises an extended length of roadway consisting of a connected series of points and segments (referred to as components of a facility in this research). Facilities are defined by two endpoints. Freeway, two-lane highway, and urban street facilities are examples of facilities as defined by the HCM. Among the three aforementioned elements of the highway system, the focus of this research is the facility element of the highway system.

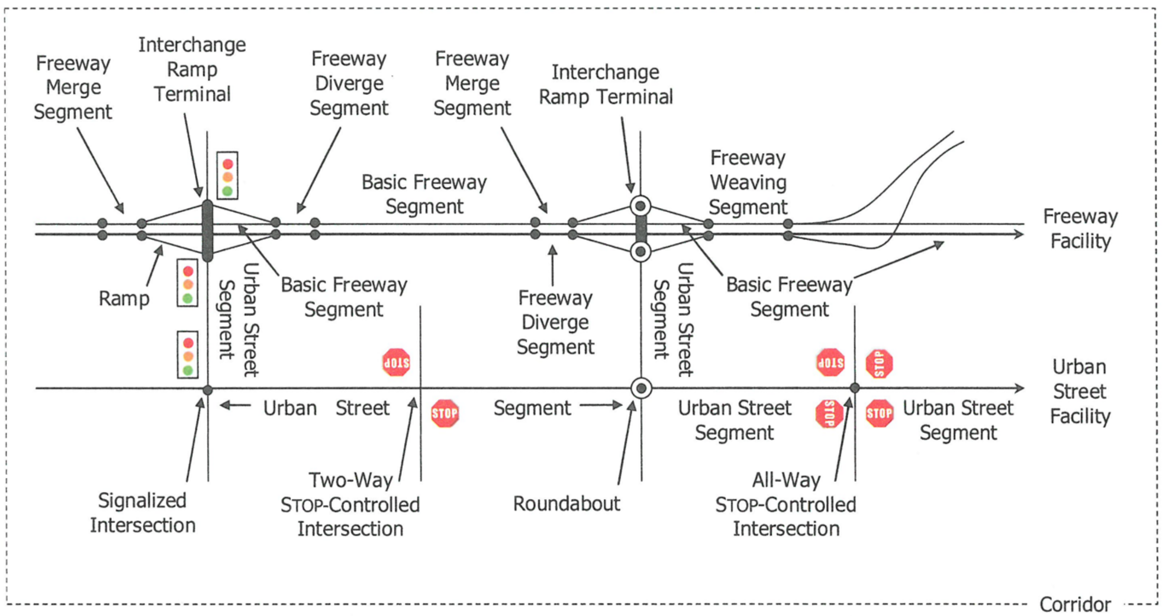


Figure 1. Points, Segments, Facilities, Corridor (HCM, Exhibit 2-1)

The HCM provides methodologies for analyzing the performance of individual components (junctions and segments) of highway systems, enabling transportation professionals and traffic engineers to evaluate the quality of service for specific segments or junctions. Additionally, the HCM incorporates facility-level analysis for freeways and urban streets, allowing transportation agencies, such as state departments of transportation (DOTs), to assess the quality of service for highway facilities on a larger scale. However, the HCM lacks a facility-level analysis methodology for rural highways, which is the focus of the current research. The facility-level analysis is consistent with the notion that drivers typically evaluate the quality of their trip over its entire length, not just on separate segments and junctions.

Apart from freeways and urban streets, rural highways constitute a significant portion of the national highway system, serving vital mobility and freight-movement functions. These highways often connect larger municipalities and may traverse through one or more small towns. They are usually more varied in horizontal and vertical alignment than urban roadways. Rural highways may consist of any combination of two-lane highways, multilane highways, and occasional intersections, such as signalized intersections or roundabouts.

As urban areas continue to expand further away from central cities, rural highways in previously less developed regions are experiencing increased traffic demand, posing challenges to maintaining acceptable levels of operational performance. Given the extended lengths of rural highways and the variation in cross-sectional elements, it is currently impractical to assess the quality of service of these highways across extended lengths (many miles) with the currently available analytical methodologies of the HCM (TRB, 2022).

Currently, HCM offers methodologies to conduct performance analyses of individual components of rural highways, including the analysis of two-lane highways, multilane highways, and analysis of intersections. However, it lacks a methodology for conducting quality of service analysis of rural highways at the facility level – where a facility encompasses any combination of two-lane highways, multilane highways, and/or intersections. The development of such a methodology would significantly enhance the ability of transportation professionals to assess and address the operational challenges faced by rural highways, supporting more effective planning and management of these critical transportation assets.

Research Problem

The procedures and methods detailed in the latest Edition of the HCM estimate capacity and various operational measures, including LOS, for freeway facilities as well as urban street facilities. However, the HCM lacks a methodology for evaluating the operational performance of rural highway facilities. The current HCM methods primarily focus on the operational analysis of individual segments and isolated intersections of a rural highway; these methods do not account for the interaction between contiguous segments or the operational impact of junctions on connected segments, both of which are crucial for an accurate evaluation of operational performance on extended rural facilities.

This research problem highlights the need for a more comprehensive and integrated approach to analyzing rural highway facilities, which would enable transportation professionals to better understand and address the operational challenges associated with these critical infrastructure components. In addition, a facility-level analysis of rural highways accurately reflects the traveler's experience over an entire trip that encompasses traveling through multiple different types of components within the highway system.

Research Objective

It is important to expand the capabilities of the HCM analysis methodologies, particularly at the facility-level, so that traffic engineers and state DOTs have the analysis methods and tools they need for performing an accurate and comprehensive quality of service assessment for rural highway facilities. Consequently, this research aims to develop a predictive methodology for performing quality-of-service analysis of rural highways at the facility-level. The development of this methodology will result in a rural highway facility-level procedure suitable for incorporation into a future edition of the HCM.

Another critical aspect of this research is the investigation of intersection influence areas, as it provides the foundation for the development and application of a quality of service methodology for rural highway facilities. By analyzing the extent to which intersections affect the operational performance of rural highways, researchers can gain insights into the complex interactions between contiguous segments and junctions. This understanding will enable accurate and efficient facility segmentation which is the first step in performing facility-level analysis.

Research Importance, Target Audience(s) and Their Needs

This research is centered on state highways that typically connect multiple municipalities and small towns, serving as crucial mobility corridors. However, funding for infrastructure improvements on rural highways is often limited in comparison to the heavily congested urban roadways. Consequently, it is imperative for agencies to maximize the return on investment for these highways. To achieve this, agencies require analysis methods that enable them to examine short sections of the highway (e.g., passing zones, signalized intersections) not only as individual components, but also within the context of an extended length (spanning many miles) of the highway.

The prospective methodology would accomplish the following objectives: 1) enable operational assessments of rural highways at the facility level, which would be infeasible using component-level methodologies alone; 2) assist highway agencies in determining the need for site-specific improvements by providing insights into the operational performance at the facility-level; and 3) enable transportation professionals to accurately delineate the spatial extent of intersection operational influence on connected approaches.

The anticipated results of this study are tailored to cater to the needs of state transportation agencies and the transportation consulting industry. By offering a more comprehensive and context-sensitive analysis of rural highway facilities, this research stands to significantly enhance the efficiency and effectiveness of highway planning, design, and investment decisions, ultimately contributing to the development of a more sustainable and resilient transportation infrastructure.

Thesis Organization

This thesis is comprised of seven chapters. Following the Introduction chapter, Chapter two provides a thorough literature review on pertinent research regarding performance analysis methodologies of rural highway components, quality of service analysis at the facility level, and facility segmentation with a particular emphasis on the influence areas of intersections. Chapter three delves into the study sites and field data used throughout this research.

Chapter four focuses on facility segmentation, presenting a detailed analysis of trajectory data to determine the influence areas of intersections. Additionally, the results of facility segmentation are summarized, and percentile analysis is performed. Based on the outcomes of the percentile analysis of influence area lengths, quantile regression models are developed and discussed. Chapter five introduces the proposed framework for the quality of service methodology for rural highway analysis at the facility-level. This chapter outlines the structure and steps required to assess the quality of service for rural highways at the facility-level, taking into account the unique challenges and characteristics of these corridors.

Chapter six presents case study corridors and demonstrates the application of the proposed methodology for quality of service analysis on real-world rural highway facilities. The results of each case study are discussed in detail, offering insights into the effectiveness and practicality of the proposed methodology. This chapter serves to validate the proposed framework and highlight potential improvements or modifications for future iterations. In chapter seven, the study culminates by summarizing the key findings and their implications. This final chapter emphasizes the significance of the study's contributions to the field and also outlines potential avenues for future exploration in the domain.

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a summary of the relevant literature on the quality of service performance measures in general and facility-level analysis in specific. The chapter includes a review of studies on (1) performance measures on highway segments and junctions, (2) HCM methodologies for facility-level analysis, and (3) facility segmentation of highways.

Quality of Service of Highway and Performance Measures

Quality of service explains how well a transportation facility or service operates and is often stated in terms of "levels of service". Level of service (LOS) is a quantitative stratification of performance scheme representing the quality of service from the traveler's perspective. LOS represents the quality of service estimated on an A to F letter-scale with LOS A representing the best operating conditions and LOS F the worst. LOS is also intended to easily communicate the results of detailed technical analyses to non-technical audiences as communicating the values of different performance measures (e.g., speed, density, etc.) to a lay audience is challenging. Traditionally, transportation engineers and planners use LOS in planning, design, as well as in operational analyses.

The HCM provides a variety of performance measures to assess the quality of service of transportation system elements. These measures can be directly observed in the field or estimated from related field-observed factors. HCM also offers tools to help analysts estimate performance measures for individual elements of a transportation system. **Table 1** presents the various service measures used to determine LOS for automobile mode operating on each system element (as well as facility type) for which the HCM provides analysis methodologies.

Table 1. Performance Measures for Quality of Service Analysis

Groups	**System Element**	**Service Measures for Automobile Mode**
Roadway Segments	Multilane Highway	Density, Speed
	Two-lane Highway	Follower Density
	Urban Street Segment	Speed
	Basic Freeway Segment	Density, Speed
	Freeway Weaving Segment	Density, Speed
	Freeway Merge and Diverge Segments	Density, Speed
Intersections	Signalized Intersection	Average Delay
	Two-Way Stop Control Intersection	Average Delay
	All-Way Stop Control Intersection	Average Delay
	Roundabout	Average Delay
Facilities	Urban Street Facility	Speed
	Freeway Facility	Density, Speed
	Rural Highway Facility	-----

----- Missing in HCM and focus of this research.

Rural Highway Facility

A rural highway facility is generally an extended length of a rural highway consisting of multiple roadway elements or components. It may consist of any combination of the following:

- two-lane highway including passing lane, passing zone, and passing constrained segments,
- multilane highway,

- urban street segments (passing through rural town), and
- intersections (stop-control, signal-control, or roundabout)

Two-Lane Highway: A roadway with a 2-lane cross-section with one lane for each direction of travel. It can be comprised of different types of segments based on passing restriction. Two-lane highway segment types are defined as follows:

- *Passing Zone*: Length of a two-lane highway for which passing in the oncoming lane is permitted, and the length and location of such passing zone provide reasonable accommodation of passing maneuvers under certain traffic conditions.
- *Passing Lane*: This segment type consists of an added lane in the analysis direction, with the intent to break up platoons that have formed upstream by allowing faster vehicles to pass slower vehicles.
- *Passing Constrained*: Length of a two-lane highway in which passing in the oncoming lane is either prohibited or effectively negligible due to lack of utilization of passing zone(s). The latter might be due to insufficient sight distance or high opposing traffic level and indicates an area where passing should be formally prohibited.

Multilane Highway: A highway with at least two lanes for the exclusive use of traffic in each direction, with no control or partial control of access, but may have periodic interruptions to flow at intersections.

Intersection: An intersection is defined as "the shared area of roadway where two or more highways join or cross at grade (same level)." The traffic control type of the intersection governs the rules for how the traffic streams from conflicting roads interact. General intersection forms include yield-control intersections, stop-control intersections, signal-control intersections, and roundabouts.

Quality of Service Methodology for Rural Highway Components

Quality of service analysis of roadways, in the US and Canada (and some other countries outside North America), is usually conducted using the methods outlined in the HCM (TRB, 2022). The underlying objective of the quality of service analysis is to quantify a roadway's performance with regard to specified traffic volumes (demand). Such evaluation relies on different performance measures for individual segments and/or facilities that are part of a highway system. Performance evaluation serves as a means by which transportation engineers can assess and rate the operating conditions of elements of the highway system.

The following subsections summarize the quality of service methodologies for individual components of rural highway facilities.

Two-Lane Highway Methodology

In the US, two-lane highways constitute a substantial proportion of the rural highway network. Passing opportunities are a critical factor that influences the performance of two-lane highways. The latest edition of the HCM introduced a new performance measure, follower density (followers/mi/ln), to assess the operational efficiency of two-lane highways (TRB, 2022). Follower density is calculated as the product of density and the percentage of vehicles in following status (percent followers), as expressed by the following equation:

$$FD = \frac{PF}{100} \times \frac{v_d}{S} \tag{1}$$

where,

FD = follower density in the analysis direction (followers/mi),

PF= percent followers in the analysis direction (%),

v_d = traffic flow rate in the analysis direction (veh/h), and

S = average speed in the analysis direction (mi/h).

The use of follower density as a performance measure for two-lane highways is warranted due to their unique characteristics and the wide range of platooning behaviors that can occur under varying levels of traffic demand. Consequently, this measure captures the quality of operating conditions on two-lane highways more accurately than density or percent followers alone. Moreover, it has gained popularity in other countries, such as South Africa, Spain, Brazil, and Japan (Van As, 2003; Van As & Van Niekerk, 2004). Percent followers, denoted as PF, refers to the percentage of vehicles traveling in the same lane with headways less than a pre-specified threshold value. For instance, a vehicle is deemed to be in a following status if its headway is smaller than the pre-specified threshold value. Recent studies have recommended a headway threshold of 2.5 seconds to better identify follower status when considering the combination of headway and speed for trailing vehicles (Washburn et al., 2018a). In contrast, previous studies, including prior editions of the HCM, used a headway threshold of 3 or 3.5 seconds (TRB, 2010, 2016; Van As, 2003; Van As & Van Niekerk, 2004).

To determine the LOS for two-lane highways, follower density criteria are used, as presented in **Table 2**.

Table 2. LOS Criteria for Two-Lane Highways (Washburn et al., 2018a)

LOS	Follower Density (followers/mi/ln)	
	High-Speed Highways PSL ≥50 mi/h	**Low-Speed Highways PSL < 50 mi/h**
A	≤ 2.0	≤ 2.5
B	>2.0 – 4.0	>2.5 – 5.0
C	>4.0 – 8.0	>5.0 – 10.0
D	>8.0 – 12.0	>10.0 – 15.0
E	>12.0	>15.0

Multilane Highway Methodology

HCM provides a comprehensive methodology for the assessment of the quality of service of multilane highway segments in Chapter 12. Multilane highways are typically comprised of four to six lanes in both directions.

While uninterrupted flow on multilane highways is similar to that on basic freeway segments, there are some significant differences. Side frictions arising from uncontrolled driveways and intersections, as well as opposing flows on undivided cross-sections, result in lower speeds on multilane highways than on similar basic freeway segments. Furthermore, the geometry of multilane highways tends to be more constrained, consistent with lower speed expectations, and isolated signalized intersections can exist along these highways. These factors result in lower speeds and capacities on multilane highways than on basic freeway segments with comparable cross-sections.

The HCM recommends that multilane highway segments be outside the influence of traffic control intersections to ensure uninterrupted flow. According to the HCM, an uninterrupted flow may exist if traffic signals are spaced 2 mi or more and the influence area of traffic signals typically extends about 1 mi on the multilane highway (TRB, 2022).

The HCM recommends three performance measures for multilane highway segments: density (pc/mi/ln), space mean speed (mi/h), and the demand flow rate to capacity ratio (v/c). These measures provide valuable insights into how well traffic is being accommodated on the multilane highway segment. However, speed remains uniform across a broad range of traffic flows and the v/c ratio is not directly discernable to road users. Thus, the primary performance measure for the multilane highway segment is the density (pc/mi/ln). Density is calculated using the following equation:

$$D = \frac{v_p}{S} \tag{2}$$

where

D = density (pc/mi/ln),

v_p = demand flow rate (pc/h/ln), and

S = mean speed of traffic stream under base conditions (mi/h)

Using the density obtained from this equation and **Table 3**, LOS is determined for the multilane highway segment. A complete analysis methodology for motorized vehicles is presented in Exhibit 12-19 in the HCM (TRB, 2022).

Table 3. LOS Criteria for Multilane Highway Segment (TRB, 2022)

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	Demand exceeds capacity OR density > 45

Signal-Control Intersection Methodology

Rural highway facilities may also contain one or more signal-control intersections. In that case, it is important to discuss the quality of service methodology for signal-control intersections. Various performance measures are proposed that fully describe intersection operations that can be used in performing operational analyses at signal-control intersections. The HCM provides a detailed methodology, in Chapter 19, to assess the quality of service provided to road users traveling through a signal-control intersection. The HCM recommends control delay (s/veh) as a primary performance measure for the signal-control intersection. The motorized vehicle analysis methodology process is given in the HCM – Exhibit 19-18. Two paths are shown in the flowchart of Exhibit 19-18, one for pre-timed signal control and one for actuated signal control (TRB, 2022). For the rural highway facility analysis methodology, pre-timed signal control is assumed in this research. If it is actuated, use field-measured average green times for the analysis period of interest.

The HCM allows to investigate the operational performance of the entire intersection, each intersection approach, and each lane group. Control delay (s/veh), as a primary performance measure, alone is used to characterize LOS for the entire intersection or approach. Whereas control delay and volume-to-capacity ratio are used to characterize LOS for a lane group. Control delay quantifies the increase in travel time due to traffic signal control and is also a surrogate measure of driver discomfort and fuel consumption. On the other hand, the volume-to-capacity ratio quantifies the degree to which the capacity of a signal phase is utilized by a lane group.

Table 4 displays the LOS criteria as a function of control delay for a signal-control intersection, as outlined in the HCM.

Table 4. LOS Criteria for Signal-Control Intersection (TRB, 2022)

	LOS by Volume-to-Capacity Ratio[a]	
Control Delay (s/veh)	≤1.0	>1.0
≤10	A	F
>10–20	B	F
>20–35	C	F
>35–55	D	F
>55–80	E	F
>80	F	F

Stop-Control Intersection Methodology

Stop-control intersections are prevalent on rural highways especially those with low traffic volumes (as in the case of four-way stop control (AWSC)) or at the intersections of minor-major roadways where the volume on the minor road is relatively small (as in the case of two-way stop control (TWSC)). In the case of TWSC intersections, the major roadway remains uncontrolled, while the minor road, which typically experiences lower traffic volume, is regulated by a STOP sign. Consequently, traffic on the major road takes priority over traffic on the minor road approaches, requiring vehicles on the minor road to come to a complete stop before entering the intersection. Typical configurations of TWSC intersections include four-leg intersections and three-leg (T-type) intersections.

Conversely, in the case of AWSC intersections, both roadways (all approaches) are controlled by STOP signs, with no specific roadway having priority. This design ensures that all vehicles approaching the intersection from any direction must come to a complete stop before entering the intersection. This configuration aims to promote a more equitable distribution of right-of-way among intersecting roadways, contributing to enhanced traffic flow management and increased safety at the intersection.

The HCM offers comprehensive methodologies for assessing the quality of service at stop-control intersections. Control delay is used as the primary performance measure for these types of intersections. However, the LOS criteria for stop-control intersections differ somewhat from those for signal-control intersections. This discrepancy stems from the fact that user perception varies between stop-control and signal-control intersections. Drivers expect signal-control intersections to be designed for higher traffic and thus to present greater delays than stop-control intersections. Moreover, stop-control intersections are associated with increased uncertainty for users due to the less predictable nature of delays compared to those at signal-control intersections.

In order to evaluate the quality of service at TWSC intersections, Chapter 20 of the HCM provides a comprehensive analysis methodology, which is also illustrated in the HCM – Exhibit 20-6, for estimating control delays and LOS. Since it is assumed that the through traffic on the major road has zero delays (uncontrolled), LOS is not defined for the major road approaches or the overall intersection. To determine the control delay for all vehicles on a specific approach, a weighted average of the control delay calculated for each movement on the approach must be taken weighted by the volume of each movement. In a similar manner, the control delay for the intersection can be calculated using a weighted average of the control delay estimates for each approach, weighted by the volume on each approach. Equations 3 and 4 are used to calculate the control delay on the approach and the control delay of the intersection, respectively.

$$d_{Approach/TWSC} = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l} \tag{3}$$

$$d_{Intersection/TWSC} = \frac{d_{A,1} v_{A,1} + d_{A,2} v_{A,2} + d_{A,3} v_{A,3} + d_{A,4} v_{A,4}}{v_{A,1} + v_{A,2} + v_{A,3} + v_{A,4}} \tag{4}$$

where,

$d_{Approach/TWSC}$ = control delay on the approach of TWSC (s/veh),

$d_{Intersection/TWSC}$ = control delay for the intersection TWSC (s/veh),

d_r, d_t, d_l = control delay for the right-turn, through, and left-turn movements, respectively (s/veh),

v_r, v_t, v_l= flow rate of right-turn, through, and left-turn traffic on the approach (veh/h),

$d_{A,x}$ = control delay on approach x (s/veh), and

$v_{A,1}$ = flow rate on approach x (veh/h).

The LOS for each approach can be determined using the computed values of control delay for the approach, in conjunction with the LOS criteria presented in **Table 5**.

Chapter 21 in the HCM provides a comprehensive analysis framework for AWSC intersections. The motorized vehicle analysis methodology process is illustrated in the HCM – Exhibit 21-10. To calculate the control delay for a specific approach of an intersection, a weighted average of the delay for each lane on the approach is computed, with the weighting based on the volume of traffic in each lane. Similarly, the control delay for the entire intersection is calculated by computing a weighted average of the delay for each approach, with the weighting determined by the volume of traffic on each approach. Equations 5 and 6 are used to calculate the control delay for an approach and the control delay for the intersection, respectively.

$$d_{Approach/AWSC} = \frac{\sum d_i v_i}{\sum v_i} \tag{5}$$

$$d_{Intersection/AWSC} = \frac{\sum d_a v_a}{\sum v_a} \tag{6}$$

where,

$d_{Approach/AWSC}$ = d_a = control delay for the approach on AWSC (s/veh),

$d_{Intersection/AWSC}$ = control delay for the entire intersection AWSC (s/veh),

d_i = control delay for lane i (s/veh),

v_i = flow rate for lane i (veh/h),

d_a = $d_{Approach/AWSC}$, and

v_a = flow rate for approach a (veh/h),

The LOS for each approach and the entire AWSC intersection is determined by using the calculated values of control delay with the LOS criteria summarized in **Table 5**.

Table 5. LOS Criteria for All-Way Stop-Control Intersection (TRB, 2022)

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio[a]	
	v/c≤1.0	v/c>1.0
0–10	A	F
>10–15	B	F
>15–25	C	F
>25–35	D	F
>35–50	E	F
>50	F	F

Roundabout Methodology

Roundabout intersections, typically in a circular shape, are characterized by yielding upon entry and counterclockwise circulation around a central island. From an operational perspective, roundabouts are highly efficient in managing traffic under lower traffic volume conditions. This is mainly attributable to their capacity to reduce the number of conflict points and the need for frequent stops, which, in turn, leads to a more streamlined and uninterrupted flow of traffic. Consequently, roundabouts can significantly enhance the overall quality of service at intersections, contributing to improved safety, reduced congestion, and lower emissions.

Chapter 22 of the HCM is dedicated to the assessment of the quality of service analysis for roundabout intersections. Similar to stop-control intersections, control delay serves as the performance measure for roundabout intersections. Furthermore, the fundamental control delay formulation and LOS criteria utilized for TWSC and AWSC intersections are also applied to roundabout intersections. Exhibit 22-10 in the HCM illustrates a comprehensive methodology for conducting LOS analysis for roundabout intersections. This analytical process allows for the computation of control delays for both individual approaches and the entire intersection (TRB, 2022).

To calculate the control delay for a specific approach, a weighted average of the delay for each lane on the approach is calculated by taking into account the volume in each lane. This process involves assessing the delays experienced by vehicles in each lane and factoring in the proportion of traffic volume for a more accurate representation of the overall control delay for the approach.

In a similar manner, the control delay for the entire intersection is calculated by computing a weighted average of the delays for each approach, factoring in the volume on each approach. This method takes into account the control delays experienced by vehicles on all approaches, providing a comprehensive understanding of the intersection's overall performance. Equations 7 and 8 are used to calculate control delays for an approach and an entire intersection, respectively.

$$d_{Approach/Roundabout} = \frac{d_{LL}v_{LL} + d_{RL}v_{RL} + d_{bypass}v_{bypass}}{v_{LL} + v_{RL} + v_{bypass}} \tag{7}$$

$$d_{Intersection/Rounabout} = \frac{\sum d_i v_i}{\sum v_i} \tag{8}$$

where,

$d_{Approach/Roundabout}$= control delay on the approach of a roundabout (s/veh),

$d_{Intersection/Rounabout}$ = control delay for the entire Roundabout intersection (s/veh),

d_{LL}, d_{RL}, d_{bypass} = control delay for the left-lane, right-lane, and bypass-lane, respectively (s/veh),

v_{LL}, v_{RL}, v_{bypass} = flow rate of left-lane, right-turn, and bypass-lane on the approach (veh/h),

d_i = control delay on approach i (s/veh), and

v_i = flow rate on approach i (veh/h).

The LOSs for each approach and for the entire roundabout intersection are determined by using the computed values of control delay with the LOS criteria summarized in **Table 6**.

Table 6. LOS Criteria for Roundabout Intersection (TRB, 2022)

	LOS by Volume-to-Capacity Ratio[a]	
Control Delay (s/veh)	v/c≤1.0	v/c>1.0
0–10	A	F
>10–15	B	F
>15–25	C	F
>25–35	D	F
>35–50	E	F
>50	F	F

Urban Street Segment Methodology

In certain instances, a rural highway facility may pass through a small rural town characterized by a small population (usually below 5,000 residents).

Urban street segments encompass two elements: links and intersections. An intersection is a boundary between links whereas the link is the length of the roadway between two intersections. When a link is combined with the intersection, it makes an urban street segment. It is important to analyze the link and the boundary intersection together, as a segment, to provide an accurate indication of overall segment performance. Chapter 18 (Urban Street Segments) in the HCM addresses the calculation of link performance, known as running time, and the aggregation of link running time with downstream intersection control delay, ultimately determining segment average travel time and average travel speed. Intersection control delay values are obtained from the methodologies detailed in the individual intersection chapters (Chapters 19 to 22 in HCM), as previously summarized.

The methodology outlined in the HCM – Chapter 18 contains a component to estimate traffic flow progression through a series of closely-spaced, coordinated, signalized intersections. This process is typically referred to as the 'platoon dispersion model'. The platoon dispersion model is input data-intensive and computationally complex; thus, it is advisable to employ the planning-level analysis, provided in Chapter 30 of the HCM, due to its simplified adjustment for flow progression. The primary difference between planning-level and operational-level methodologies lies in the simplification of the process used to account for signal progression quality on signal delay. Instead of the more intricate platoon dispersion model, the planning-level analysis makes use of the simplified progression adjustment factor (PF).

The planning-level analysis methodology is described in Section 5 of Chapter 30 (Urban Street Segments: Supplemental) in the HCM. The motorized vehicle analysis methodology process is illustrated in Exhibit 30-8. For the purposes of rural highway analysis, a section of roadway that warrants analysis as an urban street is designated as an 'arterial segment' in this research.

Travel speed serves as the primary performance measure in determining the quality of service of urban street segments. The travel speed is intrinsically dependent on the base free-flow speed, which is a critical parameter in evaluating the overall performance and efficiency of urban street segments. The base free-flow speed is defined as an unimpeded travel speed on a roadway segment, where vehicles are unhindered by the presence of other vehicles, traffic signals, or intersection-related factors. The base free-flow speed can be computed using the following equation:

$$S_{fo} = S_{calib} + S_0 + f_{cs} + f_A + f_{pk} \tag{9}$$

where

S_{fo} = base free-flow speed (mi/h),

S_{calib} = base free-flow speed calibration factor (mi/h),

S_0 = speed constant (mi/h),

f_{cs} = adjustment factor for cross-section (mi/h),

f_A = adjustment factor for access points (mi/h), and

f_{pk} = adjustment factor for on-street parking (mi/h).

The travel speed calculation incorporates the segment length, segment running time, and through delays, as represented by the following equation:

$$S_{T,seg} = \frac{3600\ L}{5280\ (t_r + d_t)} \tag{10}$$

where,

$S_{T,seg}$ = travel speed of through vehicles for a segment (mi/h),

L = segment length (ft),

t_r = segment running time (s), and

d_t = through delays (s).

The LOS criteria, based on the relationship between travel speed and free-flow speed, are outlined in **Table 7**.

Table 7. LOS Criteria for Urban Street Segment (TRB, 2022)

LOS	Travel Speed Threshold by Base Free-Flow Speed (mi/h)							V/C Ratio[a]
	55	**50**	**45**	**40**	**35**	**30**	**25**	
A	>44	>40	>36	>32	>28	>24	>20	≤ 1.0
B	>37	>34	>30	>27	>23	>20	>17	
C	>28	>25	>23	>20	>18	>15	>13	
D	>22	>20	>18	>16	>14	>12	>10	
E	>17	>15	>14	>12	>11	>9	>8	
F	≤17	≤15	≤14	≤12	≤11	≤9	≤8	
F	Any							> 1.0

[a]Volume-to-capacity ratio of through movement at downstream boundary intersection.

Facility-Level Methodologies

This section aims to provide a summary of the current HCM facility-level methodologies. A facility-level methodology offers a systematic approach to evaluating and predicting the performance of highway facilities, taking into account the complex interactions between various roadway components (segments and junctions).

Analysis Methodology for Urban Street Facility

An urban street facility is composed of two or more links (length of roadway) interconnected through intersections. Chapter 16 (Urban Street Facilities) in the HCM addresses the comprehensive assessment of the performance of urban street facilities, considering not only the perspective of motorists but also pedestrians, bicyclists, and transit riders. However, the focus of this research is primarily on motorized vehicle methodology, and therefore, the discussion will center on the analysis method for assessing the quality of service of urban street facilities from the motorists' perspective.

The LOS criteria for motorized vehicle analysis are based on performance measures that can be measured in the field and are perceivable by drivers. Given that mobility is of high importance for motorized vehicle users on urban street facilities, through-vehicle travel speed is used as the primary performance measure for quality of service analysis of urban street facilities. This speed reflects the factors influencing the running time along each link and the delay experienced by the through vehicles at each boundary intersection. LOS determination relies on travel speed, which is dependent on the base free-flow speed of the segment. The base free-flow speed is calculated for each segment using the equation outlined in Chapter 18 of the HCM.

The base free-flow speed for the urban street facility is computed using the following equation:

$$S_{fo,F} = \frac{\sum_{i=1}^{m} L_i}{\sum_{i=1}^{m} \frac{L_i}{S_{fo,i}}} \tag{11}$$

where,

$S_{fo,F}$ = base free-flow speed for the facility (mi/h),

L_i = length of segment i (ft),

m = number of segments on the facility, and

$S_{fo,i}$ = base free-flow speed for segment i (mi/h), as presented in Eq. 9 mentioned previously.

Travel speed, a primary performance measure, for the urban street facility, represents the ratio of facility length to facility travel time. It indicates an equivalent average speed for the through-vehicle traffic stream, taking into account the running speed along the street for through vehicles and any delay incurred at boundary intersections. The travel speed for through vehicles on each segment is determined using the equation in Chapter 18 (also provided previously in Eq. 10). The travel speed for the facility is computed using the following equation:

$$S_{T,F} = \frac{\sum_{i=1}^{m} L_i}{\sum_{i=1}^{m} \frac{L_i}{S_{T,seg,i}}} \tag{12}$$

where,

$S_{T,F}$ = travel speed for the facility (mi/h),

L_i = length of segment i (ft),

m = number of segments on the facility, and

$S_{T,seg,i}$ = travel speed for segment i (mi/h), as presented in Eq. 10.

LOS for the urban street facility is determined based on the calculated travel speed and the base free-flow speed, using LOS criteria presented in **Table 8**. According to the HCM, facility LOS must be interpreted cautiously as it can be misleading and may suggest acceptable operations of the facility when, in reality, a specific segment is operating at an unacceptable LOS. It is recommended to report the LOS for the poorest-performing segment as a means of providing context for the interpretation of facility LOS. This approach ensures a more accurate representation of the overall performance of the urban street facility.

Table 8. LOS Criteria for Urban Street Facility (TRB, 2022)

LOS	Travel Speed Threshold by Base Free-Flow Speed (mi/h)							V/C Ratio[a]
	55	50	45	40	35	30	25	
A	>44	>40	>36	>32	>28	>24	>20	≤ 1.0
B	>37	>34	>30	>27	>23	>20	>17	
C	>28	>25	>23	>20	>18	>15	>13	
D	>22	>20	>18	>16	>14	>12	>10	
E	>17	>15	>14	>12	>11	>9	>8	
F	≤17	≤15	≤14	≤12	≤11	≤9	≤8	
F	Any							> 1.0

[a]Volume-to-capacity ratio of through movement at downstream boundary intersection.

Analysis Methodology for Freeway Facility

A freeway facility is an extended length of freeway that consist of interconnected basic, weaving, merge, and diverge segments. Chapter 10 (Freeway Facilities Core Methodology) in the HCM presents the core methodology for analyzing freeway facilities. Furthermore, this facility-level methodology builds upon the segment-level methodologies presented in Chapters 12 to 14, which focus on the unique operational characteristics of basic freeway, weaving, merge, and diverge segments. By amalgamating the segment-level analysis into the facility-level analysis, a holistic understanding of freeway facility performance is achieved. For a more in-depth understanding, Chapter 25 (Freeway Facilities: Supplemental) elucidates all the algorithms associated with this methodology.

The complex computation of freeway facility methodology is incorporated into a computational engine known as FREEVAL. This powerful computational tool streamlines the analysis process by automating the application of freeway facility methodologies, thereby enabling transportation practitioners to efficiently evaluate the performance of freeway facilities. By leveraging the advanced capabilities of FREEVAL, practitioners can obtain accurate insights into the operational conditions, capacity, and quality of service of freeway facilities, which are crucial for informed decision-making in transportation planning and engineering processes.

Exhibit 10-8 illustrates the systematic, step-by-step approach for performing a quality of service analysis of freeway facilities (TRB, 2022). Given that the LOS criteria for basic, weaving, merge, and diverge segments of a freeway are based on density (pc/mi/ln), the LOS criteria for freeway facility LOS are similarly established on density measurements. However, it is essential to note that the LOS thresholds for rural freeway facilities deviate from those established for urban facilities (same thresholds as for individual segments). This discrepancy arises from the differing perceptions of users of rural freeway facilities, who typically anticipate lower density thresholds in comparison to the density thresholds expected by users of urban freeway facilities. The density thresholds for LOS criteria are presented in **Table 9**.

Table 9. LOS Criteria for Urban and Rural Freeway Facilities (TRB, 2022)

LOS	**Freeway Facility Density (pc/mi/ln)**	
	Urban	**Rural**
A	≤11	≤6
B	>11–18	>6–14
C	>18–26	>14–22
D	>26–35	>22–29
E	>35–45	>29–39
F	>45 or	>39 or
	Any component segment v_d/c ratio > 1.00	Any component segment v_d/c ratio > 1.00

The average density, a primary performance measure, of a freeway facility is determined by calculating the weighted average density of all the constituent segments of the facility, weighted by the segment length and the number of lanes in each segment. The following equation can be used to compute the weighted average density:

$$D_F = \frac{\sum_{i=1}^{n} D_i \times L_i \times N_i}{\sum_{i=1}^{n} L_i \times N_i} \quad (13)$$

where,

D_F = average density for the facility (pc/mi/ln),

D_i = density for segment i (pc/mi/ln),

L_i = length of segment i (mi),

N_i =number of lanes in segment i, and

n = number of segments in the defined facility.

Utilizing the computed average density for the facility and the corresponding LOS criteria, as presented in **Table 9**, the facility's LOS can be determined.

Analysis Methodology for Rural Two-Lane Highway

The two-lane highway analysis methodology, as elaborated earlier in this chapter, was developed through the National Cooperative Highway Research Program (NCHRP) Project 17-65 (Washburn et al., 2018a), which is presented in Chapter 15 in the HCM. This novel methodology not only facilitates the analysis of a homogeneous segment of two-lane highways but also possesses the capability to examine the quality of service of multiple contiguous segments of two-lane highways, encompassing a diverse range of passing configurations such as passing zone, passing constrained, and passing lane segments.

Similar to the performance measure applied to individual two-lane highway segments, the LOS assessment for multiple contiguous segments (or a facility) of a two-lane highway (excluding multilane highways and intersections) also relies on the follower density (follow/mi/ln) as the primary performance measure. To analyze the performance of an extended length of a two-lane highway consisting of various segments, the first step involves facility segmentation, that is dividing the extended length into distinct segments and conducting performance analyses for each segment.

Subsequently, a weighted average follower density is computed for all the constituent segments of the extended length of the two-lane highway, taking into account the length of each segment. This process allows for a comprehensive and nuanced understanding of the operational efficiency and user experience across the entire facility, rather than solely focusing on individual segments.

The computation of the weighted average follower density for a two-lane highway facility consisting of multiple contiguous segments can be achieved using the following equation:

$$FD_F = \frac{\sum_{i=1}^{n} FD_i \times L_i}{\sum_{i=1}^{n} L_i} \tag{14}$$

where

FD_F = average follower density for the facility in the analysis direction (followers/mi),

FD_i = follower density for segment i in the analysis direction (followers/mi), and

L_i = segment length for segment i (miles)

Facility Segmentation

A critical step in a facility-level analysis framework is facility segmentation; that is, dividing the facility in question into its basic components, which are segments and junctions (TRB, 2022; Washburn et al., 2018a). In the context of freeway facility analysis, an extended freeway length is divided into basic, weaving, merge, and diverge segments, as illustrated in **Figure 2.** Initially, the freeway facility is partitioned into sections extending from one ramp gore point to another. These sections are demarcated by changes in traffic demand occurring at on-ramps and off-ramps. These sections do not play a significant role in operational analysis; however, they are crucial for planning-level applications. Next, the facility is further divided into HCM segments to facilitate a detailed analysis. These segments are portions of the previously established sections and are created based on the influence areas of merge, diverge, or weaving operations, as outlined in HCM Chapters 12 through 14. The influence areas associated with merge, diverge, and weaving processes are illustrated in **Figure 3** and extensively discussed in HCM Chapter 10.

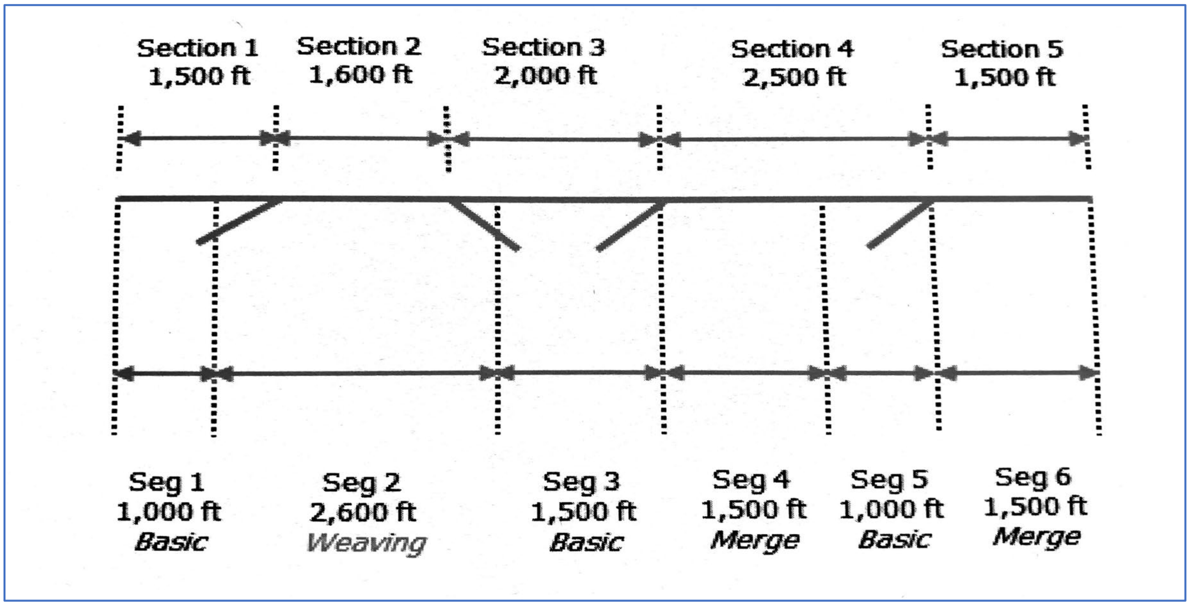


Figure 2. Facility Segmentation of an Urban Freeway Facility (TRB, 2022)

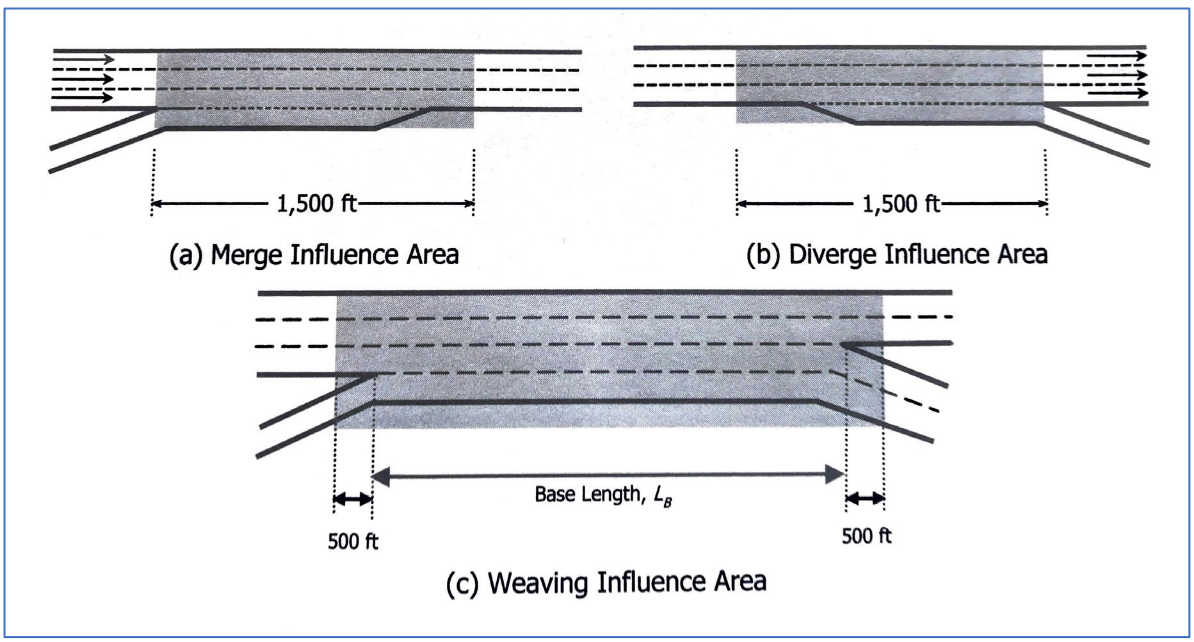


Figure 3. Influence Areas of Freeway Merge, Diverge, and Weaving Segments (TRB, 2022)

Similarly, the urban street facility, consisting of links interconnected by nodes (intersections), is divided into urban street segments. Urban street segments are composed of the link and the boundary intersection. After performing facility segmentation, the urban street segment analysis methodology, as described in HCM Chapter 18, is used to analyze individual segments (link and boundary intersection). Subsequently, the performance measures for each segment are aggregated into performance measures of the overall facility.

Furthermore, the performance analysis of an extended length of a two-lane highway necessitates facility segmentation as outlined in HCM Chapter 15 (Rural Two-Lane Highways). This process involves dividing the facility into individual components (or segments in this case), according to their passing configurations. These configurations may include passing zone segments, passing constrained segments, and passing lane segments. Following segmentation, the analysis of two-lane highways is conducted for each individual component. Subsequently, the results are aggregated into the overall two-lane highway facility through the application of a weighted average of follower density, taking into account the length of the segments, as elaborated previously in this chapter.

In the case of rural highway facilities, the process of facility segmentation may be relatively straightforward for different segments. For instance, the start (or end) of passing lane sections or multilane highway sections roughly coincide at the location of lane addition (or lane drop). Similarly, the pavement centerline markings are used to delineate passing restricted sections and passing zones. Moreover, a new segment is established when there is a change in the posted speed limit (PSL), ensuring that a consistent PSL is maintained throughout the segment. However, intersections, while represented as point locations in a link-node network configuration, have operational effects extending over some distance on connecting incoming and outgoing approaches. These operational effects, in turn, influence the performance of highway segments near intersections. The lengths along all approaches affected by the intersection are commonly known as the "influence area."

A review of the literature regarding the operational effects of intersections on the connected segments and facility segmentation yielded a limited number of studies. The most recent study, conducted in India, attempted to model driver behavior at signalized intersections under heterogeneous traffic conditions. As part of the driver behavior modeling, the authors used 100 GPS trajectories of a test car to determine the upstream spatial extent of intersection impact on the driver's behavior (mainly speed selection) and termed as intersection zone of influence (IZOI). The study reported that the upstream IZOI for cars ranges from around 525 ft to 702 ft (around 160.70 to 214.08 m) (Singh et al., 2022). Similarly, Chauhan et. al (2018) examined a driving cycle for five intersections on an urban corridor. Driving cycle analysis can be used for improving vehicle fuel consumption and emissions reduction. In this study, the researchers considered both upstream and downstream influence areas of intersections including the width of the intersection as an influence zone. The study concluded with a total influence zone of 1050 ft (320 m) for cars at urban intersections (Chauhan et al., 2018).

In order to propose a methodology for assessing the performance of a two-lane highway corridor, Li and Washburn (2014) used the effective upstream and downstream lengths of a signalized intersection to refer to the intersection influence areas. In the proposed methodology framework, effective upstream and downstream lengths were required for the segmentation of the two-lane highway corridor in question. The study used the CORSIM traffic simulation software for performance analysis of two-lane highway facilities, consisting of two-lane highway segments and signalized intersections (Li & Washburn, 2014). This study built upon the work by Yu and

Washburn (2009) which also performed facility segmentation and defined the operational boundaries for signalized intersections on a rural two-lane highway using the traffic simulation software CORSIM and TWOPAS (Yu & Washburn, 2009). Regression models were developed to estimate the upstream and downstream effective lengths of a signalized intersection. As this study was based on simulation data, the upstream effective length model incorporated different factors as they were readily available from simulation data such as demand volume, left turn percentage, green time, and cycle length. The downstream effective length model incorporates those same factors along with heavy vehicle percentage.

In another recent study, Rodegerdts et al. (2014) performed facility segmentation and determined roundabout influence area as part of evaluating the performance along roundabout corridors (i.e., corridor includes multiple roundabouts). This study used field data collected from nine roundabout corridors located in different states. The researchers found that the mean upstream and downstream influence areas are 311.0 ft. and 617 ft., respectively. It suggested that the average downstream influence area is approximately double the average upstream influence area. However, the lengths of the influence areas may not be accurate for the purpose of facility segmentation in this current research as the authors included the data from closely spaced roundabouts. In such scenarios, the influence areas of two consecutive closely spaced roundabouts overlap, i.e., the downstream influence area of one roundabout overlaps with the upstream influence area of the other roundabout, as the vehicle does not attain a free-flow operating speed of the downstream segment before it starts deceleration for the second roundabout. In this study, two separate linear regression models were developed for estimating upstream and downstream influence areas based on free-flow speed and circulating speed as significant independent variables (Rodegerdts et al., 2014).

Silva et. al. (2014) examined driver behavior while crossing a corridor of three roundabouts in Portugal. The site had a posted speed limit of 31.25 mph (50 kph). The researchers found that the total influence area including upstream, downstream, and the width of the roundabout is between 1300 ft. to 1640 ft. (400 and 500 meters) (Silva et al., 2014b). In another study, Violette and Cardon (1992) suggested that the total length of the influence zone can be between 1900 ft. and 3280 ft (600 and 1000 m). These relatively high values are likely due to higher roadway speeds, upstream and downstream of the intersection, of the rural area study (Violette & Cardon, 1992).

Besides operational impacts, the influence area of the intersection is also important for traffic safety analyses. To study intersection-related crashes at unsignalized intersections, Kay et. al. (2022) selected 1070 ft (326 m) for the upstream and downstream influence areas on the major approach, and 300 ft (91 m) for the upstream and downstream influence areas on the minor approach (Kay et al., 2022). These influence area lengths are consistent with the recommendation of the Informational Guide on Median U-Turn Intersections by the Federal Highway Administration (Reid et al., 2014). To examine drivers' behavior on the approach to stop-controlled intersections and develop a warning algorithm component of an intersection collision avoidance system (ICAS) to warn inattentive drivers and reduce violations, Doerzaph et. al. found that drivers start applying the brakes approximately 400 ft (120 m) on average for intersections with posted speed limits of 25 mph, 35 mph, and 45 mph (40.2 km/h, 56.3 km/h, and 72.4 km/h) (Doerzaph et al., 2007). In addition, the roundabout influence area has been part of the research on environmental and noise assessment of roundabouts. Mudgal et. al. (2013) conducted a test car study to model driver behavior and emissions at a roundabout on a multilane highway in Iowa, US. The researchers found that each upstream and downstream influence area is 500 ft (152 m) on average. The test site (roundabout) is along an urban corridor that has multiple upstream and downstream intersections and a posted speed limit of 35 mph (56.3 km/h) (Mudgal et al., 2014).

All the aforementioned studies have attempted to identify the spatial extent of operational effects of either signalized intersections or roundabouts, however, each study has certain limitations such as analyzing only urban street intersections instead of rural intersections (Chauhan et al., 2018; Silva et al., 2014a; Singh et al., 2022), studies based on traffic simulation instead of empirical data or validation using field data (Li & Washburn, 2014; Yu & Washburn, 2009), use of very limited data (small sample) in the study(Singh et al., 2022), heterogeneous traffic condition that includes two- and three-wheel motor vehicles (Chauhan et al., 2018; Singh et al., 2022), and closely spaced intersections or roundabouts that have overlapped influence areas (Chauhan et al., 2018; Rodegerdts et al., 2014). To address these limitations, the current study utilized extensive empirical data with multiple sites each for signal control, stop control, and roundabout intersections on rural highways. **Table 10** presents a summary of the reviewed studies that examined the spatial extent of operational impacts of intersections on connecting approaches.

Table 10. Summary of Previous Studies

Authors	**Intersection Control**	**Urban/ Rural**	**Study Purpose**	**Limitations / Relevance**
(Singh et al., 2022)	Signal	Urban	Driver behavior	Heterogeneous traffic, urban intersection, a small sample size of 100 trajectories
(Chauhan et al., 2018)	Signal	Urban	Driving cycle	Heterogeneous traffic, urban intersection, a small sample size
(Li & Washburn, 2014)	Signal	Rural	Operational impact	Simulation only study
(Yu & Washburn, 2009)	Signal	Rural	Operational impact	Simulation only study
(Rodegerdts et al., 2014)	Roundabout	Suburban	Operational impact	Roundabouts only, Overlapped influence areas at closely spaced roundabouts
(Silva et al., 2014a)	Roundabout	Urban	Driver behavior	Roundabouts only, Urban streets
(Violette & Cardon, 1992)	Roundabout	Rural	Driver behavior	Roundabouts only, old study as vehicle performance is different now
(Kay et al., 2022).	Stop	Suburban	Intersection safety	Only focused on intersection-related crashes and safety
(Doerzaph et al., 2007)	Stop	Urban	Collision avoidance	Includes low posted speed limit study sites
(Ahn et al., 2009)	Roundabout	Urban	Emissions	Urban corridor with a low posted speed limit, closely spaced roundabouts

CHAPTER THREE

STUDY SITES AND DATA

Overview

This study emphasizes the critical role of field data in the development of new methodologies for the analysis of quality of service of rural highways at the facility-level. In particular, the HCM highly recommends that new operational analysis methodologies be based on empirical data (TRB, 2022). However, collecting extensive traffic data at a microscopic level with high resolution (e.g., vehicle trajectory data) and a larger sample size, is a time-consuming and costly effort. Consequently, the current study leveraged the established research collaborations and acquired data from research partners and other entities, which were previously collected for other transportation projects. Additionally, the state DOTs were also contacted for other relevant data that was accessible at no cost. This data is comprised of traffic counts and highway geometric attributes. The acquired data were used to determine influence areas of intersections and formulate new methodologies for the rural highways at the facility-level.

This chapter presents a detailed exposition of the study sites and the field data utilized in this research. To ensure the diversity of study sites, data were collected from multiple sites and regions. For the intersection influence area, the number of study sites for each type of intersection and the available data sources are summarized in **Table 11**.

Table 11. Total Number of Study Sites with Attributes

Intersection Control	Data Type	# of Sites	Directions (EB/WB or NB/SB)	Samples	Data Resolution (Hz)
Signal Control	Trajectory	4	Both	4x2=8	1/3
Stop Control	Trajectory	7	One	7x1=7	1/3
Roundabout	Trajectory	3	Both	10	1

Study Sites and Data for Roundabout Influence Area

Facility segmentation is an important step in facility-level quality of service analysis, as it allows for accurate estimation and prediction of performance. In this context, the roundabout influence area is a crucial factor to consider, as it can significantly affect the performance of a given roadway segment. The data used to determine the roundabout influence area in this study is a subset of the high-resolution floating car data collected as part of the National Cooperative Highway Research Program (NCHRP 03-100) project (Rodegerdts et al., 2014). High-resolution (1 Hz) floating car data were collected using a highly accurate GPS logger on two test cars. The data were collected during peak and off-peak (morning and evening) hours for three days on each study corridor. Each study corridor was comprised of multiple roundabouts and more than 100 test runs were conducted by test cars at each study site. The GPS trajectory data consisted of trajectory ID, latitude, longitude, speed, heading angle, and time stamp for each way-point. The participating drivers were informed that the data would be used for institutional research and not for legal enforcement, and thus were encouraged to maintain normal driving behavior. For this study, trips involving only through movements (non-turning trips) were used for the determination of the influence area of roundabouts.

Out of the nine roundabout corridors used in the NCHRP 3-100 project (Rodegerdts et al., 2014), only three corridors passed the screening criteria used in this study: two corridors in the state of Washington and one corridor in Colorado. The criteria used in screening the sites were: i) drivers should be able to accelerate from an upstream junction and then travel at the desired speed (free-flow speed) for a certain distance before they start to decelerate for the downstream roundabout; that is the distance between two consecutive roundabouts should be long enough to avoid overlapping influence areas; and ii) the resolution of differential GPS data should be no less than 0.33 Hz (one data point per 3 seconds). This high resolution of GPS data enabled us to accurately estimate the vehicle speed and acceleration every second of the vehicle trajectory. **Figure 4** shows a layout map for one of the three test corridors along Borgen Boulevard in the state of Washington.

The screening criteria resulted in excluding six study sites from consideration as well as eliminating short segments at the selected three sites used in this study (for example, only the last two roundabouts were selected based on the screening criteria at the study site shown in **Figure 4**). The selected three sites are:

1. *Site 1*: SR – 539 in Whatcom County, Washington [start (lat/long – 48.86543298/-122.48589689), end (lat/long – 48.93271443/-122.48545581)]
2. *Site 2*: Borgen Boulevard in Gig Harbor, Washington [start (lat/long – 47.35994383/-122.60378050), end (lat/long – 47.35995657/-122.58853120)]

3. *Site 3*: Golden Road in Golden, Colorado [start (lat/long – 39.73749400/-105.19291996), end (lat/long – 39.74700220/-105.21031307]

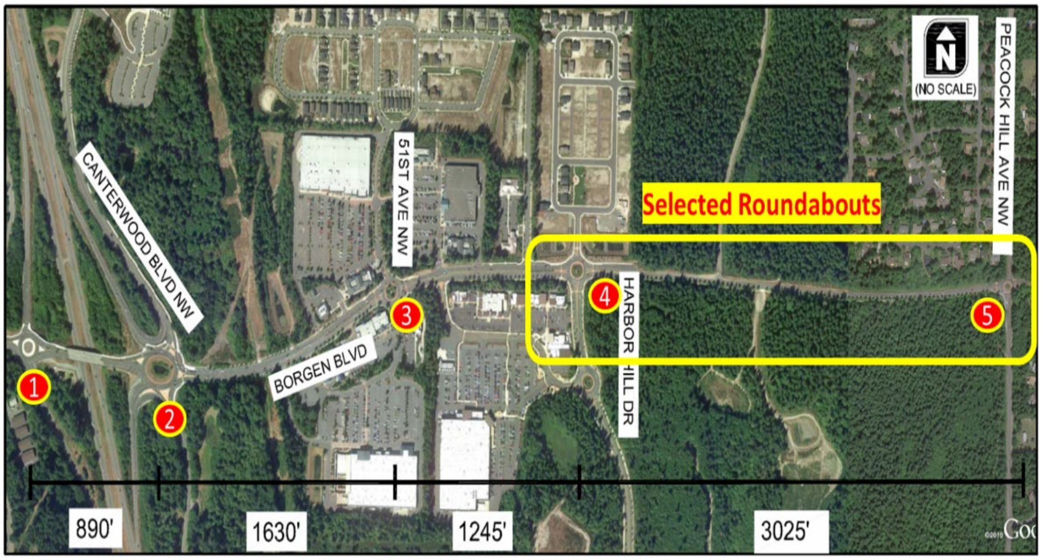


Figure 4. Layout Map of the Borgen Boulevard, Washington

Figure 5 to **Figure 10** present the map-view and street view of the three roundabout study sites, while the characteristics of the three study sites are presented in **Table 13.** Summary of Test-Runs at Study Sites. The selected three sites were characterized by low traffic volumes, reducing the potential for restricted vehicle flow, and heavy vehicle volumes were significantly low at all three sites. Traffic volume data was collected during the same time the test vehicle runs were conducted. The measured traffic volumes at Sites 2 and 3 were particularly lower than that at Site 1 as shown in **Figure 11**. The 15-min directional traffic counts for approximately a 12-hour period (starting at 7:00 am) at the three sites are shown in **Figure 11**. The data from the three selected sites were utilized to determine the roundabout influence area and develop new methodologies for facility segmentation in traffic analysis.

<u>Site 1: SR – 539 in Whatcom County, Washington</u>

Intersection Attributes

- Four roundabout intersections in the corridor
- Posted speed limit of 50 mi/h
- Dual-lane roundabouts

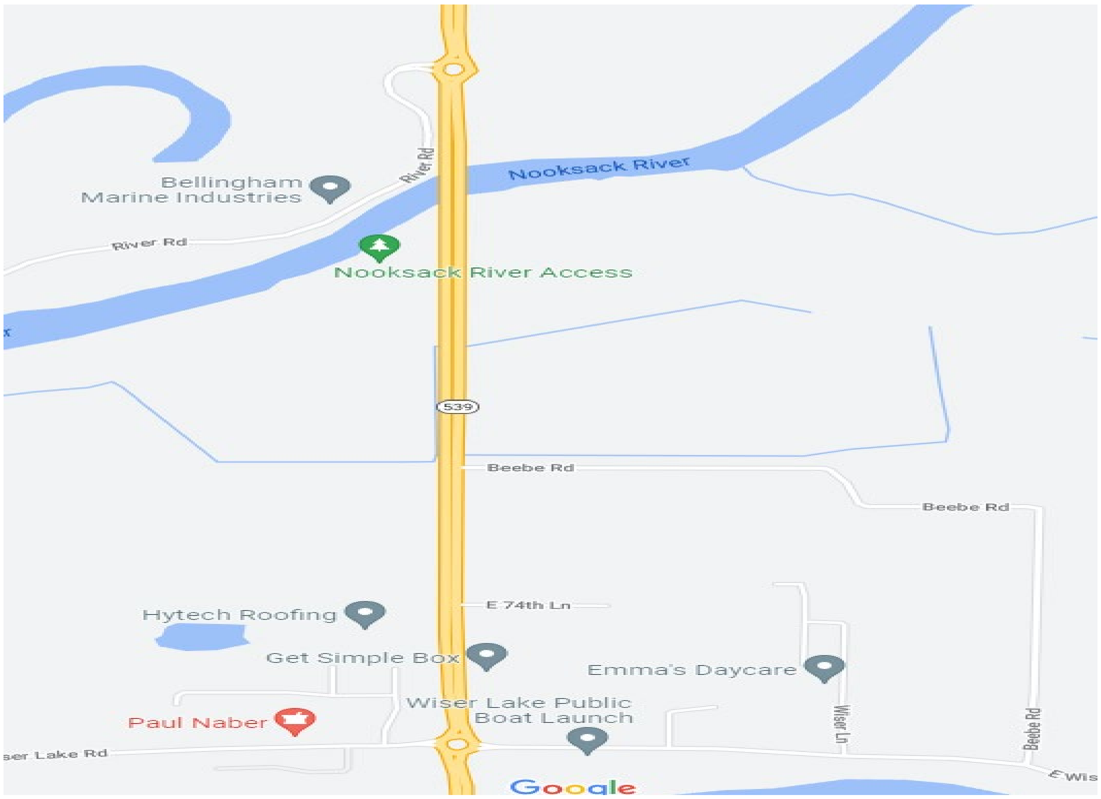


Figure 5. Site 1: SR-539 in Whatcom County, Washington (Map View)

Figure 6. Site 1: SR-539 in Whatcom County, Washington (Street View)

Site 2: Borgen Boulevard in Gig Harbor, Washington

Intersection Attributes

- Five roundabout intersections in corridor
- Posted speed limit of 35 mi/h
- Dual-lane roundabouts
- Only roundabouts number 4 and 5 are considered for analysis

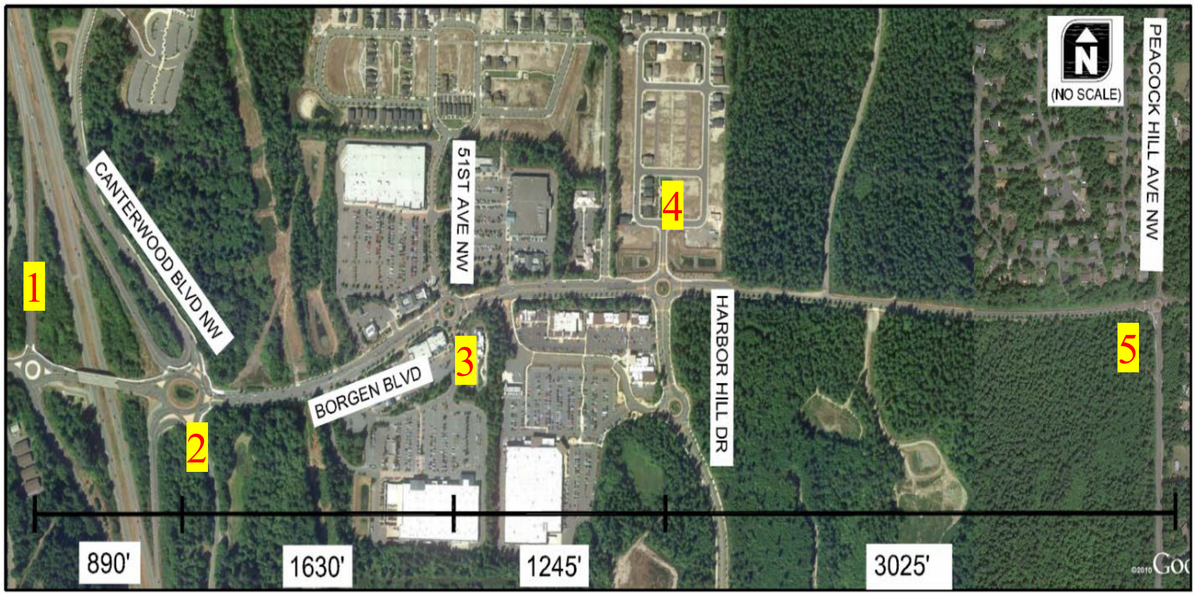


Figure 7. Site 2: Borgen Boulevard in Gig Harbor, Washington (Map View)

Figure 8. Site 2: Borgen Boulevard in Gig Harbor, Washington (Street View)

Table 12. Description of Roundabout Sites

Site No.	Road Name	# of Rbts	Arterial # of Lanes	Rbt Lanes	Rbt Diameter (ft)	Posted Speed Limit (mi/h)	Corridor Length (mi)	Area Type
1	SR 539	4	4	2	175	50	3.7	Rural / Suburban
2	Borgen Boulevard	4	4	2	175	35	1.4	Suburban
3	Golden Road	5	4	2	175	35	1.0	Suburban

*Rbt – Roundabout

Site 3: Golden Road in Golden, Colorado

Intersection Attributes:

- Five roundabout intersections in corridor
- Posted speed limit at the approach of Roundabout 4 is 25 mi/h and Roundabout 5 is 35 mi/h
- Dual-lane roundabouts
- Only roundabouts number 4 and 5 are considered for analysis

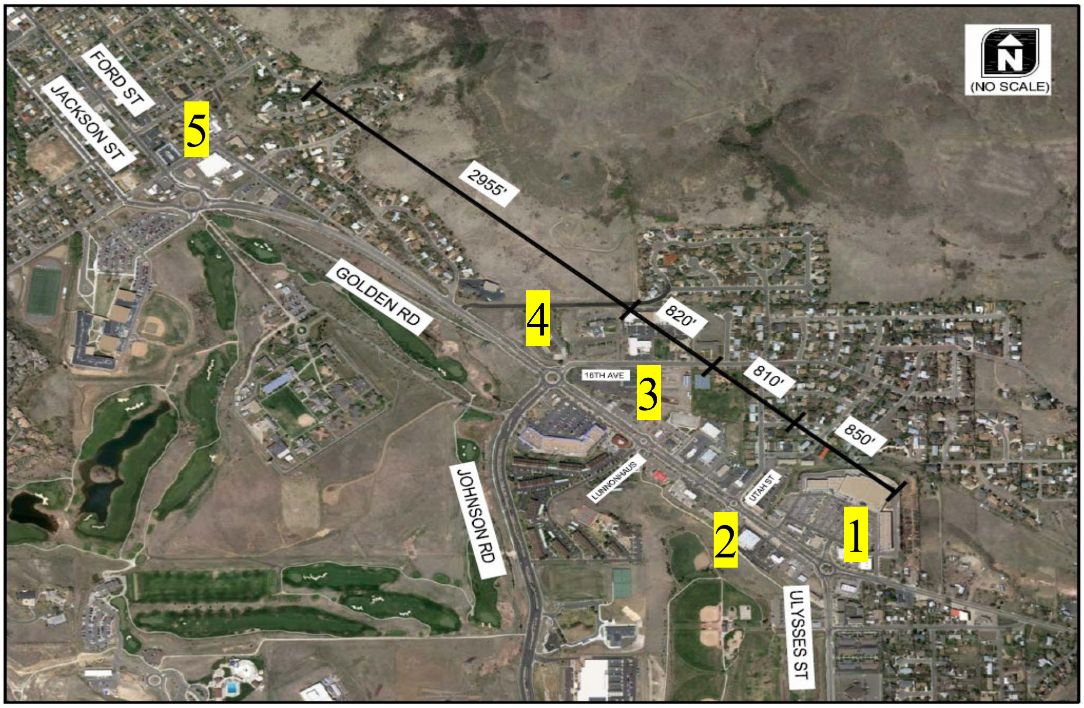
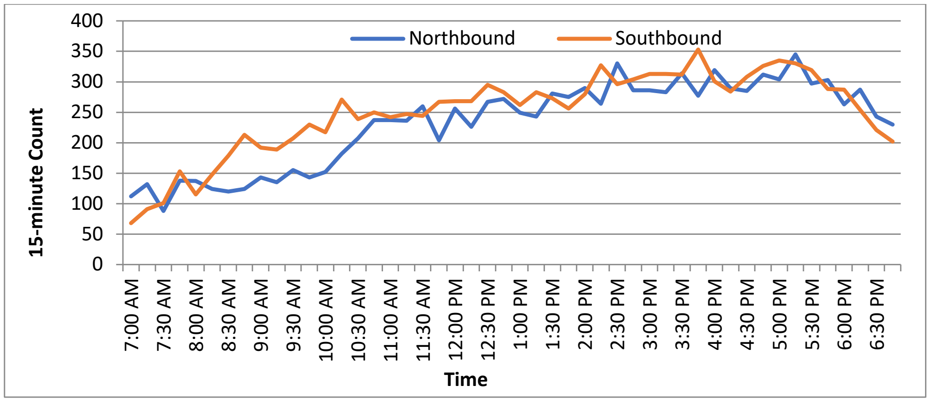
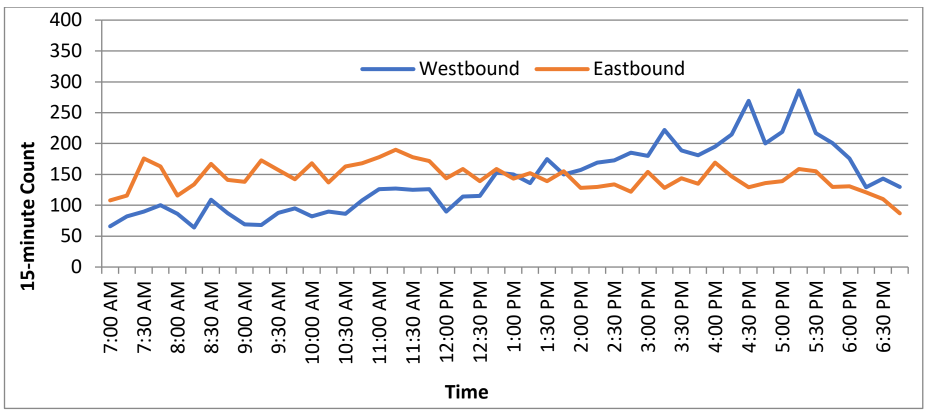


Figure 9. Site 3: Golden Road in Golden, Colorado (Map View)

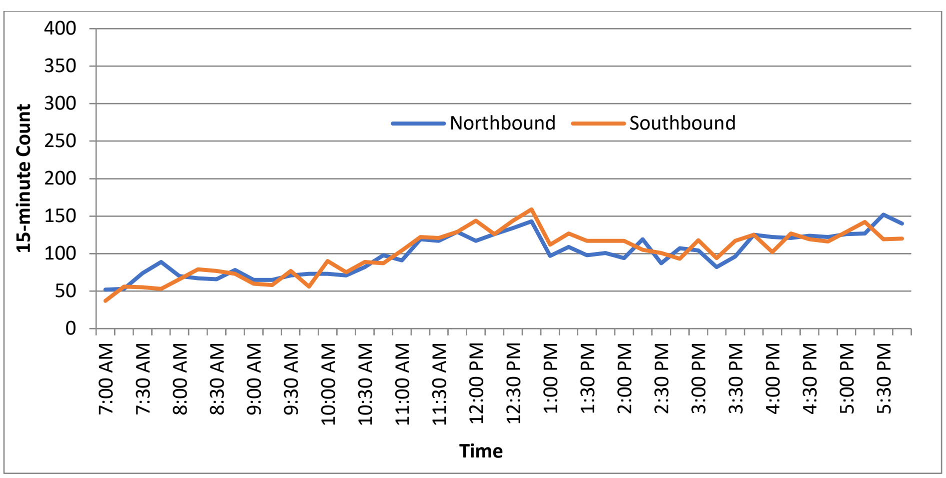
Figure 10. Site 3: Golden Road in Golden, Colorado (Street View)



(a)



(b)



(c)

Figure 11. 15-min Traffic Counts on: (a) SR 539, WA; (b) Borgen Boulevard, WA;

Study Sites and Data for Signal-Control Intersection Influence Area

This section discusses the characteristics of study sites and field data used in the analysis of the influence area at signal-control intersections. Four signal-control intersection sites were selected in Central Florida, all located in rural areas, as illustrated in **Figure 12** The names of the intersections, along with their geocoordinates [latitude/longitude] are provided below:

1. Yeehaw Junction [27.69971604, -80.90432579];
2. E. Irlo Memorial Hwy at Arthur J Gallagher Blvd [28.191844854249652, -81.15472021880018];
3. FL–520 at Maxim Pkwy [28.513960380069964, -81.06232455557888];
4. FL–46 at N. County Rd 426 [28.73337366038518, -81.11515460683309].

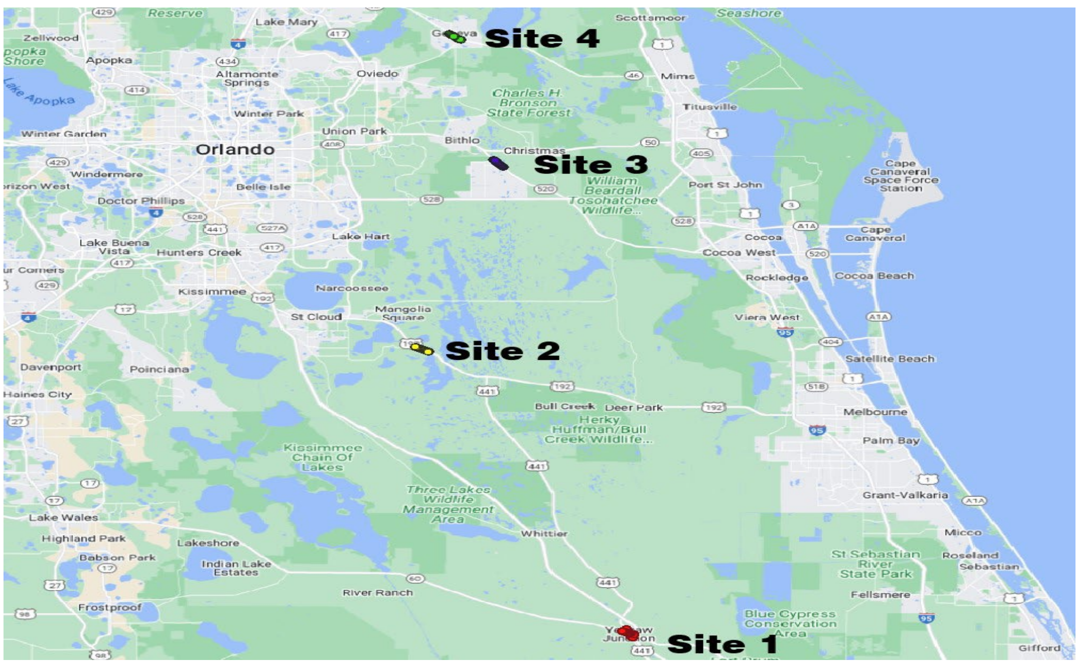


Figure 12. Signal-Control Intersection Study Sites

It is important to note that the intersection Site 1 (Yeehaw Junction) is located near an interchange for Florida's Turnpike toll road (see **Figure 13**). The distance between the intersection and the interchange is about 875 ft. A high number of heavy vehicles (constituting about 35% of the AADT) are observed crossing this intersection (using Hwy 60) to and from Florida's Turnpike toll road. This signalized intersection has one lane on each approach, with no exclusive left or right turning lanes.

<u>Site 1: Yeehaw Junction (High Truck Percentage)</u>

Intersection Attributes

- East-West – State Rd 60 (Major)
  - Speed limit 45 mi/h in the vicinity of the intersection
  - Two lane highway and no passing zone, no left/right turn bays
  - Junction for toll highway – located downstream of EB Rte-60
  - High traffic of heavy vehicles on the East-West corridor
- North-South – Hwy 441 (Minor)
  - Speed limit: 50 mi/h in the vicinity of the intersection
  - Two-lane highway, no left/right turn bays

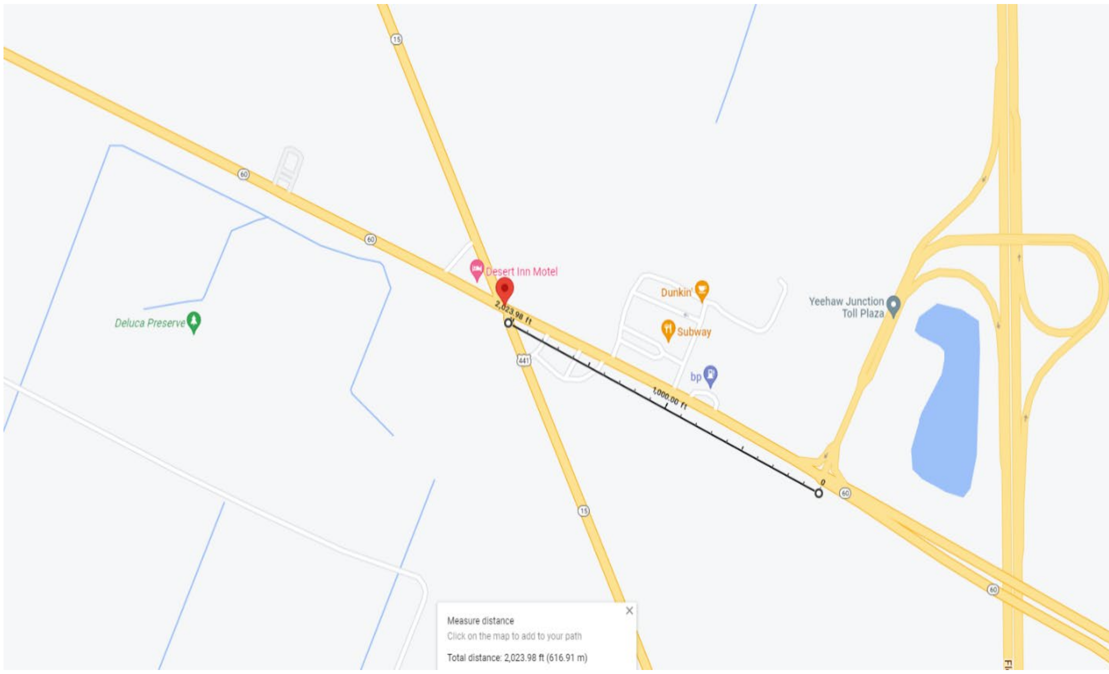


Figure 13. Site 1: Yeehaw Junction Site (Map View)

Figure 14. Site 1: Yeehaw Junction Site (State Rd 60 – East to West Corridor)

<u>Site 2: Bronson Memorial Hwy and Arthur Gallagher Blvd</u>

Intersection Attributes

- T – signalized intersection
- Major road is multilane highway
- 2 through lanes and one right turn lane for EB (also bike lane)
- Speed limit: 55 mi/h

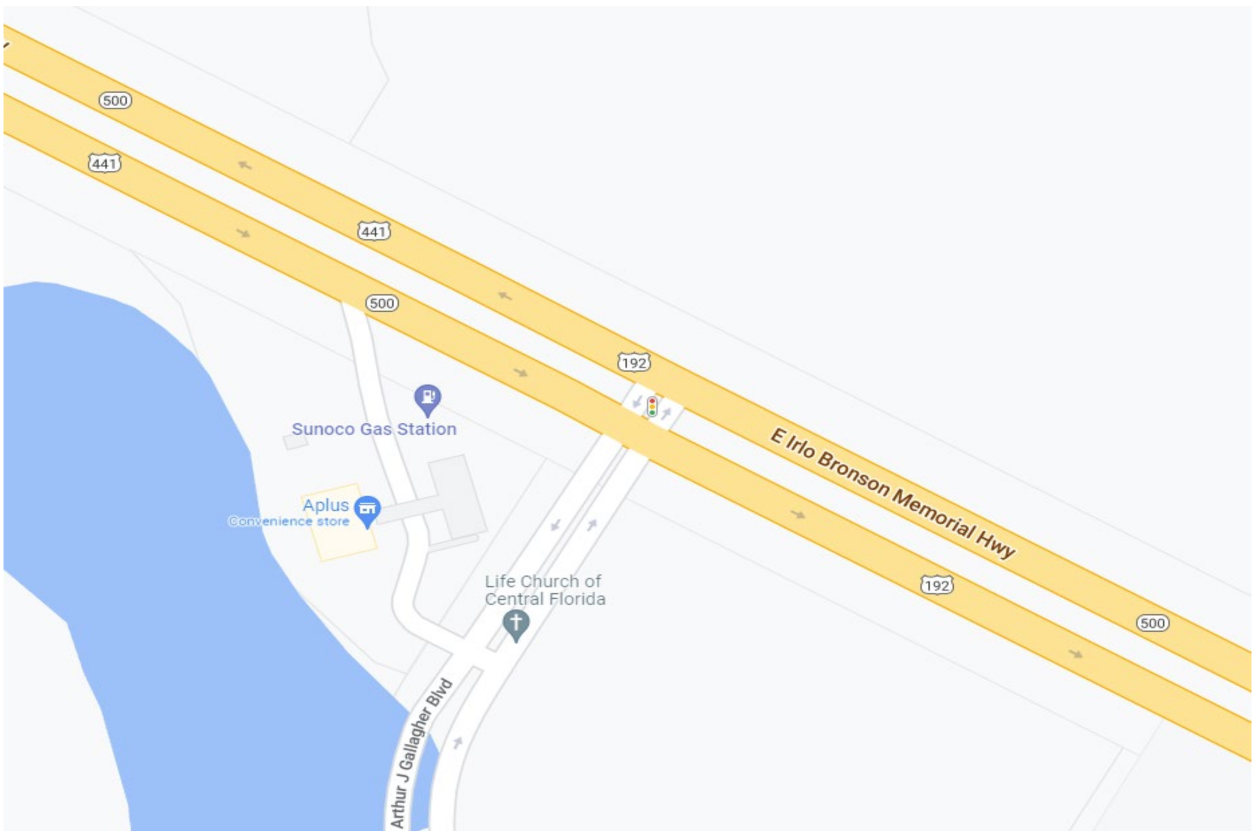


Figure 15. Site 2: Bronson Memorial Hwy and Arthur Gallagher Blvd Site (Map View)

Figure 16. Site 2: Bronson Memorial Hwy and Arthur Gallagher Blvd Site (EB – Upstream)

Site 3 SR-520 and Maxim Parkway Intersection

Intersection Attributes

- Multilane divided highway (Major)
- Signalized ‘T’ intersection
- Speed limit: 55 mi/h in the vicinity of the intersection
- 2 through lanes, U-turn lane on EB approach (see **Figure** 18)
- 2 through lanes, left-turn lane on WB approach

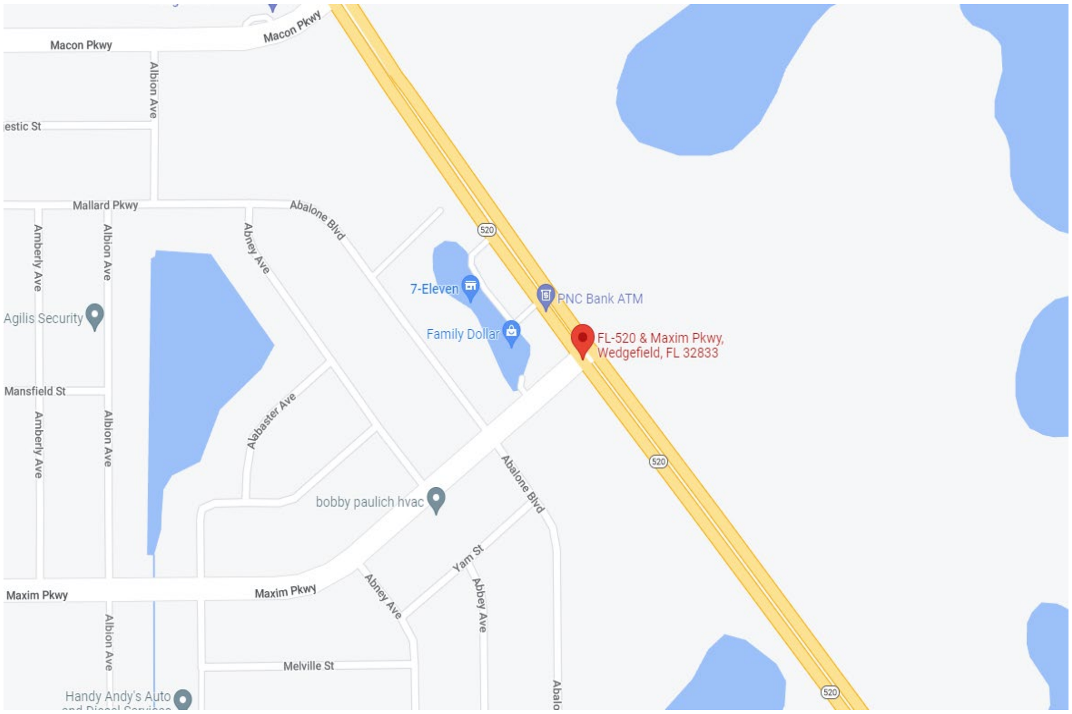


Figure 17. Site 3: SR-520 and Maxim Parkway Site (Map View)

Figure 18. Site 3: SR-520 and Maxim Parkway Site (Upstream Eastbound)

<u>Site 4 CR-426 & FL-46, Geneva, FL</u>

Intersection Attributes

- Major two-lane highway, FL-46, intersection with 1st Street (minor)
- Skewed Intersection
- Gas stations and driveways in the vicinity of the intersection
- Major street has a dedicated left turn lane and a shared though-right lane
- Speed limit on major street is 55 mi/h, reduced to 45 mi/h at 1500 ft upstream of the intersection

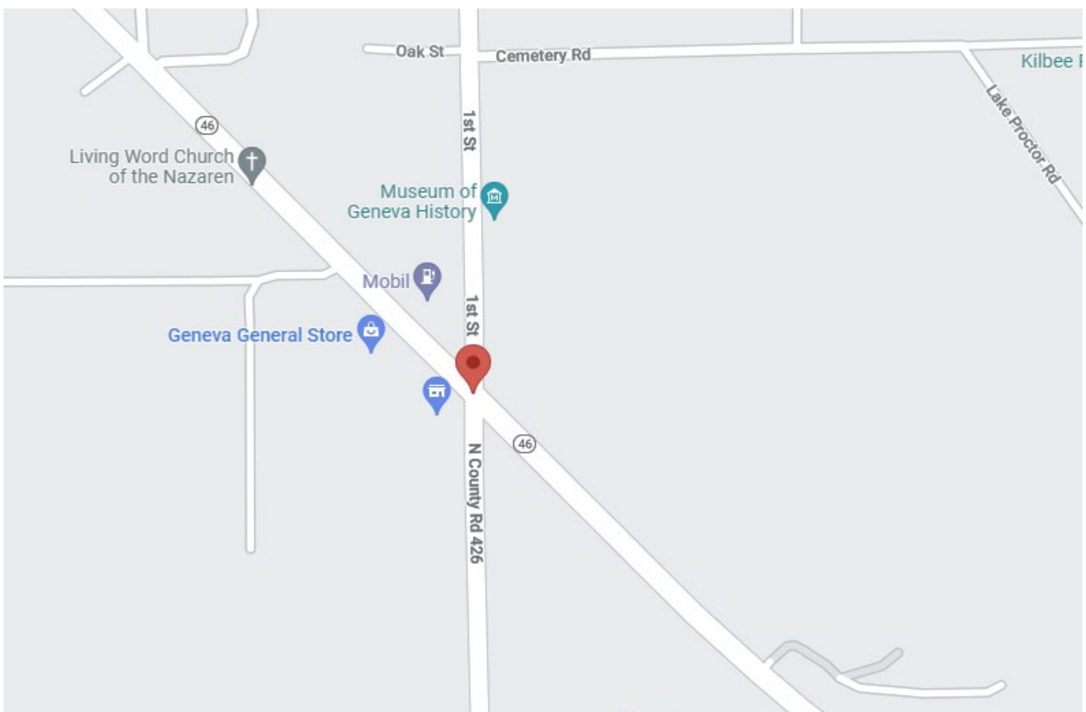


Figure 19. Site 4: FL-46 and CR-426/1st Street Site (Map View)

Figure 20. Site 4: FL-46 and CR-426 (CR-426, Northbound Direction)

The study data consists of high-fidelity GPS trajectory data collected on multiple full days at each study site. The data consisted of individual vehicle waypoints with a temporal interval of 3 seconds (frequency 1/3 Hz) and positional accuracy of a 4.90 ft (1.5-meter) radius (Saldivar-Carranza et al., 2021). Every waypoint has the following attributes:

- unique trajectory ID,
- timestamp,
- latitude/longitude,
- speed, and
- heading angle.

The upstream and downstream approaches of each intersection were geofenced for 3000 ft in each direction (total 6000 ft length in one direction) for collecting data on each site. As data were collected on both approaches of intersections, a total of eight approaches (4 sites x 2 approaches) were analyzed for upstream and downstream influence areas.

<u>Study Sites and Data for Stop-Control Intersection Influence Area</u>

To examine the influence area of stop-control intersections, seven study sites were selected on rural roadways in Central Florida. The stop-control intersections primarily consist of T-intersections with major uninterrupted highways. The locations of the seven sites are shown in

Figure 21. Intersection names along with intersection geocoordinates [latitude/longitude] are provided below.

1. Lake Pickett Rd. at N. Fort Christmas Rd. [28.59868562737476, -81.07542409814873];
2. Taylor Creek Rd. at E. Colonial Dr. [28.53655356333482, -81.01220531644309];
3. S. Fort Christmas Rd at E. Colonial Dr. [28.53683001935565, -81.01789051145427];
4. Taylor Creek Rd. at FL–520 [28.462825456163536, -80.99278804104223];
5. Deer Park Rd. at Nova Rd. [28.282567428223185, -80.92317557563702];
6. Nova Rd. at E. Irlo Bronson Memorial Hwy. [28.243980091596192, -81.22311904061856];
7. Holopaw Rd. (US-441 S) at E. Irlo Bronson Memorial Hwy. [28.144799048160237, -81.0761156732036].

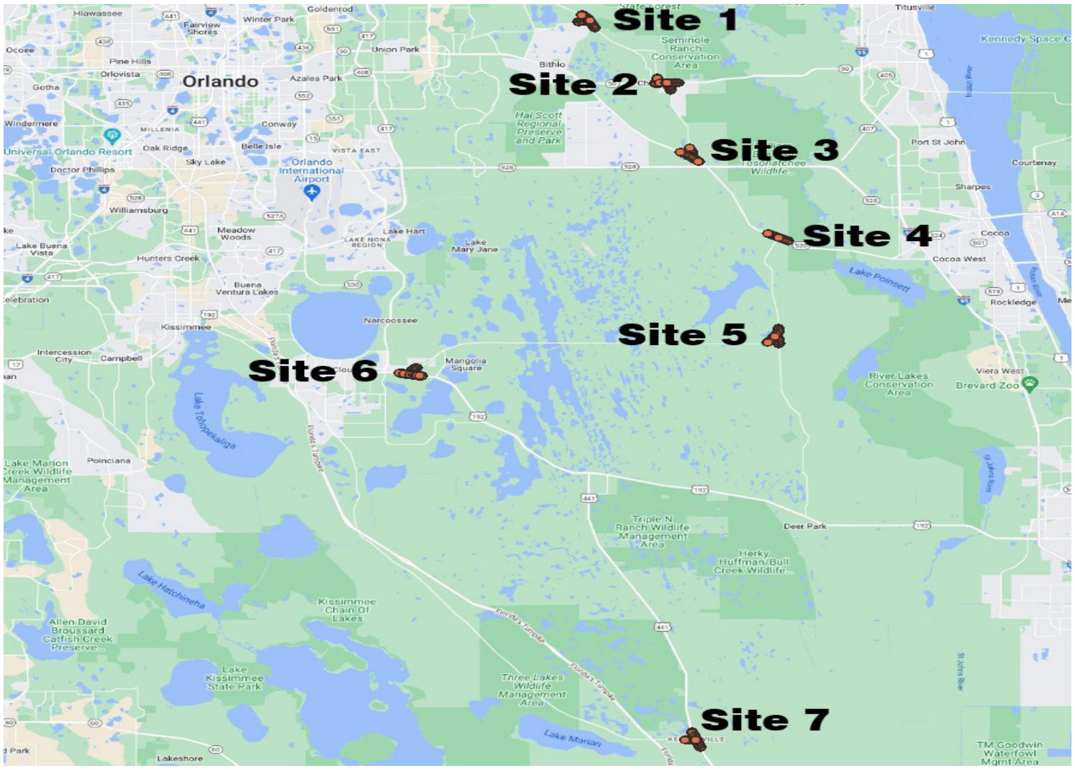


Figure 21. Stop-Control Intersection Study Sites

To assess the extent of influence area at stop-control intersections, data similar to that collected at signal-control sites were collected from the seven selected study sites. Given that stop-control intersections are of the T-intersection type, the analysis was focused exclusively on one direction (intersection approach) of travel. Moreover, the analysis of the downstream influence areas of stop-control intersections was performed by examining left-turn and right-turn movements and adjusting them for turning distance.

<u>Site 1 Lake Pickett Rd at N Fort Christmas Rd, FL</u>

Intersection Attributes

- Stop controlled T – intersection
- Dedicated left and right turn lanes
- Posted speed limit of 45 mi/h

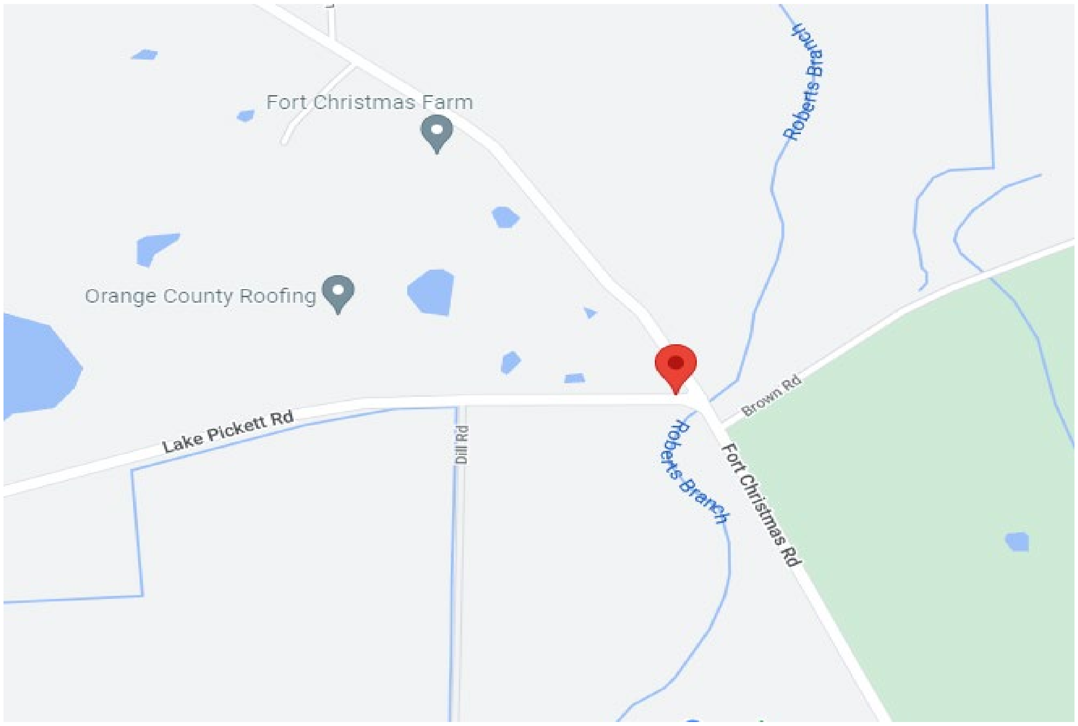


Figure 22. Lake Pickett Rd at N Fort Christmas Rd, FL (Map View)

Figure 23. Lake Pickett Rd at N Fort Christmas Rd, FL (Street View)

Site 2 Taylor Creek Rd at E Colonial Drive

Intersection Attributes

- Stop controlled T – intersection
- Posted speed limit of 35 mi/h
- Major highway is a multilane divided highway

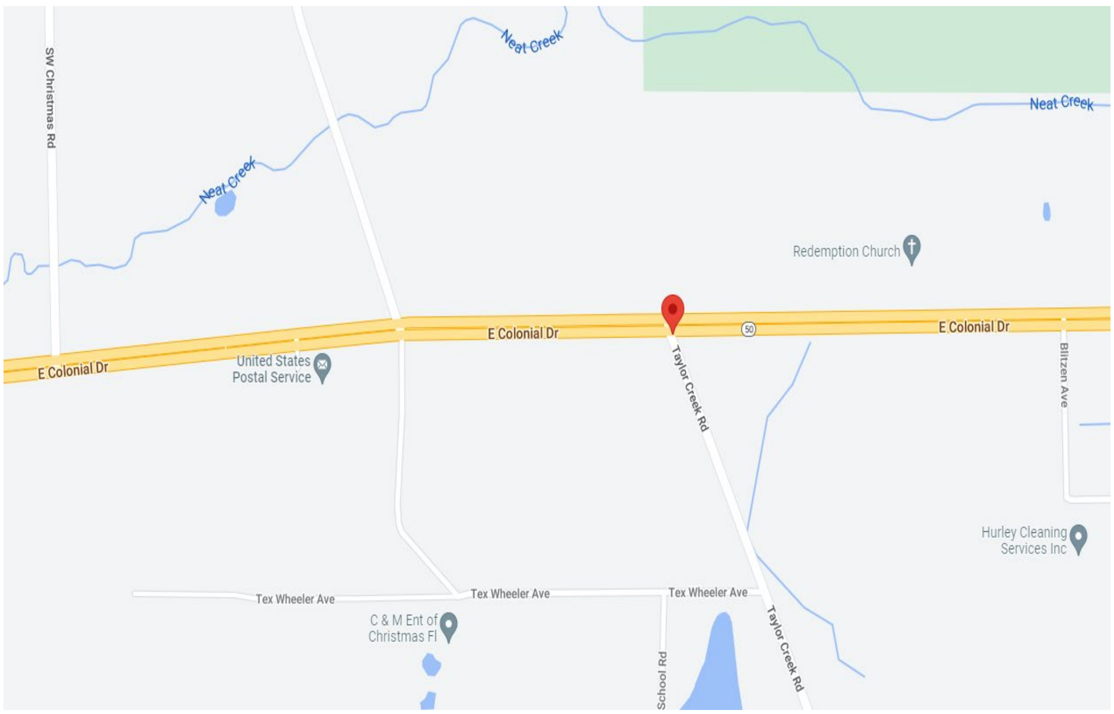


Figure 24. Taylor Creek Rd at E Colonial Drive, FL (Map View)

Figure 25. Taylor Creek Rd at E Colonial Drive, FL (Street View)

<u>Site 3 S Fort Christmas Rd at E Colonial Drive</u>

Intersection Attributes

- Stop controlled T – intersection
- Posted speed limit of 45 mi/h
- Major highway is a multilane divided highway

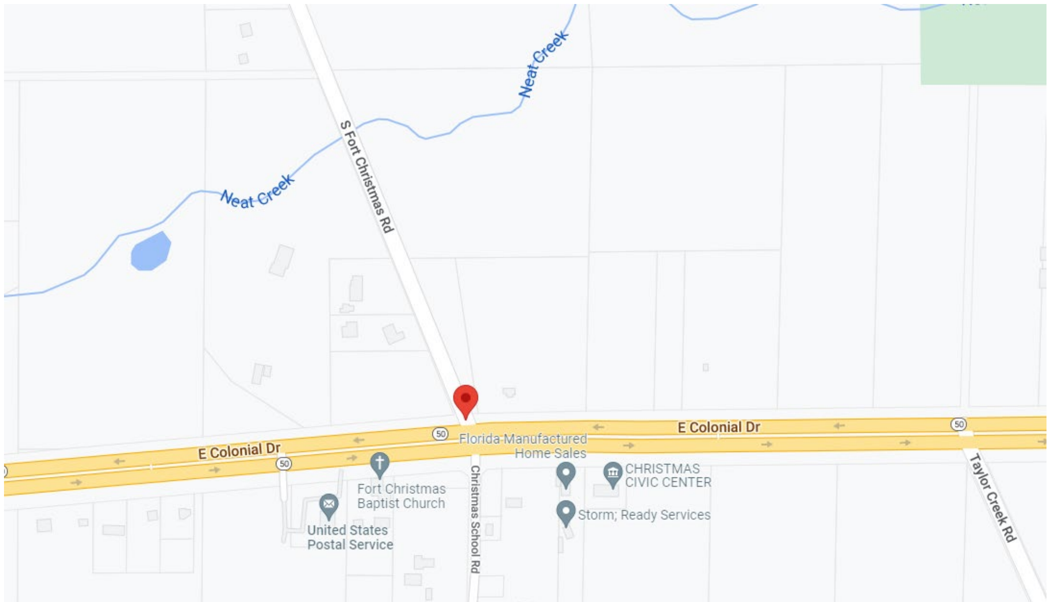


Figure 26. S Fort Christmas Rd at E Colonial Drive, FL (Map View)

Figure 27. S Fort Christmas Rd at E Colonial Drive, FL (Street View)

<u>Site 4 Taylor Creek Rd at FL–520</u>

Intersection Attributes

- Stop controlled T – intersection
- Posted speed limit of 35 mi/h
- Major highway is a multilane divided highway

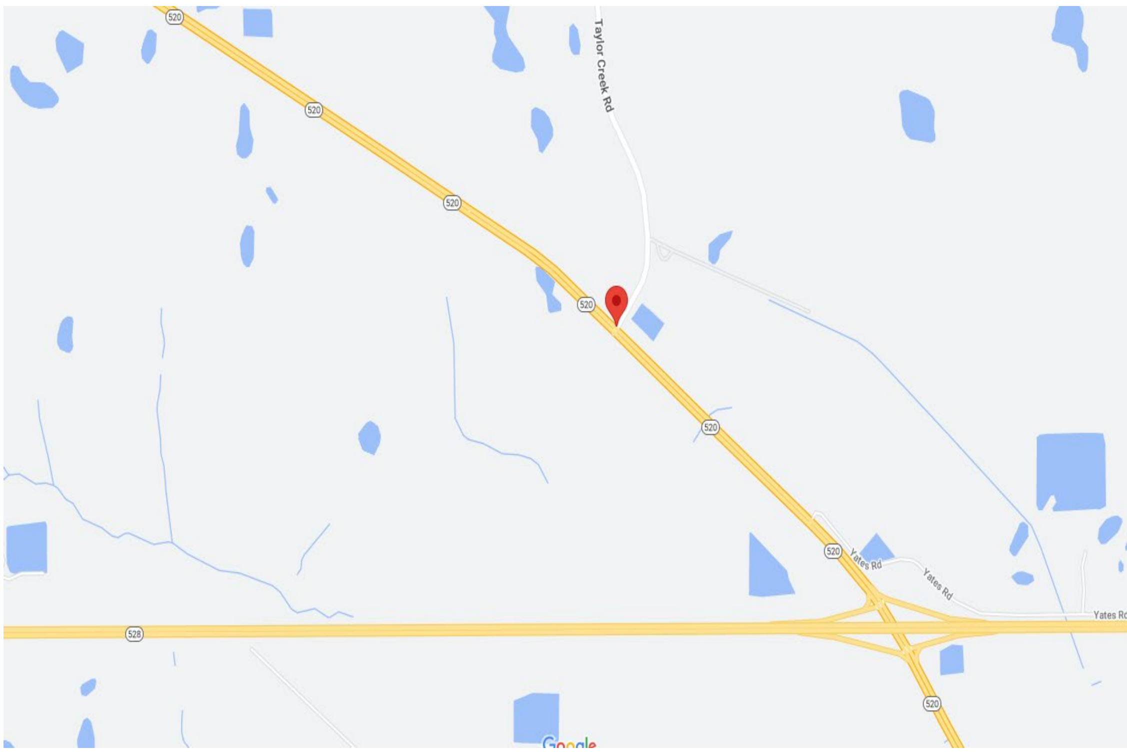


Figure 28. Taylor Creek Rd at FL-520 (Map View)

Figure 29.Taylor Creek Rd at FL-520 (Street View)

Site 5 Deer Park Rd at Nova Rd

Intersection Attributes

- Stop controlled T – intersection
- Posted speed limit of 55 mi/h
- Major highway is a two-lane undivided highway

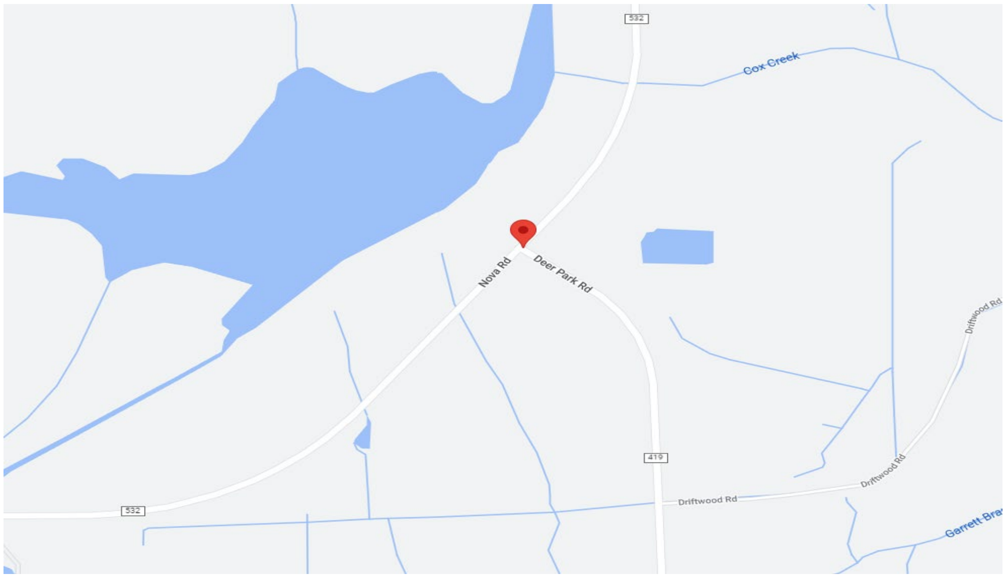


Figure 30. Deer Park Rd at Nova Rd (Map View)

Figure 31. Deer Park Rd at Nova Rd (Street View)

<u>Site 6 Nova Rd at E Irlo Bronson Memorial Hwy</u>

Intersection Attributes

- Stop controlled T – intersection

- Posted speed limit of 55 mi/h
- Major highway is a multilane divided highway
- Dedicated right turn and left turn lanes on minor

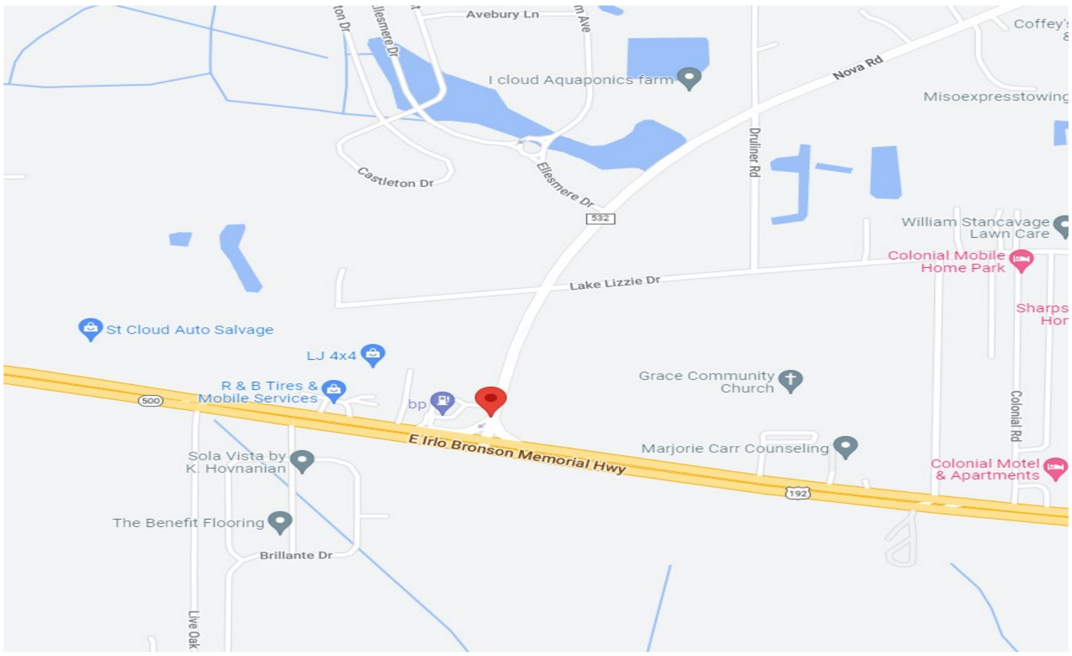


Figure 32. Nova Rd at E Irlo Bronson Memorial Hwy, FL (Map View)

Figure 33. Nova Rd at E Irlo Bronson Memorial Hwy, FL (Street View)

<u>Site 7 Holopaw Rd (US-441 S) at E Irlo Bronson Memorial Hwy</u>

Intersection Attributes

- Stop controlled T – intersection
- Posted speed limit of 55 mi/h
- Junction of two major highways (US-441 S with US-192)
- Dedicated right turn and left turn lanes on minor

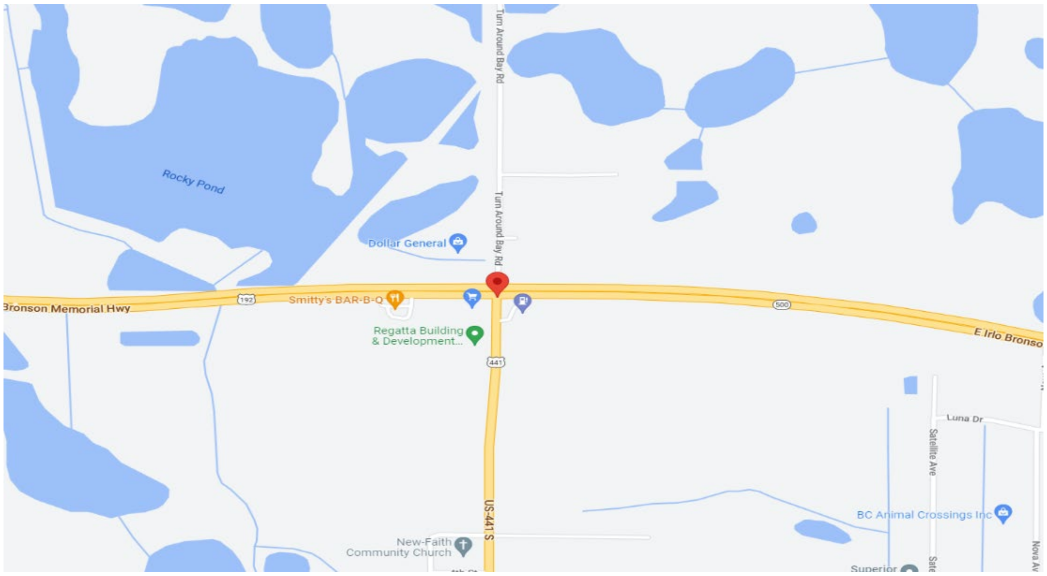


Figure 34. Holopaw Rd (US-441 S) at E Irlo Bronson Memorial Hwy, FL (Map View)

Figure 35. Holopaw Rd (US-441 S) at E Irlo Bronson Memorial Hwy, FL (Street View)

<u>Data for Case Study Corridors</u>

In order to assess the effectiveness of the proposed quality of service methodology, a study was conducted on three different rural highway corridors located in Oregon, Montana, and Tennessee. The objective was to test the proposed methodology using different real-life scenarios.

To conduct a performance analysis of the aforementioned corridors, data were acquired from the respective state departments of transportation for each of the selected rural highway corridors. The data collected included highway geometry information as well as traffic data. In addition, the location of posted speed limit changes and passing configuration (passing zone / no passing zone) of each corridor was determined using Google Map streetview services. These attributes are important in performing facility segmentation.

The specific details of each rural highway corridor studied are provided in Chapter 6 of this dissertation. Overall, the selection of rural highway corridors from different states provided a diverse sample of roadway configurations and traffic conditions to evaluate the proposed quality of service methodology.

CHAPTER FOUR

ANALYSIS AND RESULTS OF FACILITY SEGMENTATION

Overview

Facility segmentation is a critical step in a facility-level analysis framework; that is, dividing the facility in question into its basic components, which are segments and junctions (TRB, 2022; Washburn et al., 2018b). In the context of freeway facility analysis, an extended freeway length is divided into basic, weaving, merge, and diverge segments based on the influence areas of merge, diverge, or weaving operations, as outlined in HCM Chapters 12 through 14. Similarly, the urban street facility is divided into urban street segments that consist of the link and the boundary intersection (TRB, 2022).

This chapter presents the framework for facility segmentation of rural highway facilities. It also discusses the evaluation and results of empirical data analysis for intersection influence areas (roundabout, stop-control, signal-control) along rural highways. The findings of the influence area analysis provide important information about the spatial extent of the operational effect of intersections on connecting approaches and enable transportation analysts to perform facility segmentation of a rural highway facility that includes roundabouts, signal-control intersections, and/or stop-control intersections. **Figure 36** displays the organization of this chapter.

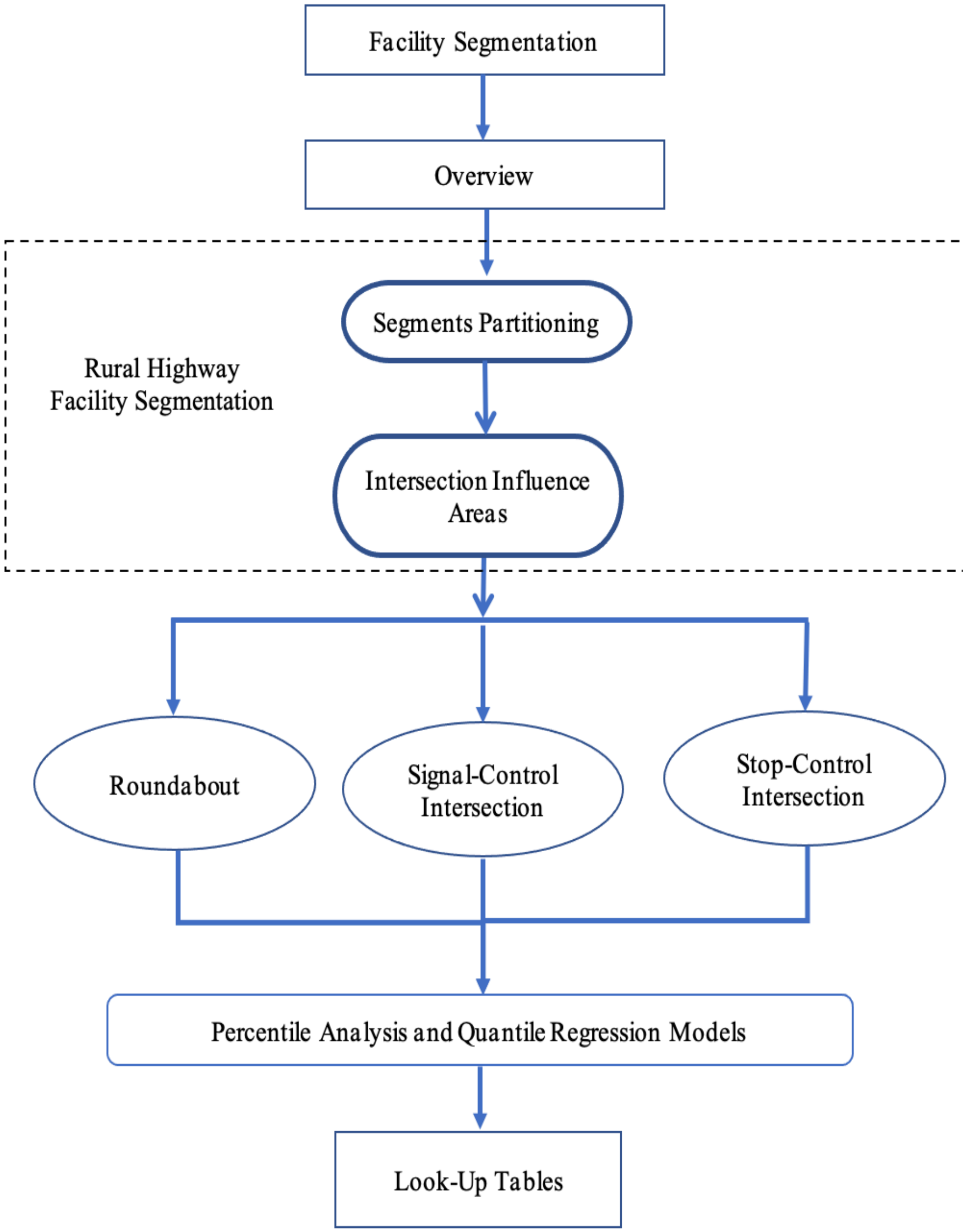


Figure 36. Flow Chart of Chapter Organization

Rural Highway Facility Segmentation

In the present study, the rural highway facility analysis entails a systematic partitioning of the facility into its constituent components, taking into account several critical factors. These factors are integral to understanding the complexity of rural highway facilities and their performance. The factors considered in this research include:

- cross-section – number of lanes
- passing configuration for two-lane highways – passing lanes, passing permitted, and passing constrained
- posted speed limit
- geometric alignment – grades and horizontal curves
- area context (rural versus rural town)
- intersections and their influence area – the distance upstream and downstream from the intersection where traffic operation is strongly influenced by intersection control (signal, stop, or roundabout)

Cross Section

In the context of rural highway facility analysis, the segmentation process for various segment types is relatively straightforward. For example, the start (or end) of passing lane sections or multilane highway sections roughly coincide with the location of lane addition (or lane drop). As a result, it is proposed to introduce a new segment.

Passing Configuration on Two-Lane Highways

The pavement centerline markings are used to delineate passing restricted sections and passing zones. Such pavement markings may also be accompanied by ‘DO NOT PASS’ and/or ‘NO PASSING ZONE’ signage. These signs are designated in the Manual on Uniform Traffic Control Devices (Federal Highway Administration. (FHWA)., 2009) as ‘R4-1’ and ‘W14-3’, respectively.

Posted Speed Limit Changes

In the process of facility segmentation for rural highway analysis, it is generally expected that a segment maintains a consistent posted speed limit (PSL) throughout its entire length. When a change in the PSL occurs, it is recommended to create a new segment to account for the variation in operational characteristics associated with the PSL.

However, in instances where the length of the roadway segment with a specific PSL is considerably short, it may be deemed appropriate to incorporate this segment of the roadway within an adjacent segment. This approach can reduce the number of segments to make the analysis process efficient.

Geometric Alignment Considerations

Vertical and horizontal alignment along a rural highway route can be quite variable and introducing a new segment for each change in grade and/or horizontal curvature will likely result in a large number of segments for a route of 20 miles or more. For this analysis methodology, it is proposed to only introduce a new segment for geometry that will likely result in significant speed reductions for heavy vehicles. Consequently, the following segmentation guidelines with respect to geometric alignment are proposed to account for such speed impacts on heavy vehicles:

- Two-lane highway segments
  - Only consider vertical curves that are class 2 or higher (per the HCM two-lane highway methodology)
  - Combine contiguous segments with the same vertical alignment classification
  - Only consider horizontal curves that are class 3 or higher (per the HCM two-lane highway methodology)
  - Combine contiguous segments with the same horizontal alignment classification
- Multilane highway segments
  - Current 'level' and 'rolling' terrain guidelines in HCM will apply; for steeper/longer grades, only the specific grade approach will be applied—the 'mixed flow' model will not be applied because of its complexity; when there are consecutive grades that should be analyzed with the specific grade approach, the following guidance applies: if the individual grades are less than or equal to 0.5 miles, they are combined into a single segment and the highest grade percentage is applied over the entire length. If a grade is longer than 0.5 miles, it is treated as an individual segment.

<u>Area Context (Rural Versus Rural Town)</u>

Rural highways often include short lengths of roadway (up to a few miles) that pass through one or more small rural towns along the route. The first question to answer is whether such a stretch of roadway should be included in the rural highway facility analysis or not. In making this determination, the first consideration is to assess the context classification of the developed area that connects to a rural highway, per AASHTO's A Policy on Geometric Design of Highways and

Streets (American Association of State Highway and Transportation Officials (AASHTO), 2018), hereafter referred to as the “Green Book”.

The Green Book provides the following context classifications (from Section 1.5: Context Classification for Geometric Design):

- Rural
- Rural Town
- Suburban
- Urban
- Urban Core

Regarding the definitions for these context classifications, the Green Book states:

These contexts are defined based on development density (existence of structures and structure types), land uses (primarily residential, commercial, industrial, and/or agricultural), and building setbacks (distance of structures to adjacent roadways). These five contexts were initially presented in NCHRP Report 855, An Expanded Functional Classification System for Highways and Streets (Stamatiadis et al., 2018), which has prepared a guide for classifying contexts and applying the context classes in design.

In terms of considering whether to include a stretch of roadway through a town as part of the rural highway facility, only roadways that would be classified as ‘rural town’ should be included. Roadways that fit in the suburban, urban, or urban core context should be excluded from the rural highway facility analysis methodology. In rural town areas, the highway passing through the town is generally the only major roadway in the town and a large percentage of traffic on this specific roadway is pass-through traffic. While the above discussion from the Green Book emphasizes a qualitative-based determination of the context, it should be noted that highways that fit within the rural town context are usually in towns with a population of 5000 or less. This population value is the threshold used in the FHWA classification for an urban versus a rural area.

If the stretch of roadway through a developed area is consistent with the rural town context, and therefore should be included in the rural highway facility analysis, then the next step is to determine which analysis methodology, or methodologies, to apply to the stretch of roadway through the town. For example, if the posted speed limit does not exceed 45 mph and one or more of the following conditions/attributes exist:

- Presence of roadside curbs
- Presence of sidewalks
- Availability of a two-way left-turn lane
- One or more intersections per mile (Stop controlled/Signalized/Roundabout) and posted speed limit changes within 1 mile upstream and 1 mile downstream of the intersection
- Driveway density is more than 5 per mile in travel direction
- Presence of pedestrian signals or crosswalks
- Reduction of the speed limit and increase of speed limit within two miles of distance
- Gateway or Welcome signboard to town

Then these characteristics of the roadway may make it most suitable for analysis with the 'Urban Street Facilities' analysis methodology (HCM Chapter 16). Otherwise, it may be more appropriate to treat the roadway section as a combination of uninterrupted flow segments (multilane or two-lane highway) and isolated intersections (with influence areas). In some situations, however, the roadway characteristics may be similar to basic two-lane or multilane highway segments, but with low posted speed limits through the urbanized area (e.g., a small town). In these situations, it may be reasonable to apply the two-lane or multilane highway analysis methodology rather than the Urban Street Facilities analysis methodology.

Intersections Influence Area

On interrupted flow facilities such as urban street networks and non-freeway rural facilities, the need to slow down or stop at intersections has its impacts on the traffic stream operational characteristics. In practice, intersections are represented as point locations in a link-node network configuration, however, its operational effects extend for some distance on the connecting incoming and outgoing approaches, thus affecting the operational performance of highway segments in the proximity to intersections. For instance, the presence of a signal-control intersection may significantly affect two-lane highway operations. Vehicles approaching a signal-control intersection start to decelerate and prepare to stop if facing a red indication, or decelerate to follow a discharging queue during the early part of green time, thus triggering interrupting traffic flow. In situations in which a left-turn bay is not present on the intersection approach, mainline traffic may also be affected by turning vehicles, even during the green time. Therefore, knowing the locations at which such effects on mainline traffic become significant is essential. The distance between this critical location and the intersection approach stop/yield bar is defined as the upstream influence area. Similarly, the presence of an intersection may also change the traffic flow characteristics on the downstream highway segment. Generally, traffic flow returns to its former state (i.e., non-signal influenced state) after some distance downstream of the signal. The location at which traffic flow returns to a non-signal influenced state and attain the segment operating speed is identified as the end point of the downstream influence area. The start and end points of the influence area delineate segment boundaries; thus, the intersection essentially becomes a segment, with the upstream/downstream influence areas a function of the traffic and intersection-control characteristics. **Figure 37** illustrates the approach to roundabout influence areas definition.

Proper segmentation of rural highway facilities will improve the accuracy of analysis by applying the component analysis methods over the appropriate spatial boundaries. In the following sections, an in-depth examination and results of the trajectory data pertaining to intersection influence areas are provided.

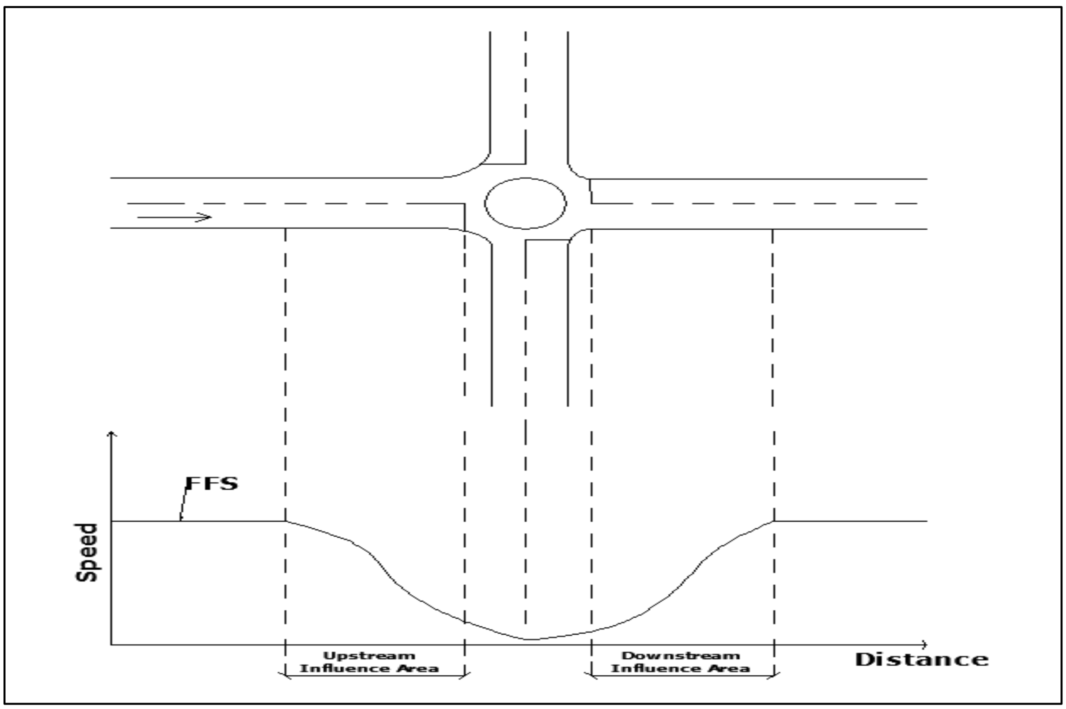


Figure 37. Roundabout Influence Area Definitions

Roundabout Influence Area

This section focuses on the assessment of speed profiles of test-vehicles traversing roundabout intersections in order to determine upstream and downstream influence areas. Such guidance is invaluable for the operational analysis of rural highways that include roundabout intersections.

To achieve this, trajectory data, comprising variables such as anonymized vehicle ID, vehicle location (latitude, longitude), timestamp (including date), speed, and heading (bearing angle) at 1-second intervals, were utilized for determining the upstream and downstream influence areas for roundabout intersections.

Data Processing for Roundabout Influence Area

In order to analyze trajectory data for the influence area, the initial step involved cleaning and processing the raw data for errors and anomalies. This was accomplished using QGIS software (8) and a program developed in Matlab (7) to clean the data by removing waypoints located outside the roadway. The output of the cleaned data using QGIS is presented in **Figure 38**.

Subsequently, the coordinates of the raw data were transformed from latitude and longitude to Universal Transverse Mercator (UTM) coordinate system to obtain X-Y location coordinates in meters, which were required for distance computation. The next step was to separate the raw mixed data into individual trajectories based on a unique identifier (ID). The data were then separated into directional trajectories based on the heading (bearing) angle at each study site. For instance, the roadway of Site I runs north–south direction. A bearing angle of waypoints between 90° and 270° depicts the southbound traveling direction while a bearing angle less than 90° or greater than 270° indicates the northbound traveling direction. The data processing steps are illustrated in **Figure** 39.

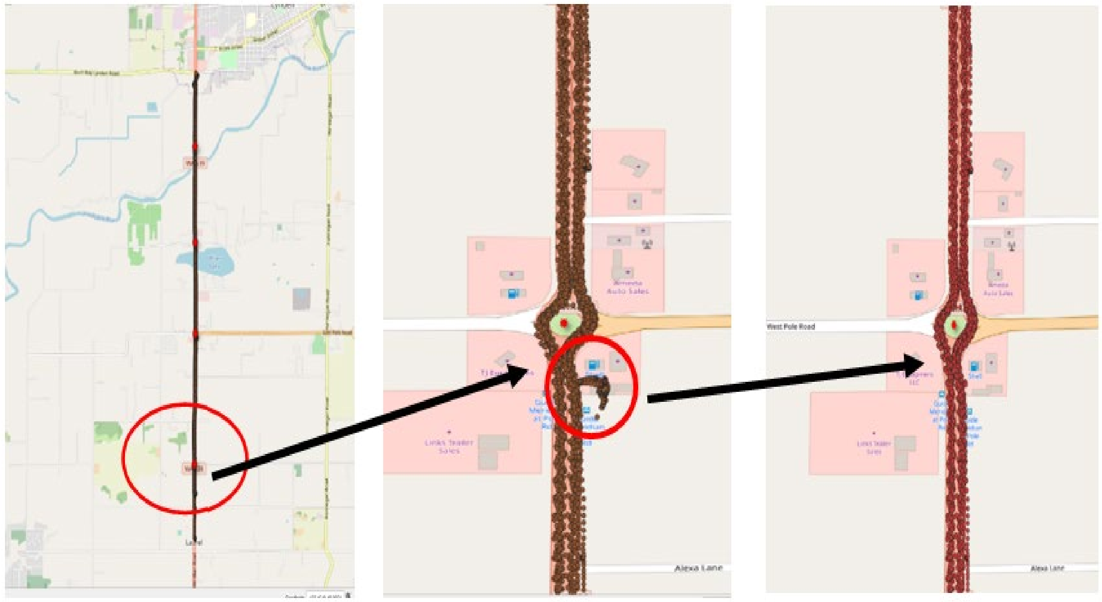


Figure 38. Cleaning Roundabout Trajectories Data using QGIS Software

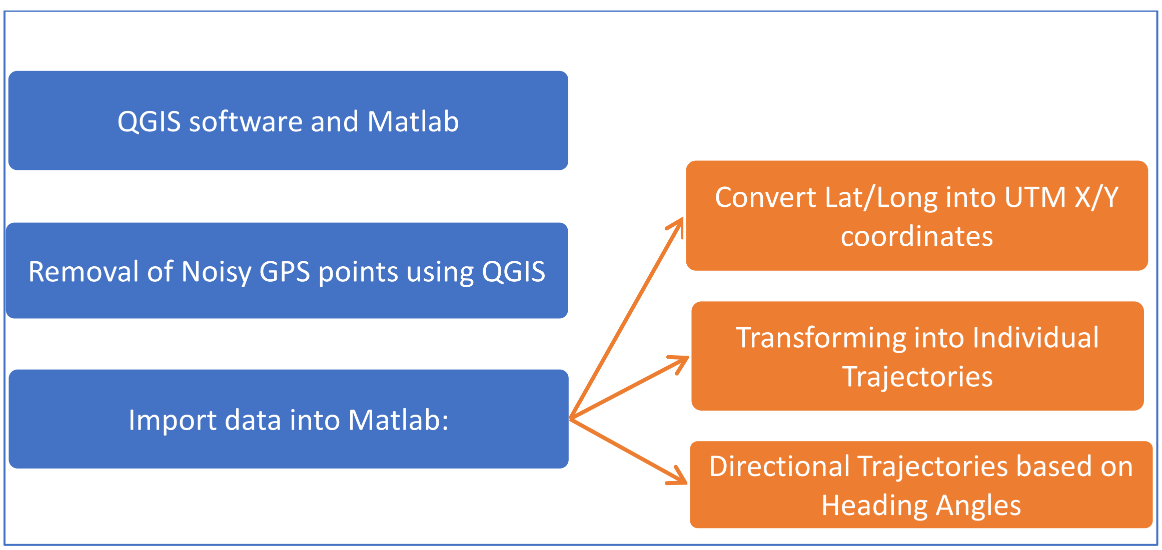


Figure 39. Steps in Pre-Processing of Trajectories Data

More than 100 test vehicle runs were conducted at each study site, and a few runs influenced by unknown factors between two consecutive roundabouts were excluded from analysis as their speeds were much lower than the speed limit or the average operating speed. The total number of upstream and downstream approaches used in the analysis is summarized in **Table 13**. A single approach refers to the event where the test vehicle traverses either the upstream or the downstream influence area of a single roundabout.

Table 13. Summary of Test-Runs at Study Sites

Site No.	Road Name	# Rbts	Total Test-Runs	# of Test Segments	Selected Upstream Approaches	Selected Downstream Approaches
I	SR 539	4	104	4	410	410
II	Borgen Boulevard	4	102	1	96	96
III	Golden Road	5	150	1	140	143

As it is uncommon (if not impractical) to use cruise control along study corridors of multiple roundabouts, small fluctuations in speed between acceleration and deceleration cycles (outside influence areas) are expected. There are several filtering and smoothing techniques, such as the Kalman filtering technique, Savitzky Gloay filtering method, moving average method, and many more to deal with such fluctuations and eliminate errors. It was decided to use the three-point centered moving average technique to smoothen the speed profile for each trajectory as the data were highly accurate and the fluctuation in speed was minimal. Using this technique, the average speed of a vehicle at time t is calculated as the average speed for time t-1, t, and t+1 using one-second time increments. A sample speed profile of a trajectory at Site – I is shown in **Figure** 40.

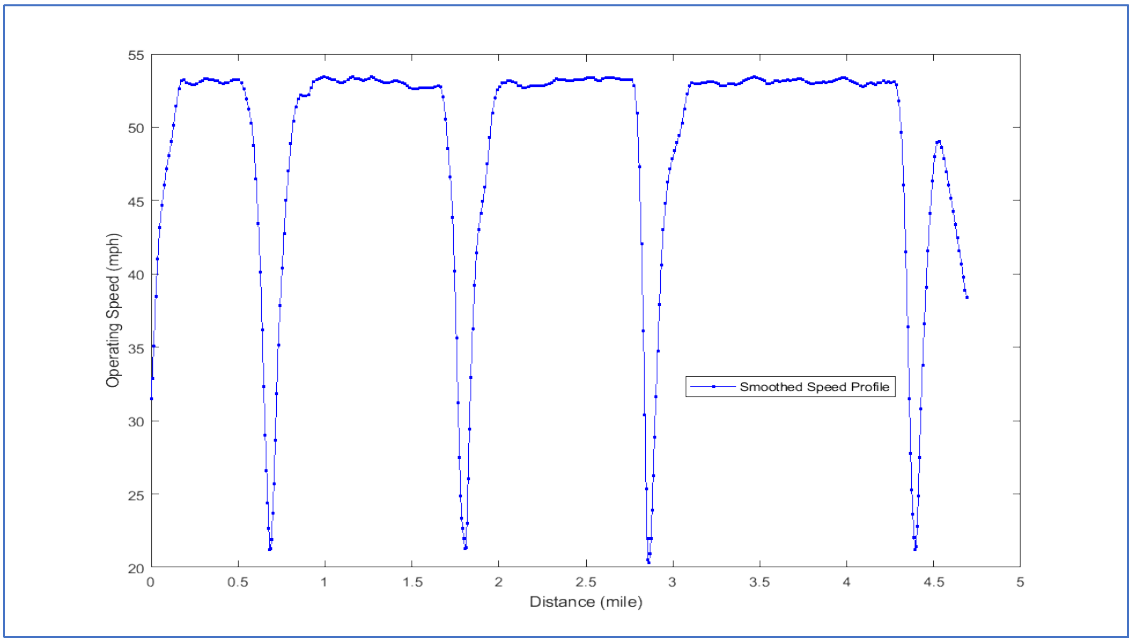


Figure 40. Sample Speed Profile of a Single Trajectory at Study Site I

After cleaning raw data for anomalies, trajectory data were filtered for missing data and considered only complete trajectories of through-traffic for further detailed analysis. The data are filtered based on various attributes as summarized in **Figure 41**.

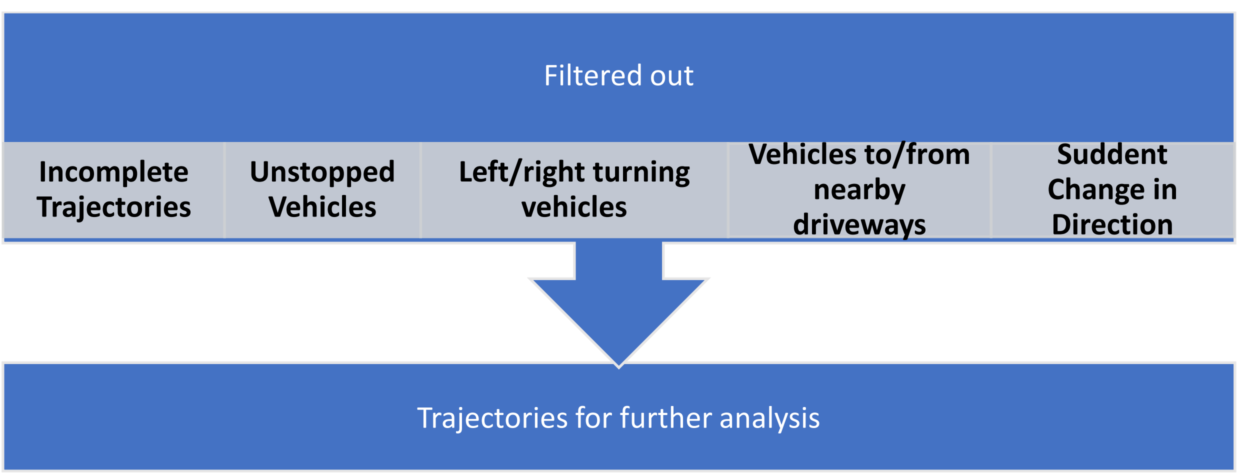


Figure 41. Filtering of Trajectory Data

Roundabout Influence Area Determination

Once the GPS trajectory data conversion and processing were carried out, a heuristic algorithm was developed to identify the start and end of the upstream and downstream influence areas of the roundabout and determine the lengths of the influence areas as discussed in the following 7 steps.

i. Determine a point on the trajectory path near the mid-point of roundabout p_i, and select 25-s upstream (p_{i-25}) and 30-s downstream of the mid-point (p_{i+30}).

ii. For upstream influence area and deceleration rate, examine the speed profile and determine the point from which the speed drops at least 0.5 mi/h/s ($a \leq -0.805$ km/h/s) for a minimum of seven consecutive seconds. Once that point is determined, the distance between the point and the yield line at the roundabout is calculated. The threshold of a minimum of 7 consecutive seconds was selected to include all speed profiles in the analysis, even those with abrupt braking behavior.

iii. For the downstream influence area, the speed profile is examined for 30 seconds after the minimum speed location (i.e., minimum speed was typically at the center of the roundabout for through movements). The end of the acceleration or downstream influence area is identified when the speed increase for two consecutive points becomes less than 0.5 mi/h/s ($a<0.805$ km/h/s). Step-i to step-iii to determine the influence area is illustrated in **Figure 42**.

iv. The location of the minimum speed is either at the yield-line (for yielded or stopped vehicles) or approximately at the center of the roundabout for through movements.

As the traffic flow was very low, about 98% of vehicles were traversing the roundabouts without stopping at the yield line.

v. If the minimum speed (V_{min}) is less than 5 mi/h (8 km/h), it is considered as a "yielded/stopped vehicle" at the yield-line and the influence area is the distance between the starting point of deceleration determined in *step-ii* and the location of minimum speed (V_{min}). However, if the minimum speed V_{min} is greater than 5 mi/h (8 km/h), then the upstream influence area is the distance between the starting point of deceleration determined in *step-ii* and the location of minimum speed (V_{min}) minus half of the diameter of the roundabout. It was observed that speeds within the roundabout for vehicles not stopping at the yield line were on the order of 15 to 18 mi/h (24 to 29 km/h) (see **Figure 42)**

vi. For the downstream influence area, if the vehicle is yielded/stopped at the yield-line, then the downstream influence area is the distance between the location of minimum speed (V_{min}) and the endpoint determined in *step-iii* minus the full diameter of the roundabout. However, if the vehicle is not yielded/stopped at yield-line, then the downstream influence area is the distance between the location of minimum speed (V_{min}) and the endpoint determined in step-iii minus half the diameter of the roundabout.

vii. The upstream deceleration time is the time in seconds from the start of deceleration determined in *step-ii* until the vehicle reaches the minimum speed approaching the roundabout. Similarly, the downstream acceleration time is the time in seconds from the minimum speed until the end of acceleration determined in *step-iii.*

After identifying the upstream and downstream influence areas and deceleration and acceleration times, a detailed analysis was conducted separately for each site. The influence area data were examined for outliers based on Tukey's interquartile range (IQR) technique (Tukey, 1977). The IQR method is less sensitive to extreme values and is robust against any deviation from a normal distribution of data because it uses quartiles that are resistant to extreme values – hence can be applied to both normal and skewed distributions efficiently (Seo, 2006). According to the IQR rule, any value that falls below the 25th percentile minus 1.5xIQR or above the 75th percentile plus 1.5xIQR is considered an outlier. Using this rule at the three study sites, the numbers of outliers detected in the upstream data were 17, 0, and 1, whereas the numbers of outliers in the downstream data were 4, 0, and 2. Unless specified, the discussions in the following sections all refer to the data upon excluding outliers.

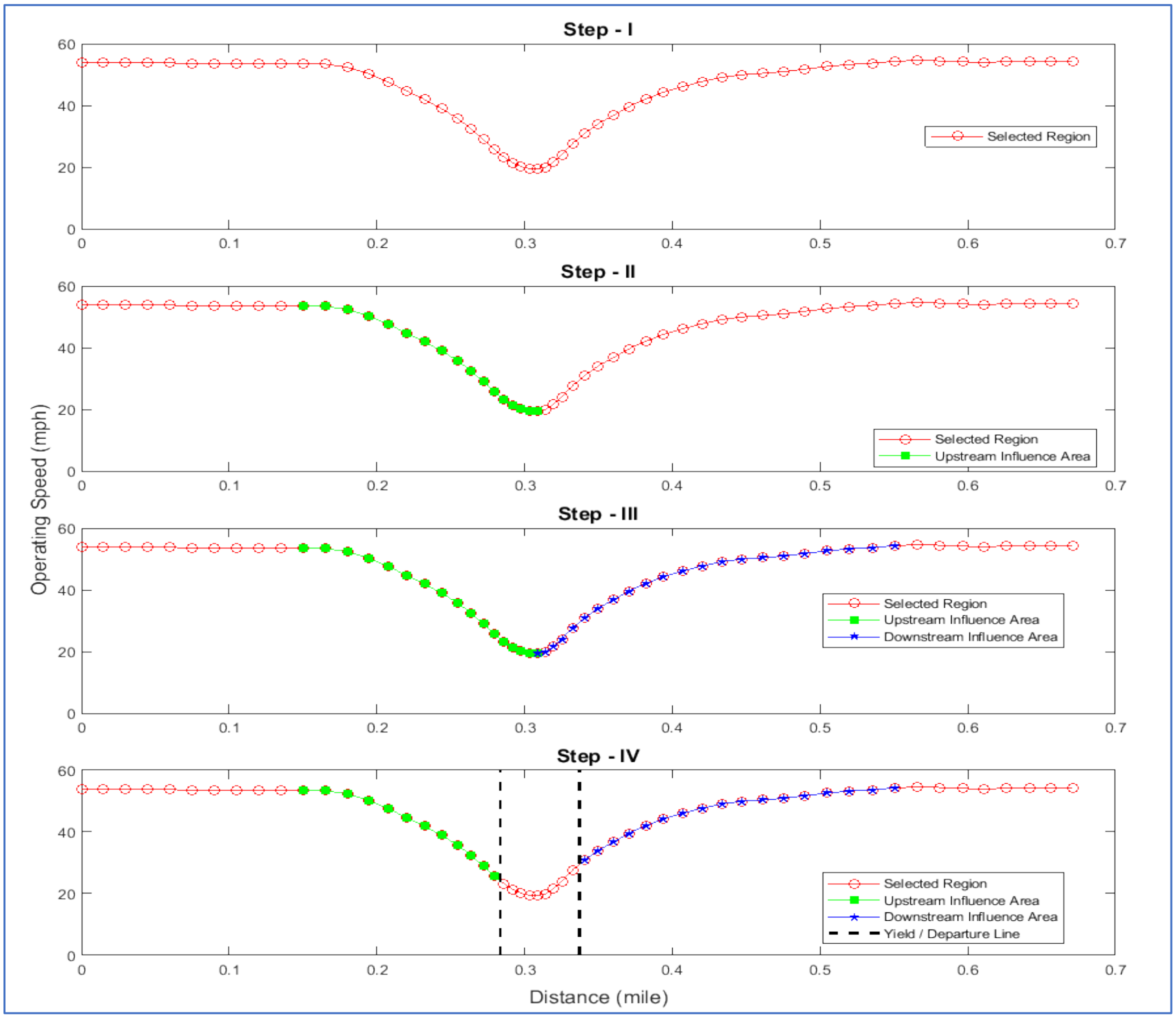


Figure 42. Upstream and Downstream Influence Area of Roundabout

Results of Roundabout Influence Area

This section discusses the results of the roundabout influence area at the three study sites. The descriptive statistics of influence area and deceleration/acceleration time are presented in **Table 14**. Site – I (SR – 539) is the longest roundabout corridor among the three selected sites in this study. After screening the data for midblock-impeded and/or stopped vehicles, 410 appropriate approaches for each upstream and downstream were obtained (a total of 820 approaches combined).

For Site I (SR – 539), the results indicate that the average distance the driver started decelerating was approximately 627 ft upstream of the “Yield” line at the roundabout. In addition, the results also show that drivers took an average of 15.5 seconds to decelerate from the desired operating speed along the upstream segment to the speed at which the car yielded at the “Yield” line or traversed through the roundabout at the lower roundabout circulating speed. For the downstream influence area, the results indicate that it took a driver an average distance of 874 ft and an average duration of 18.5 seconds to accelerate downstream of the roundabout and return to the desired operating speed under prevailing conditions (as shown in **Table 14**). This confirms that the downstream influence area is notably longer than the upstream influence area (by an average of 247 ft). Consistent with this finding, the average acceleration time (18.5 s) is longer than the average deceleration time (15.5 s) by an average of 3 seconds. This implies that the deceleration rate upstream of the roundabout is higher than the acceleration rate downstream of a roundabout even when the vehicle is not impeded.

The length of the Site II (Borgen Blvd.) corridor is much shorter than the SR-539 corridor and has only one test segment, i.e., only one upstream approach and one downstream approach in each direction of travel. The results of the upstream influence area indicate that the drivers start decelerating at an average distance of 532 ft upstream of the “Yield” line of the roundabout. In addition, the results suggest that the drivers took an average of 15.6 s to decelerate from the operating speed to the speed at which they could yield at the “Yield” line or traverse through the roundabout at the circulating speed as shown in **Table 14**. The results of the downstream influence area show that the drivers took an average of 15.8 seconds to accelerate downstream of the roundabout and traversed an average distance of 446 ft before returning to the desired speed under prevailing conditions. The length of the upstream and downstream influence areas and their associated deceleration and acceleration times are all lower than their counterparts at Site I. This can largely be attributed to the lower posted speed limit of 35 mi/h (compared to 50 mi/h at Site I).

Table 14. Roundabout Influence Area Descriptive Statistics

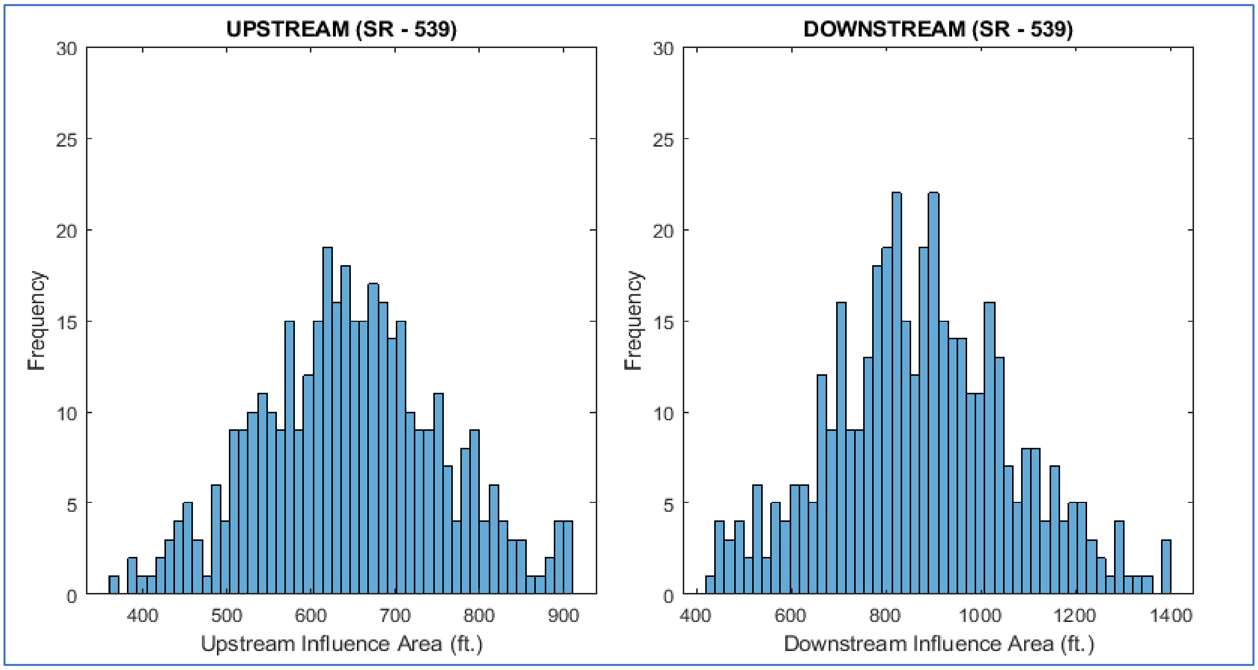
Site I – SR 539				
	Influence Area (ft)		**Deceleration/Acceleration Time (s)**	
Attributes	**Upstream**	**Downstream**	**Upstream**	**Downstream**
Sample Size	393	406	403	404
Min.	362.98	427.39	10	12
Max.	907.40	1396.10	21	27
Mean	627.35	873.86	15.27	18.58
Standard Deviation	102.57	192.55	2.13	3.20
85^{th} Percentile	729.50	1068.80	18	22
Site II – Borgen Blvd.				
	Influence Area (ft)		**Deceleration/Acceleration Time (s)**	
Attributes	**Upstream**	**Downstream**	**Upstream**	**Downstream**
Sample Size	96	96	96	96
Min.	253.80	251.05	9	10
Max.	946.50	931.87	23	25
Mean	532.40	446.26	15.64	15.78
Standard Deviation	182.32	173.69	3.80	3.97
85^{th} Percentile	743.41	687.03	20	20
Site III – Golden Road				
	Influence Area (ft)		**Deceleration/Acceleration Time (s)**	
Attributes	**Upstream**	**Downstream**	**Upstream**	**Downstream**
Sample Size	139	141	140	140
Min.	181.18	207.50	9	9
Max.	891.00	958.00	24	25
Mean	407.45	522.42	13.77	16.54
Standard Deviation	165.03	164.63	3.63	3.93
85^{th} Percentile	588.75	700.29	18	21

Similar results were obtained at Site III, shown in **Table 14**. Site III is also much shorter than Site I and has only one test segment, i.e., only one upstream approach and one downstream approach in each direction of travel. The results of the upstream influence area and the deceleration time imply that the drivers at this site started decelerating at an average distance of 407 ft upstream of the "Yield" line and needed an average of 13.8 s to decelerate from the segment operating speed to the speed at which it yielded/stopped at the "Yield" line or traversed through the roundabout at the circulating speed. The downstream influence area statistics show that the drivers took an average of 16.5 s to accelerate downstream of the roundabout and traveled an average distance of 522 ft before vehicles returned to the desired operating speed under prevailing conditions. Similar to Site II, the upstream and downstream influence areas and their associated deceleration and acceleration times were lower at this site compared to Site I, likely due to the lower speed limit along this corridor as well.

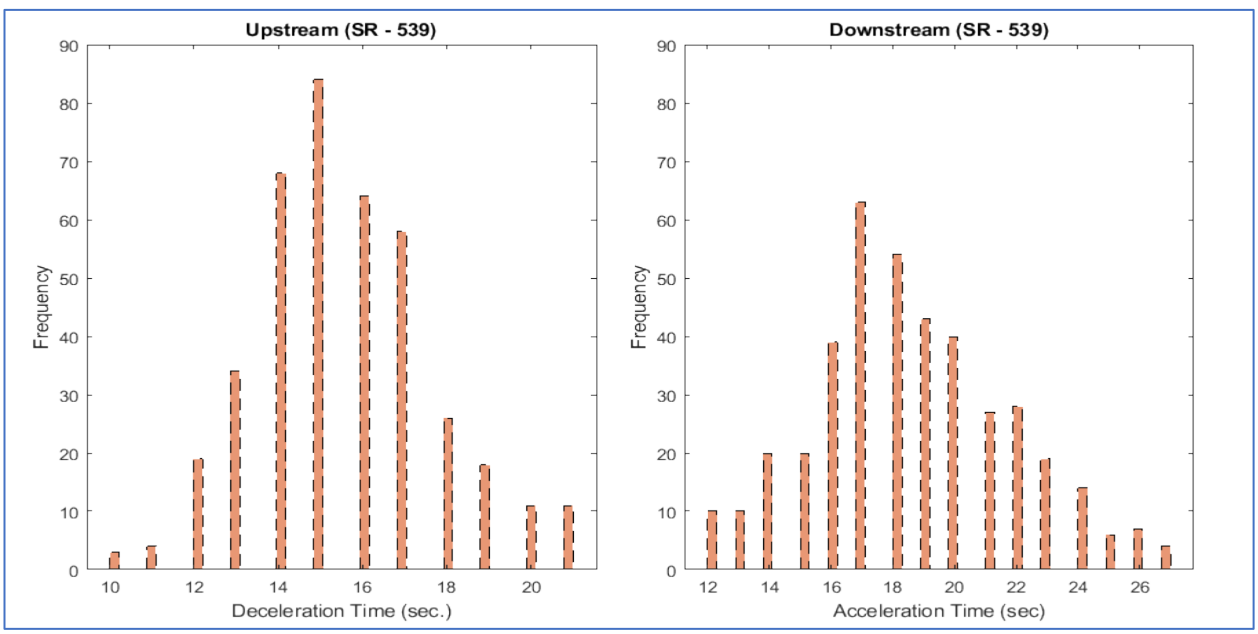
The results discussed, in **Table 14,** are significantly different from the findings of the previous NCHRP study (Rodegerdts et al., 2014). The discrepancy in the results of the two studies can possibly be explained by the criteria used in this study for screening the data and selecting study sites and segments which resulted in using only a subset of the original data and avoided study sites with overlapping influence areas (closely spaced roundabouts). Further, the heuristic method used in defining the influence areas in this research could be much different from the method used in the previous study (details unpublished).

Roundabout Influence Area Distribution. This section expands upon the descriptive statistics of the previous section by examining the data distribution characteristics. In this analysis, only data from Site I was used as it constituted the majority of the observations. **Figure 43** illustrates the distributions of influence area length and the deceleration/acceleration time. Overall, the graphs show that the data are distributed somewhat evenly around the center of the distributions, similar to the overall "bell-shape" of the normal distribution. The distribution of the upstream influence area is centered around 600 ft with a minimum length of about 363 ft and a maximum length of about 908 ft as shown in **Figure 43a**. The distribution of the downstream influence area is centered around 800 ft which is consistent with the results from the descriptive statistics. Moreover, the distribution of deceleration time indicates that the data is centered around 17 s as shown in **Figure 43b**. Compared to the deceleration time, acceleration time has a wide range and flatter distribution.

The cumulative frequency distribution diagrams for the influence area and deceleration/acceleration time are plotted to examine the range and 85^{th} percentiles as shown in **Figure 44**. In general, these graphs all show smooth S-shape cumulative distributions with the downstream influence area and acceleration time distributions shifted to the right. As expected, the 85^{th} percentile upstream influence area length is significantly lower than that of the downstream influence area.

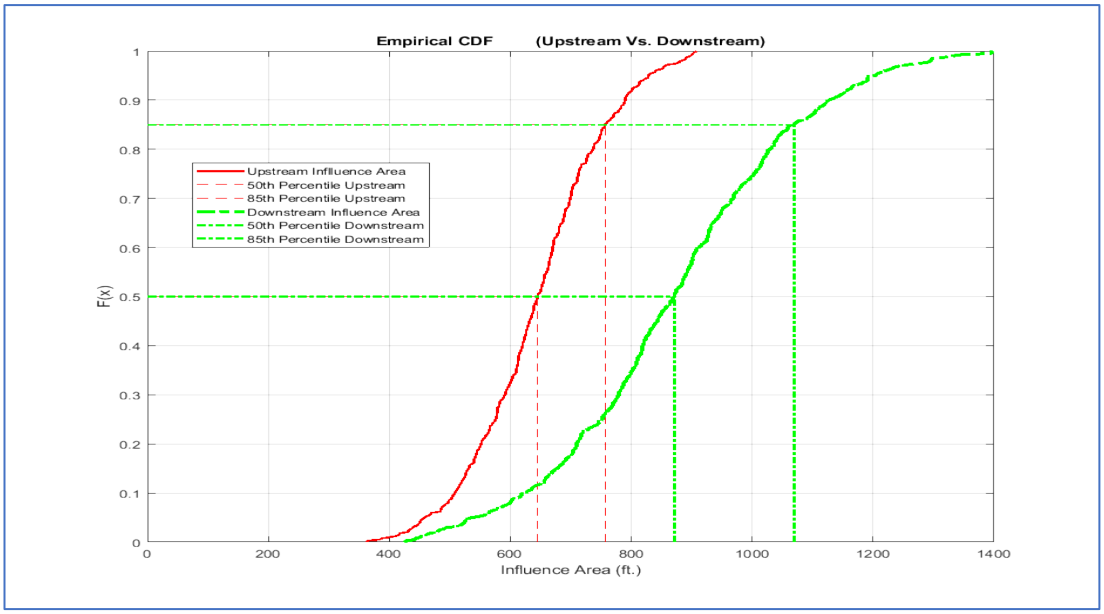


(a)

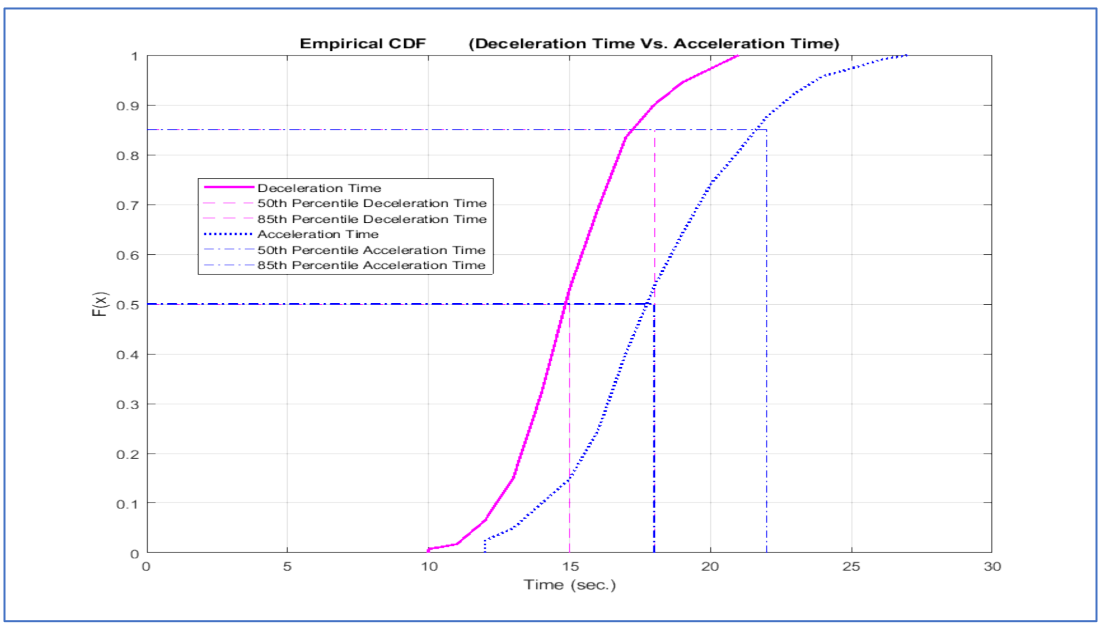


(b)

Figure 43.Data Distribution (a) Influence Area, (b) Deceleration/Acceleration Time



(a)



(b)

Figure 44. Empirical Cumulative Distribution of Roundabout (a) Influence Area, (b) Deceleration/Acceleration Time

Impact of Traffic Flow and Speed Limit on Influence Area. As mentioned earlier, the study sites are characterized by low traffic volumes, particularly Sites II and III, despite the data being collected during daytime peak and off-peak periods for three days at each site. The descriptive analysis suggested that the roundabout upstream and downstream influence areas were different at the three sites, possibly due to the different posted speed limits. This section describes a test of the effect of the speed limit and traffic volume (which may affect operating speeds) on the roundabout influence areas. To test the impact of traffic flow rate on the influence area, only Site I was examined as the other two sites had low traffic volumes throughout the entire data collection period. The traffic flow rates were divided into two levels: "lower flow level" which has a directional traffic flow rate of less than 800 veh/h, and "higher flow level" which has a directional traffic flow rate of more than 1000 veh/h. In this analysis, a series of hypothesis tests were conducted using a two-sample t-test.

i. Compare the mean length of the upstream influence area under lower and higher traffic flow rates.
ii. Compare the mean length of the upstream influence area under different posted speed limits (PSL).
iii. Compare the mean length of the downstream influence area under lower and higher traffic flow rates.
iv. Compare the mean length of the downstream influence area under different posted speed limits (PSL).

All these tests were performed at a 95% confidence level. The results found strong evidence that the posted speed limit had a significant impact on the length of upstream and downstream influence areas (2-sided p-value < 0.0001), which is consistent with the descriptive statistics at the three study sites. However, results suggest no evidence of a statistical significance for the impact of traffic flow level on the upstream and downstream influence areas. This is largely expected due to the fact that traffic flow levels on rural and suburban corridors are generally low, and the impacts on speed tend to be negligible (i.e., no queues at roundabout entries and no tangible effect on mid-segment operating speeds). The results are presented in Table 15.

Table 15. Results of Hypothesis Testing – (t-tests)

Upstream Influence Area					
Flow Rate ***(High vs. Low)***			**Posted Speed Limit** ***(50mi/h vs. 35mi/h)***		
t-stats	***p-value***	***C.I***	***t-stats***	***p-value***	***C.I***
-1.27	0.2055	-Inf – 6.85	15.32	<0.0001	187.44 – Inf
Downstream Influence Area					
t-stats	***p-value***	***C.I***	***t-stats***	***p-value***	***C.I***
-1.22	0.1119	-Inf – 10.77	23.80	<0.0001	345.32 – Inf

Signal-Control Intersection Influence Area

This section delves into the analysis of the influence area of signal-control intersections in rural settings. Utilizing trajectory data, the speed profiles of vehicles traversing these intersections were examined to determine the length of influence areas, thereby contributing to the broader understanding of facility segmentation in rural transportation systems.

Data Processing for Signal-Control Intersection Influence Area

The raw data processing involved program development in MATLAB (MATLAB, 2018) and the use of QGIS software (QGIS Development Team, 2019) for cleaning the data. The coordinates of the raw data (in latitude and longitude) were transformed to Universal Transverse Mercator (UTM) coordinates, in order to get X-Y location coordinates in meters (instead of degrees) which was required for distance computation. The trajectory data which is comprised of waypoints per 3 seconds were converted to a complete trajectory of waypoints based on the unique trajectory identifier (ID). Next, the trajectories were separated based on the direction of travel at each study site using the heading angle. Filtering data consisted of removing trajectories with missing points and short trajectories of less than 10 waypoints.

Signal Control Intersection Influence Area Determination

For the analysis of the influence area, only the trajectory data for vehicles that stopped at the intersection were considered. Vehicles that traverse the intersection without stopping were not included in the analysis as they are not much affected by traffic control. Once the GPS data transformation and processing were conducted, a 4-step heuristic algorithm was developed to identify the start and end of the upstream and downstream influence areas of the intersection, as follows.

i. *Identify start of upstream influence area*: For upstream influence area and deceleration rate, examine the speed profile and determine the point from which the vehicle speed drops at least 4 ft/s ($a \leq -4$ ft/s^2) for three consecutive GPS waypoints (i.e., 9 s) and continues decelerating until it stops. Once that point is determined, the distance between the location of the point and the stop line at the intersection approach is calculated. The threshold of a minimum of 9 consecutive seconds was selected to include all speed profiles in the analysis, even those with high deceleration rates and short stopping distances.

ii. *Identify end of downstream influence area*: For the downstream influence area, the speed profile is examined beyond the minimum speed location near the stop-line. The end of the acceleration or downstream influence area is identified when the speed increase for two consecutive GPS waypoints (i.e., 6 s) becomes less than 1 ft/s^2. Step-i and step-ii are presented in **Figure 45**.

iii. *Determine upstream influence area length*: For a stopped vehicle in a queue, the upstream influence area is the distance between the starting point of deceleration determined in step-i and the location when vehicle speed reaches zero plus the distance from the stop-line.

iv. *Determine downstream influence area length*: For the downstream influence area, a vehicle that is stopped upstream of the stop-line at the intersection approach, the downstream influence area is the distance between the location of the stopped vehicle and the endpoint of the downstream influence area determined in step-ii minus the width of intersection and the distance between the stopped vehicle and the stop-line (zero for the first vehicle in a queue).

After identifying the upstream and downstream influence areas, a detailed analysis was conducted separately at each site of signal-control intersections. The influence area data were examined for outliers based on Tukey's interquartile range (IQR) technique (Tukey, 1977). As stated earlier, t The IQR method is less sensitive to extreme values and is robust against any deviation from a normal distribution of data because it uses quartiles that are resistant to extreme values – hence can be applied to both normal and skewed distributions efficiently (Seo, 2006). According to the IQR rule, any value that falls below the 25^{th} percentile minus 1.5×IQR or above the 75^{th} percentile plus 1.5×IQR is considered an outlier. Unless specified, the discussions in the following sections all refer to the data upon excluding outliers.

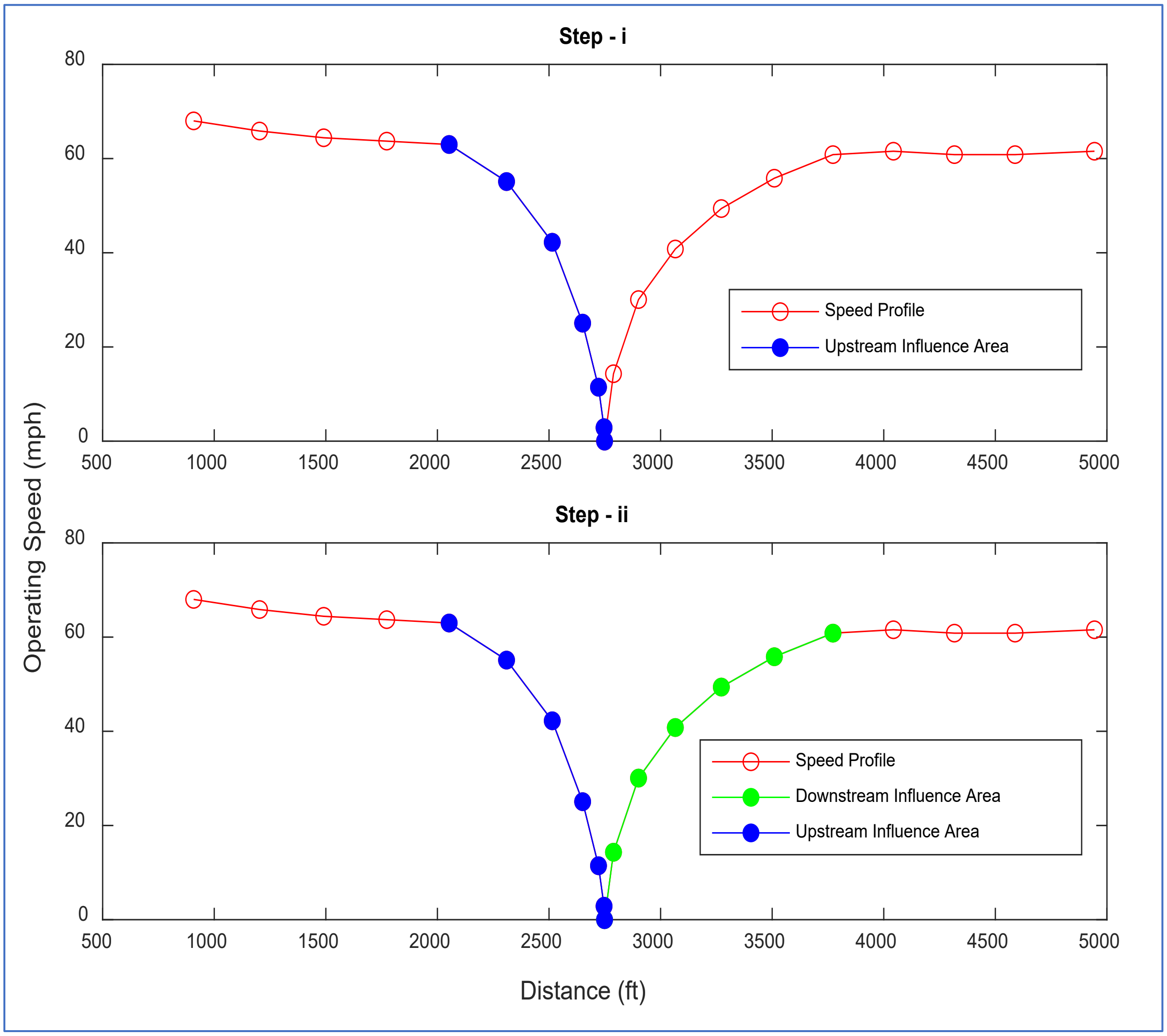


Figure 45 Sample Trajectory: Upstream and Downstream Influence Area of Signal-Control Intersection

<u>Results of Signal-Control Intersection Influence Area</u>

This section characterizes the influence area at signal-control intersections. The descriptive statistics of the upstream influence area at the signalized intersection sites are presented in **Table 16.** Upstream Influence Area at Signalized Intersection. The table summarizes the sample size, mean, standard deviation, 50th percentile, and 85th percentiles of upstream influence areas as well as the operating speeds on the upstream approach segment for each of the four study sites. The results show that the average influence areas are close to the 50th percentile influence area lengths, which may suggest a largely normal distribution for the influence area length. Furthermore, the results are consistent with the expectation that higher operating speeds on the upstream segment result in longer influence areas due to increased stopping distance.

For Site 1, the results indicate that the average influence areas of the first three approaches are longer compared to the influence areas of the other sites with similar average operating speeds. This may be due to the higher percentage of heavy vehicles (about 35% compared to about 8 – 13 % at other study sites) and the fact that each approach has only one lane, which in turn leads to longer queues. This confirms that the heavy vehicles start decelerating far upstream of the intersection stop-line. Furthermore, the standard deviation of influence area lengths at the study sites are relatively high, which could be induced by the higher variation in drivers' behavior and vehicle performance.

For the downstream influence at signalized intersections, the results indicate that the downstream influence areas are notably longer than the upstream influence areas as shown in **Table 17**. This implies that the deceleration rate upstream of the intersection is higher than the acceleration rate downstream of the intersection even when the vehicle is not impeded. This can partly be explained by the fact that vehicles are released at the start of the green phase in platoons and their acceleration rates are affected by lower-performance vehicles, especially on single-lane highway segments. Further, the uncertainty about the duration of the yellow interval (and the ability to cross the intersection legally) may result in high deceleration rates for vehicles close to the intersection. Moreover, similar to the upstream influence area for Site 1, the downstream influence areas for the first three departure approaches are longer than the downstream influence areas for other sites with a similar average operating speed.

Table 16. Upstream Influence Area at Signalized Intersection

Site	Bound	N	Mean IA ft (Speed mi/h)	Std. Dev IA ft (Speed mi/h)	50th Percentile IA ft (Speed mi/h)	85th Percentile IA ft (Speed mi/h)
01	NB	56	1239.10 (62.00)	356.68 (8.27)	1223.30 (63.70)	1684.60 (69.58)
	SB	103	1443.40 (64.15)	398.51 (8.64)	1391.90 (62.99)	1869.40 (72.33)
	EB	303	1056.80 (57.19)	396.94 (9.54)	965.29 (56.55)	1534.90 (68.01)
	WB	509	547.55 (42.84)	202.98 (7.17)	502.95 (42.94)	774.90 (50.11)
02	EB	878	877.52 (61.05)	301.88 (7.13)	835.71 (60.64)	1228.10 (68.01)
	WB	541	799.95 (62.16)	279.48 (7.67)	750.88 (61.56)	1071.10 (70.86)
03	EB	502	867.03 (64.26)	286.60 (6.54)	821.18 (64.42)	1186.10 (70.86)
	WB	544	891.98 (69.85)	305.88 (7.74)	854.06 (69.43)	1205.40 (77.30)
04	NB	593	927.66 (54.38)	315.83 (6.55)	908.80(55.12)	1270.60 (60.52)
	SB	644	761.84 (49.57)	208.92 (5.56)	739.40 (49.39)	975.55 (55.83)

*IA = Influence Area

Table 17 Downstream Influence Area at Signalized Intersection

Site	Bound	N	Mean IA ft (Speed mi/h)	Std. Dev IA ft (Speed mi/h)	50th Percentile IA ft (Speed mi/h)	85th Percentile IA ft (Speed mi/h)
01	NB	48	1716.90 (63.36)	546.99 (10.29)	1850.0 (64.42)	2270.70 (73.94)
	SB	100	1798.10 (62.20)	436.52 (6.27)	1830.80 (62.98)	2252.20 (68.01)
	EB	297	650.80 (42.32)	352.98 (7.22)	542.73 (41.51)	1027.0 (50.11)
	WB	470	1535.80 (58.25)	450.90 (8.26)	1573.20 (58.70)	2057.60 (66.57)
02	EB	881	1469.20 (60.41)	519.46(7.06)	1408.10 (60.12)	2128.80 (68.01)
	WB	557	1224.94 (58.71)	353.25 (6.07)	1187.10 (58.69)	1616.70 (65.14)
03	EB	490	1822.50 (67.01)	459.37 (6.46)	1811.30 (67.28)	2404.01 (73.72)
	WB	515	1538.20 (64.23)	431.58 (6.12)	1498.90 (64.42)	2056.10 (70.15)
04	NB	592	1060.01 (49.69)	342.02 (5.35)	1044.40 (50.11)	1453.60 (55.12)
	SB	651	1267.97 (56.26)	366.07 (5.95)	1324.30 (56.55)	1668.50 (62.27)

*IA = Influence Area

Stop-Control Intersection Influence Area

This section discusses the assessment of the influence area of stop-control intersections, which are commonly found on minor roadways within rural highways.

Data Processing for Stop-Control Intersection Influence Area

Trajectory data, similar to the data from signal-control intersections, were used in the analyses of influence areas at stop-control intersections. Data were collected from 7 study sites on rural highways in the state of Florida. The same steps as discussed prior (for signal-control intersection) were followed to perform data cleaning and data processing.

Stop-Control Intersection Influence Area Determination

As the stop-control intersections were T-type intersections (i.e., minor road meeting a major arterial, with stop control on a minor road), the downstream influence area was determined based on right-turning and left-turning vehicles after adjustment for distance traversed during turning left/right. Once the GPS data transformation and processing were conducted, a 4-step heuristic algorithm was developed to identify the start and end of the upstream and downstream influence areas of the intersection, as follows.

i. *Identify start of upstream influence area*: For upstream influence area and deceleration rate, examine the speed profile and determine the point from which the vehicle speed drops at least 4 ft/s ($a \leq -4$ ft/s^2) for three consecutive GPS waypoints (i.e., 9 s) and continues decelerating until it stops. Once that point is determined, the distance between the location of the point and the stop line at the intersection approach is calculated. The threshold of a minimum of 9 consecutive seconds was selected to include all speed profiles in the analysis, even those with high deceleration rates and short stopping distances.

ii. *Identify end of downstream influence area*: For the downstream influence area, the speed profile is examined beyond the minimum speed location near the stop-line. The end of the acceleration or downstream influence area is identified when the speed increase for two consecutive GPS waypoints (i.e., 6 s) becomes less than 1 ft/s.

iii. *Determine upstream influence area length*: For a stopped vehicle in a queue, the upstream influence area is the distance between the starting point of deceleration determined in step-i and the location when vehicle speed reaches zero plus the distance from the stop-line.

iv. *Determine downstream influence area length*: For the downstream influence area, a vehicle that turned right or left after a complete stop at the stop-line at the intersection approach, the downstream influence area is the distance between the location of the stopped vehicle and the endpoint of the downstream influence area determined in step-ii minus 25 ft or 50 ft for right and left turn movement respectively (distance traversed during turning movement). **Figure 46** shows the right-turning vehicle trajectory at the stop-control intersection, while **Figure 47** illustrates the upstream and downstream influence areas of stop-control intersections.

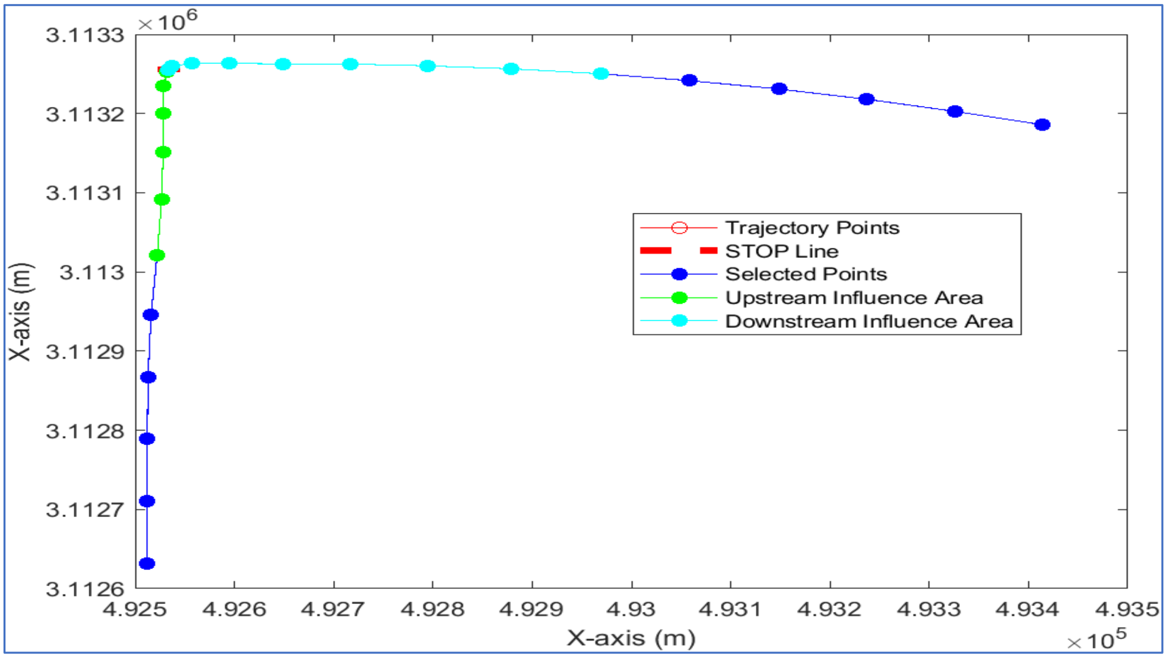


Figure 46. Vehicle Trajectory Showing Right-Turning Vehicle – Influence Area at a Stop-Control Intersection

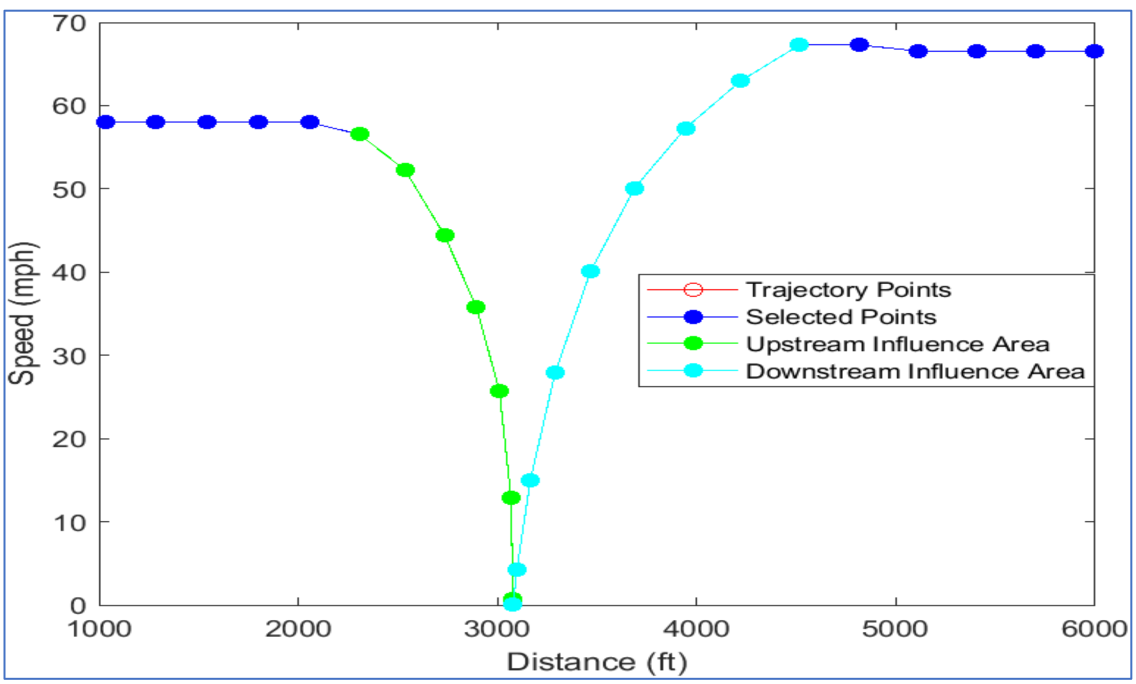


Figure 47. Speed Profile Showing Upstream and Downstream Influence Area at a Stop-Control Intersection

Results of Stop-Control Intersection Influence Area

The stop-control intersections investigated are mainly present on minor roads in rural areas with lower traffic volumes and lower posted speed limits compared to the study sites for signalized intersections. The results of the stop-control intersections, summarized in **Table 18**, show that the lengths of the upstream influence areas are considerably shorter compared to the upstream influence areas at signalized intersections. This difference is likely a result of lower speed limits on stop-control approaches and the lack of queues on these approaches due to lower traffic volumes. Furthermore, the downstream influence area of the stop-control intersections is significantly longer than the upstream influence area at the stop-control intersections as shown in **Table 19**.

Table 18. Upstream Influence Area at Stop-Control Intersection

Site	**Bound**	**N**	**Mean IA ft (Speed mi/h)**	**Std. Dev IA* ft (Speed mi/h)**	**50th Percentile IA ft (Speed mi/h)**	**85th Percentile IA ft (Speed mi/h)**
01	EB	131	689.33 (49.62)	255.79 (7.12)	681.50 (48.67)	950.13 (56.54)
02	NB	123	517.28 (44.92)	170.95 (7.54)	482.75 (45.09)	709.75 (52.29)
03	SB	252	735.95 (51.94)	248.08 (7.07)	700.71 (51.89)	1031.20 (59.04)
04	SB	51	599.99 (45.92)	288.35 (7.05)	460.21 (45.09)	999.26 (55.00)
05	NB	20	903.87 (58.94)	309.75 (6.43)	827.90 (59.05)	1289.30 (64.78)
06	SB	22	829.46 (51.24)	309.72 (6.71)	789.79 (50.46)	1205.10 (58.70)
07	NB	526	768.54 (51.62)	210.37 (7.02)	753.15 (52.25)	976.33 (58.69)

*IA = Influence Area

Table 19. Downstream Influence Area at Stop-Control Intersection

Site	Bound	Turn	N	Mean IA ft (Speed mi/h)	Std. Dev IA ft (Speed mi/h)	50th Percentile IA ft (Speed mi/h)	85th Percentile IA ft (Speed mi/h)
01	EB	RT	36	1200.00(54.26)	319.82(4.72)	1091.37(54.04)	1695.60(60.20)
		LT	99	977.53(48.34)	348.69(6.96)	1109.30(46.53)	1330.50(56.54)
02	NB	RT	63	1415.40(61.51)	270.71(7.12)	1409.90(62.27)	1687.50(66.60)
		LT	33	1332.6(64.07)	282.40(6.98)	1257.10(63.70)	1573.10(72.36)
03	SB	RT	27	1217.20(57.45)	86.87(4.93)	1240.90(57.26)	1302.40(64.02)
		LT	212	1452.95(61.07)	326.98(6.88)	1469.38(61.56)	1832.77(67.28)
04	SB	RT	12	1589.40(63.70)	282.94(5.78)	1657.60(62.63)	1857.70(69.93)
		LT	10	1929 (68.43)	481.52 (8.26)	1934.95(68.71)	2556.98(75.87)
05	NB	RT	---	---	---	---	---
		LT	44	1471.01(59.36)	331.25(6.79)	1427.90(59.05)	1882.30(67.06)
06	SB	RT	11	1232.40(58.88)	229.98(7.60)	1177.30(58.69)	1510.90(67.75)
		LT	88	1474.40(61.95)	299.77(5.57)	1504.60(62.27)	1805.20(68.00)
07	NB	RT	44	1766.90(65.23)	407.56(6.52)	1728.10(66.57)	2282.30(71.50)
		LT	474	1785.20(64.69)	390.89(5.39)	1735.90(65.14)	2234.70(70.15)

--- Missing data for right-turn movements

Percentile Analysis of Influence Areas

In transportation engineering, percentiles have been used in practice in many design and safety applications. For instance, it has been an established practice to use the 85th percentile speed as a reference in setting legal speed limits (American Association of State Highway and Transportation Officials (AASHTO), 2018). Similarly, the 15th percentile pedestrian walking speed has been used in practice for determining the pedestrian right-of-way time in signal timing design. These are just a couple of examples of using percentiles in safety applications where the objective is to make sure that the design incorporates the majority of road users. This section analyzes the percentile influence areas at the study sites to better understand the variation in drivers' braking habits when drivers decelerate or accelerate at the location of intersections. Specifically, conservative drivers may start deceleration farther upstream from the intersection, while more aggressive drivers may start deceleration a short distance upstream from the intersection. Similar variations in drivers' behavior may be observed as drivers accelerate back to operating speeds on the downstream segments.

Upstream Influence Area

Initially, the trends for the upstream influence area percentile (ranging from 35^{th} to 85^{th} percentiles, in increments of 5) are established for roundabout, signal-control and stop control intersections as illustrated in **Figure 48** to **Figure 50**, respectively. The trendline of the upstream influence area at the roundabout intersection starts at about 530 ft for the 35^{th} percentile, 600 ft for the 50^{th} percentile, and 745 ft for the 85^{th} percentile as shown in **Figure 48.** While the trendline of the upstream influence area at signalized intersections is relatively higher and starts at about 700 ft for the 35^{th} percentile, 810 ft for the 50^{th} percentile, and 1240 ft for the 85^{th} percentile as shown in **Figure 49**. On the other hand, the trendline of the upstream influence areas at the stop-control intersections, as shown in **Figure 50**, is relatively lower compared to that of signal control but higher than that of the roundabout intersection. The trendline of the upstream influence area at the stop-control intersection starts at around 540 ft for the 35^{th} percentile, 640 ft for the 50^{th} percentile, and approximately 960 ft for the 85^{th} percentile as shown in **Figure 50**.

The lower influence areas observed at roundabout intersections, as compared to those for other traffic controls, can be attributed to the distinct operational conditions and drivers' behavior prevailing at these intersections. Vehicles approaching a roundabout typically reduce their speeds from the upstream segment's operating speed to the roundabout circulating speed (approximately

15-20 mph), whereas vehicles at other controls come to a complete stop. Similarly, the probable reason for the lower influence areas at stop-control intersections compared to signal-control intersections is the lower posted speed limits at stop-control intersection sites. This results in reduced operating speeds and, consequently, smaller influence areas. These differences in drivers' behavior and operational conditions result in the observed variations in the upstream influence areas for the different types of intersection controls.

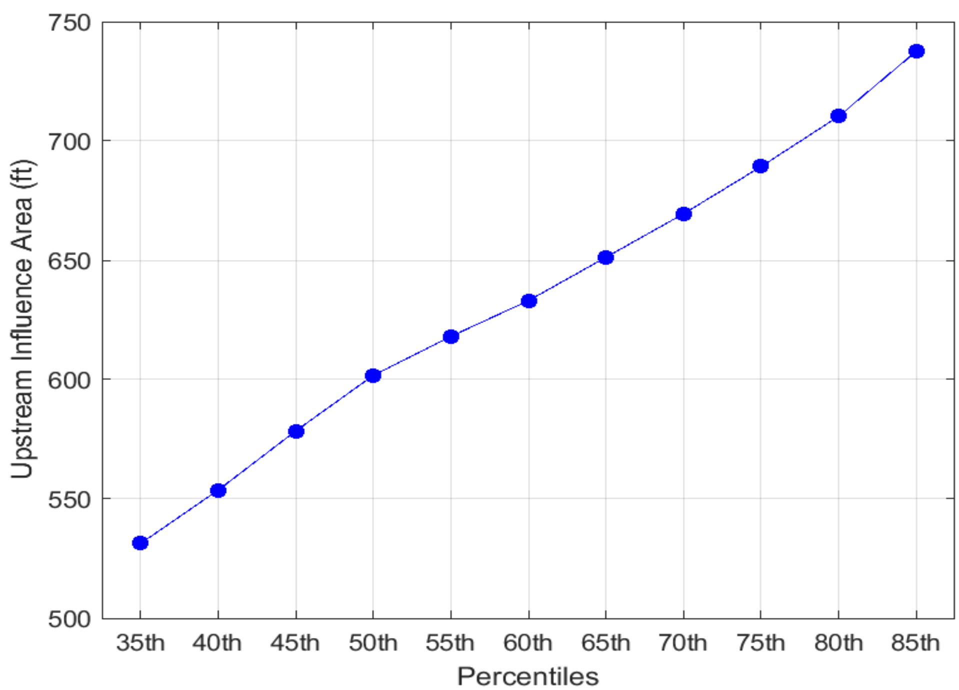


Figure 48. Roundabout: Upstream Influence Area Lengths at Different Percentiles

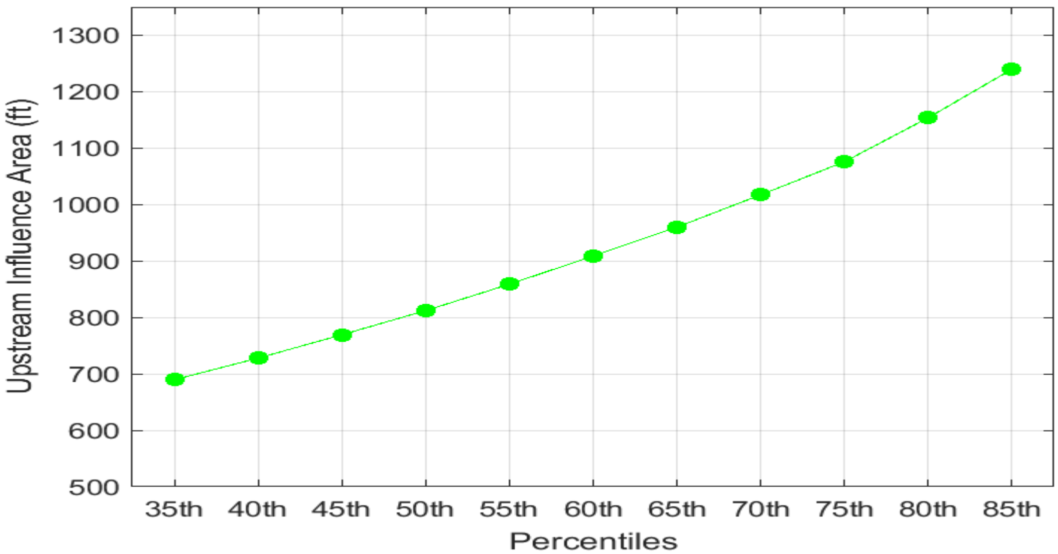


Figure 49. Signal: Upstream Influence Area Lengths at Different Percentiles

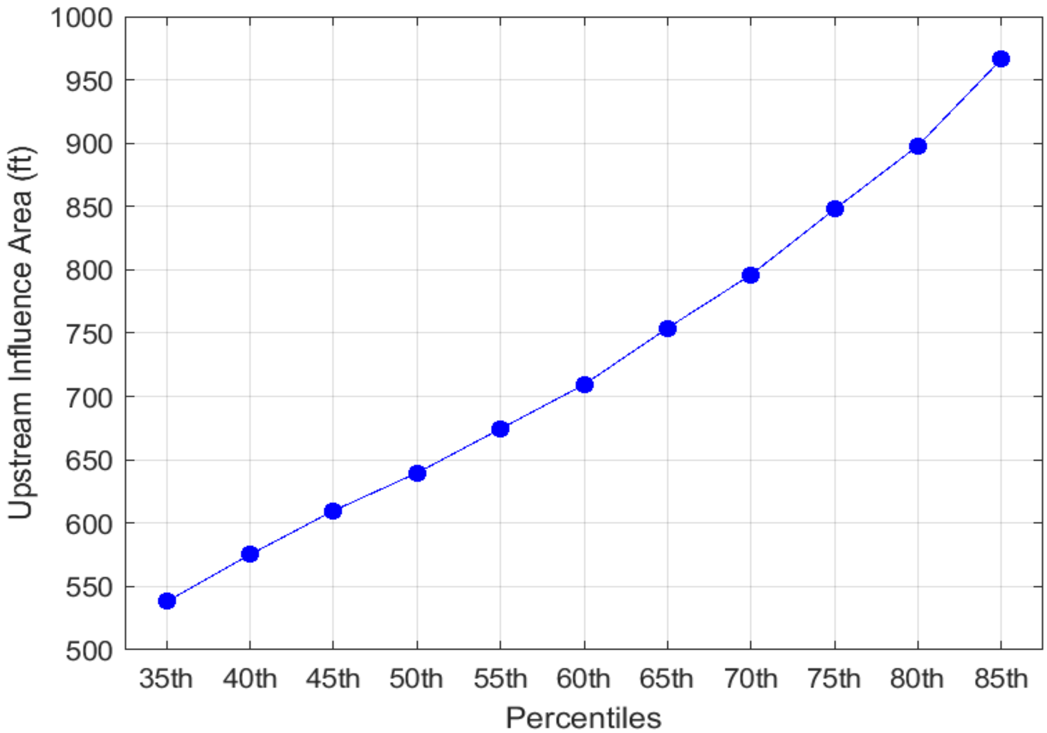


Figure 50. Stop: Upstream Influence Area Lengths at Different Percentiles

Upstream Influence Area: Speed Reduction. Instead of selecting any specific percentile of influence area length and proceeding with further analysis, it was decided to examine the operational impact of intersection in terms of speed reduction. Thus, the speed reduction from the operating speed of the upstream segment to the speed at the location of different influence area percentiles were assessed.

To determine the speed drop from the operating speed of the upstream segment on the approach to the intersection, average speed reductions at different locations (different percentile upstream influence area lengths) on the upstream approach were calculated. **Figure 51** to **Figure 53** show the average speed reduction from the operating speed to the distance of specific percentile of upstream influence area length. For instance, the average speed reduction from the operating speed to the position of the 50th percentile influence area length at roundabout study sites is 2.35 mi/h, and to the position of the 70th percentile is 1.70 mi/h as shown in **Figure 51**. Whereas the average speed reduction from the operating speed to the position of the 50th percentile influence area length at signal control study sites is 5 mi/h, and to the position of the 70th percentile is 3.8 mi/h as shown in **Figure 52**. Similarly, the average speed reduction from the start of the influence area to the 50th percentile location upstream of the stop control study sites is about 4.35 mi/h, whereas at the 70th percentile position, the average speed reduction is about 3.4 mi/h as shown in **Figure 53**. The speed reduction upstream of the roundabout is different from the other two types of intersections because most of the vehicles do not stop at the “Yield” line of the roundabout approach.

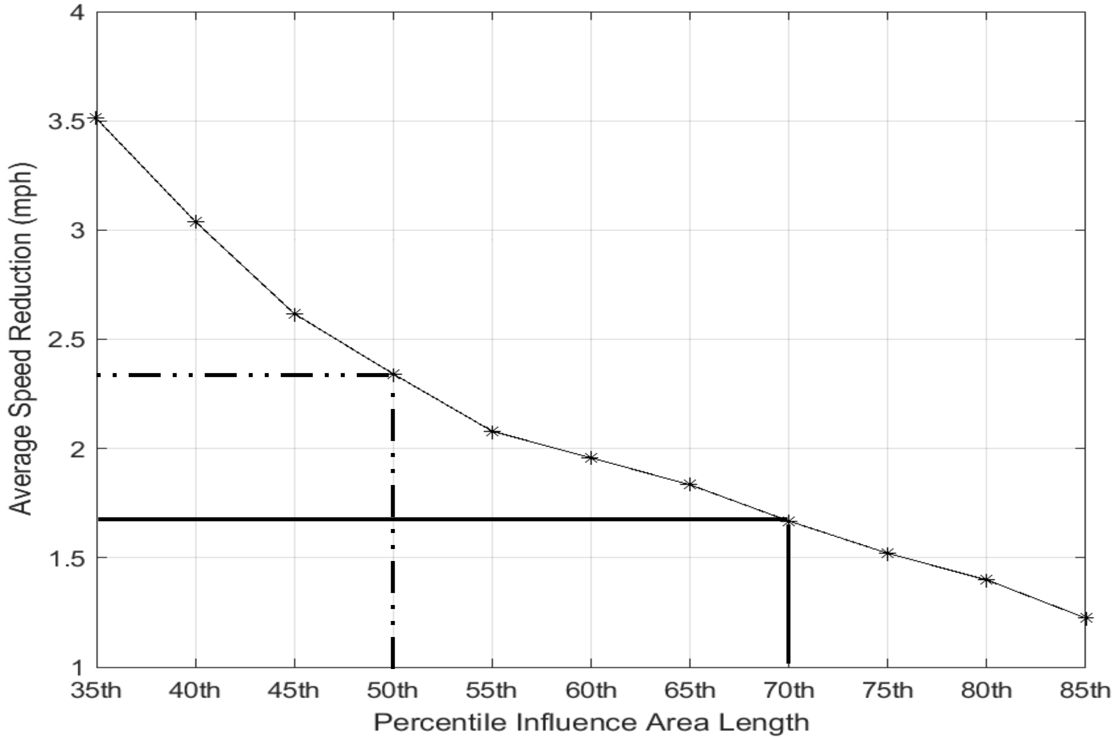


Figure 51. Roundabout: Average Speed Reduction at Different Percentile Distances

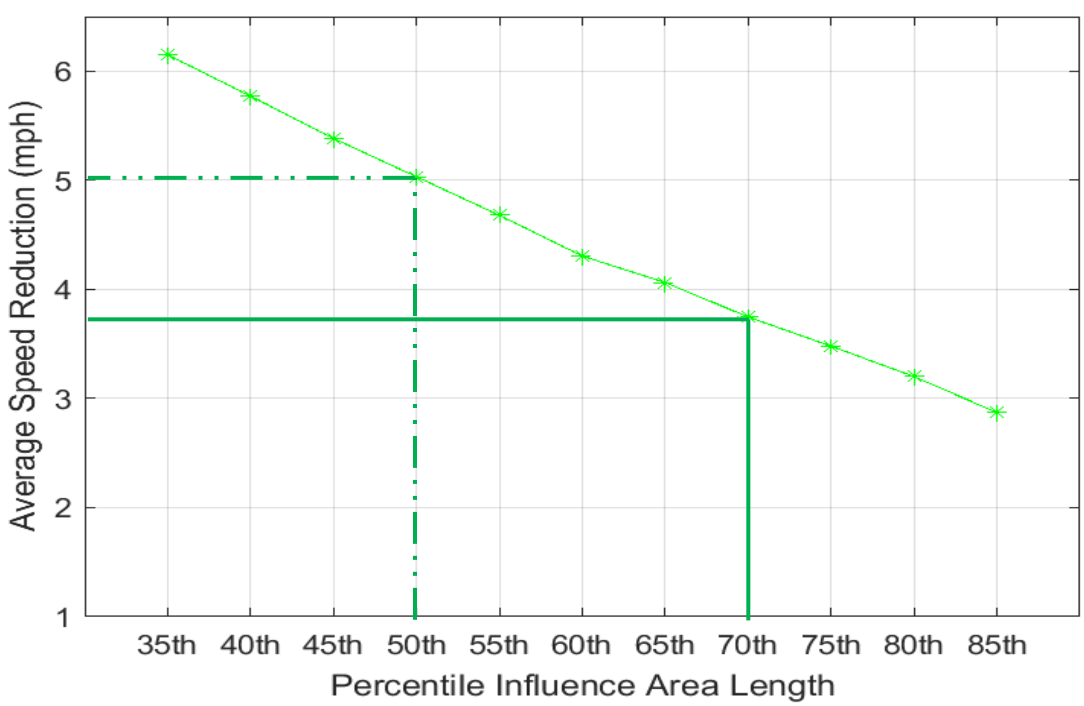


Figure 52. Signal: Average Speed Reduction at Different Percentile Distances

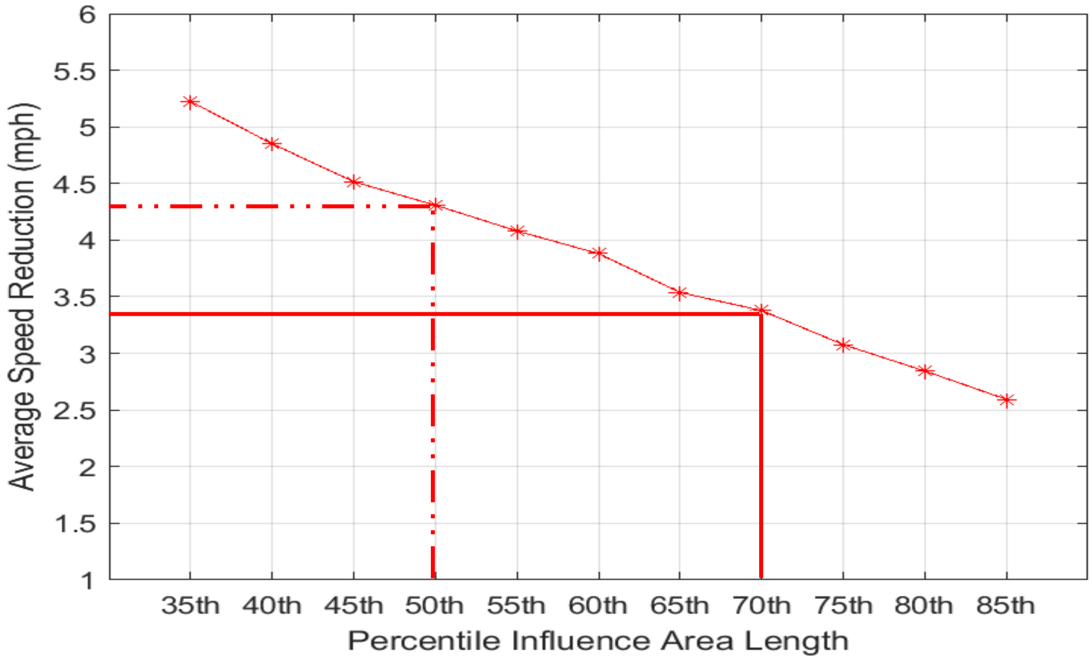


Figure 53. Stop: Average Speed Reduction at Different Percentile Distances

Upstream Influence Area: Average percentage speed reduction. The posted speed limits at different sites were different. Therefore, instead of comparing the magnitude of speed reduction for different intersection controls, the average percentage speed reduction is a better measure to select an upstream influence area length based on percentile length as shown in **Figure 54** to **Figure 56**

Figure 54 to **Figure 56** illustrate the percent speed reduction at various percentile influence area positions for all three types of intersection controls. It is interesting to note that, while the average speed reduction for a given percentile influence area is quite different among the three control types, the percentage speed reductions are mostly comparable. For instance, the average percent speed reduction at the location of the 50th percentile upstream influence area is approximately 7.9% both for the signalized and stop-control intersections. However, the average percent speed reduction at the location of the 50th percentile upstream influence area for the roundabout is approximately 4.51% which is comparatively lower than the other two intersection's control types. The reason is that most of the vehicles do not come to a complete stop at a roundabout (i.e., do not reduce speed from segment operating speed to 0 mi/h) and traverse the roundabout with a certain speed known as roundabout circulating speed. This lower percentage speed reduction at roundabout influence areas compared to the other two control types of intersection is attributed to vehicles not stopping at the yield line in roundabouts.

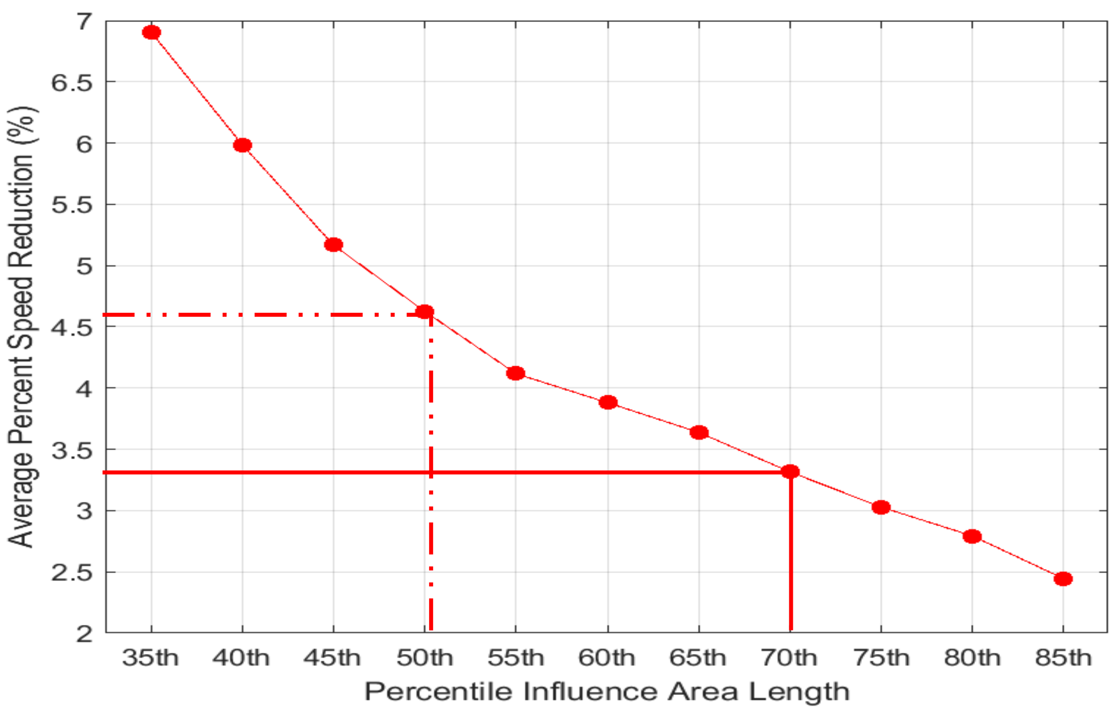


Figure 54. Roundabout: Average Percentage Speed Reduction at Different Percentile Distance

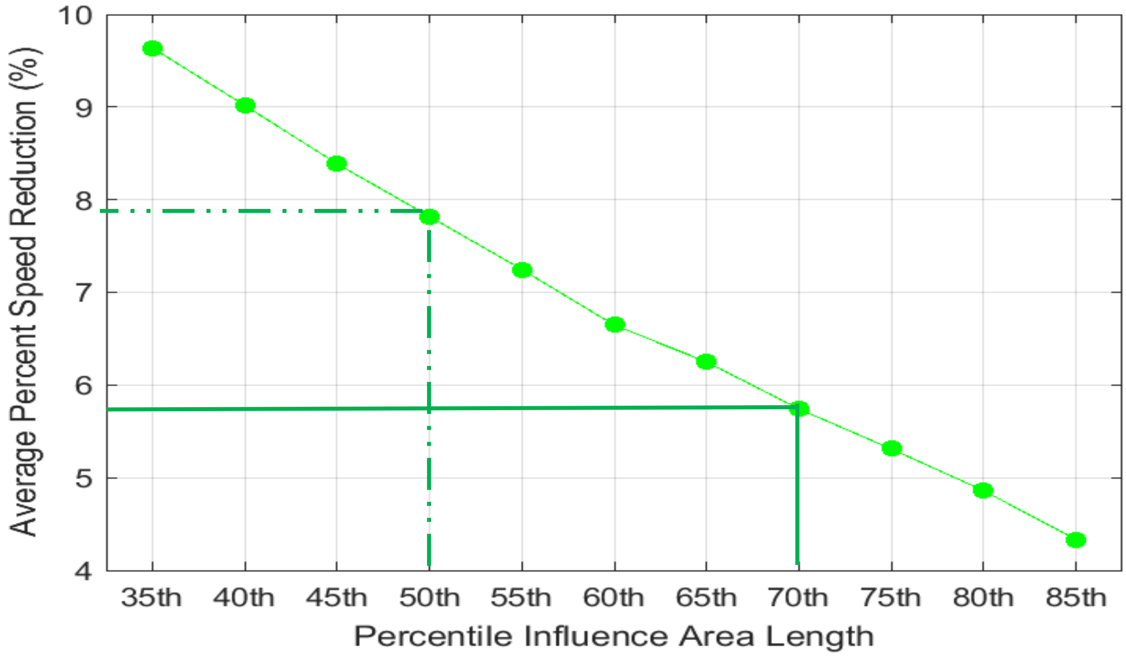


Figure 55. Signal: Average Percentage Speed Reduction at Different Percentile Distance

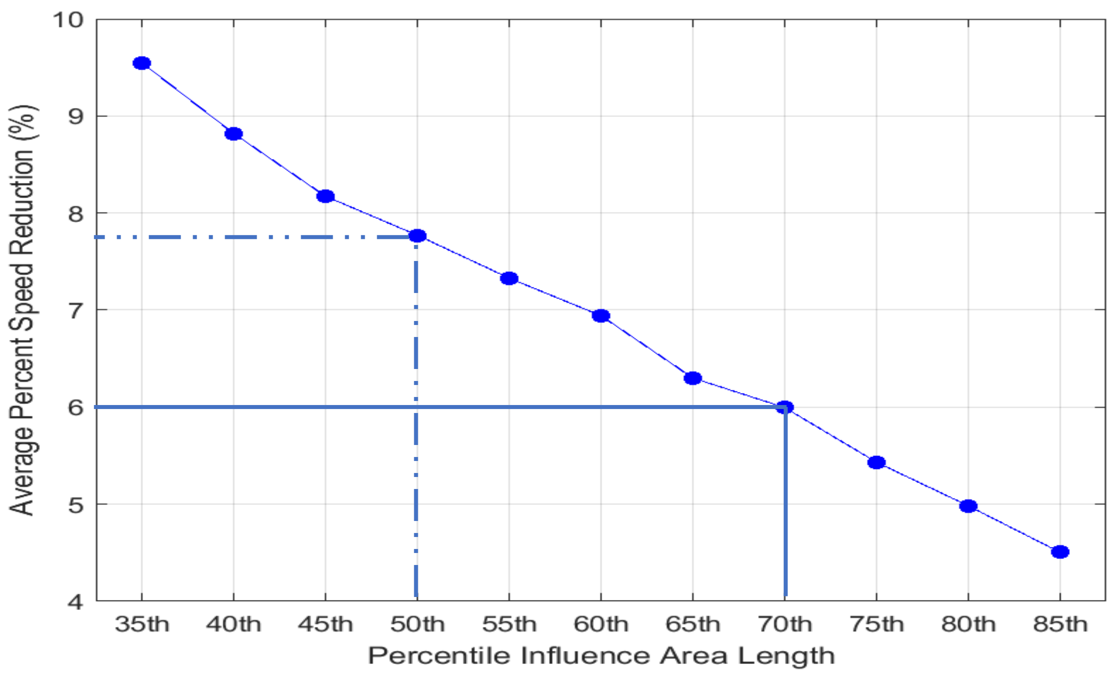


Figure 56. Stop: Average Percentage Speed Reduction at Different Percentile Distance

Upstream Influence Area Selection. Traffic operational analysis is different from safety applications in transportation engineering. Therefore, it was decided to adopt an influence area length of intersections based on tangible impact on traffic operations rather trying to incorporate a vast majority of drivers as it would result in a significantly longer influence area. Based on this criterion, the research team recommends a 70th percentile of influence area length for signal and stop control intersections as the speed is lower (reduction) by more than 5% from the operating speed of the upstream segment at this location. On the other hand, the 50th percentile of influence area length is recommended for a roundabout that corresponds to the location with around 4.5% (2.4 mi/h) average speed reduction. This is because vehicles come to a complete stop at signal and stop control intersections whereas vehicles may not stop or yield at a roundabout approach as rural highways have lower traffic. In addition, the posted speed limits on the roundabout corridors were lower compared to the signal and stop control study sites.

Downstream Influence Area

Similar to the upstream influence area, the trendlines for the downstream influence area percentiles (ranging from 35th to 85th percentiles, in increments of 5) are established for all three intersection control types as shown in **Figure 57** to **Figure 59**. For roundabout intersections, the trendline for the downstream influence area is approximately 640 ft for the 35th percentile, 760 ft for the 50th percentile, and 1010 ft for the 85th percentile, as shown in **Figure 57**. In contrast, the trendlines for signal control and stop control intersections are significantly higher, with the 50th percentile downstream influence areas for the two control types measuring approximately 1370 ft and 1500 ft, respectively (illustrated in **Figure 58** and **Figure 59**)

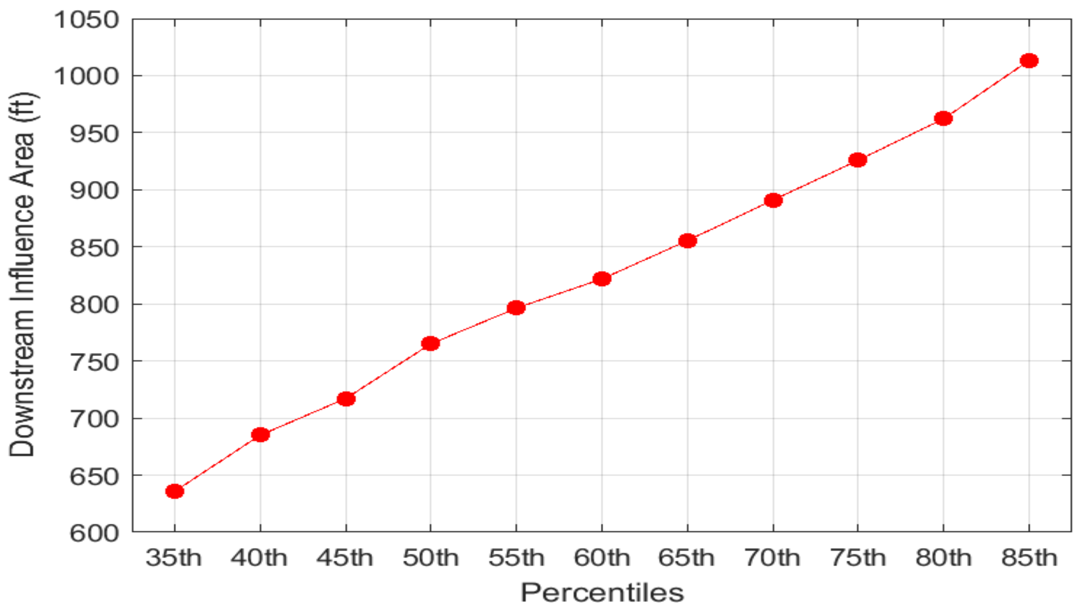


Figure 57. Roundabout: Downstream Influence Area Lengths at Different Percentiles

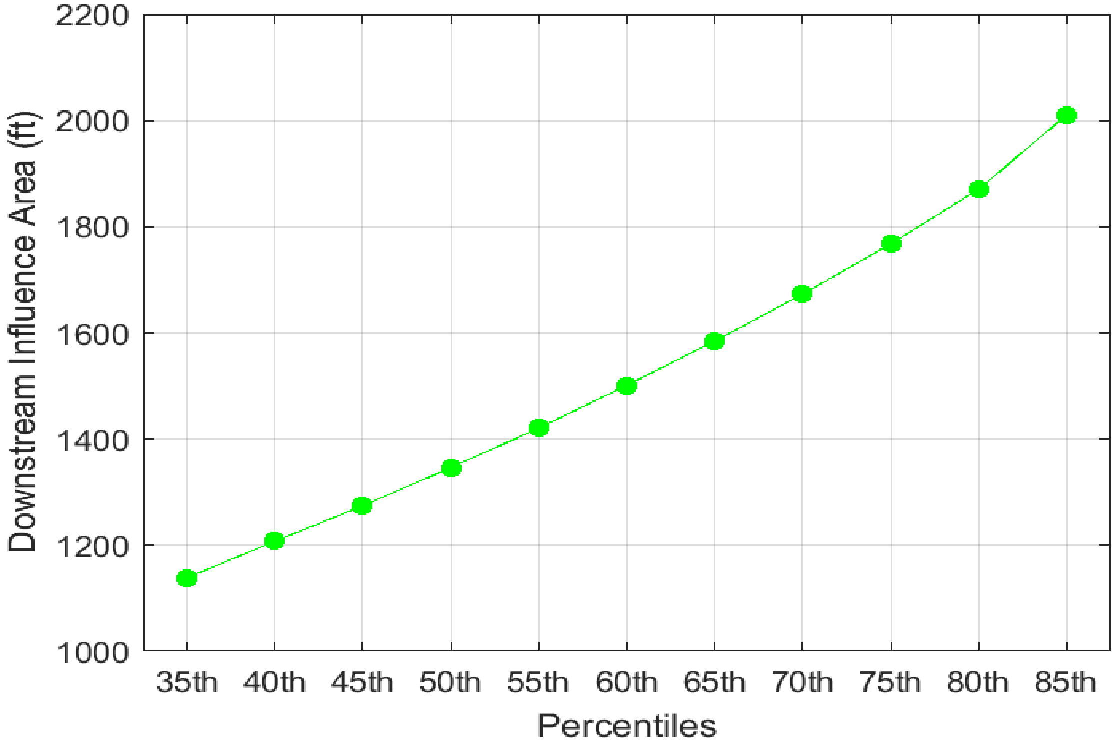


Figure 58. Signal: Downstream Influence Area Lengths at Different Percentiles

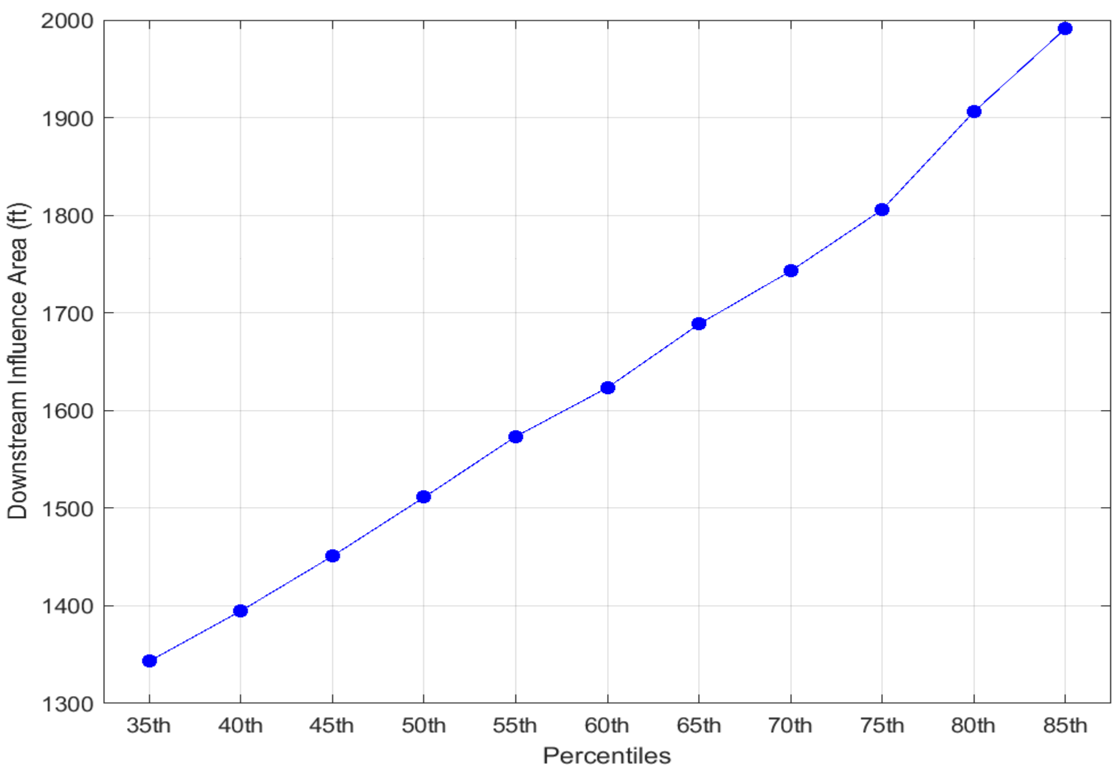


Figure 59. Stop: Downstream Influence Area Lengths at Different Percentiles

Downstream Influence Area: Speed difference. Using the percentile influence area lengths, the speed difference from the operating speed of the downstream segment to the speed at the location of a specific percentile (downstream influence area) were calculated and plotted as shown in **Figure 60** to **Figure 62**. For instance, the average speed difference between the downstream segment operating speed and the speed at the location of the 50th percentile influence area length at roundabout study sites is 3 mi/h, and at the location of the 70th percentile is 2.4 mi/h as shown in **Figure 60**. Similarly, the average speed difference between the downstream segment operating speed and the speed at the location of the 70th percentile influence area lengths at signal-control and stop-control intersections, as shown in **Figure 61** and **Figure 62**, are 4.4 mi/h and 2.6 mi/h, respectively.

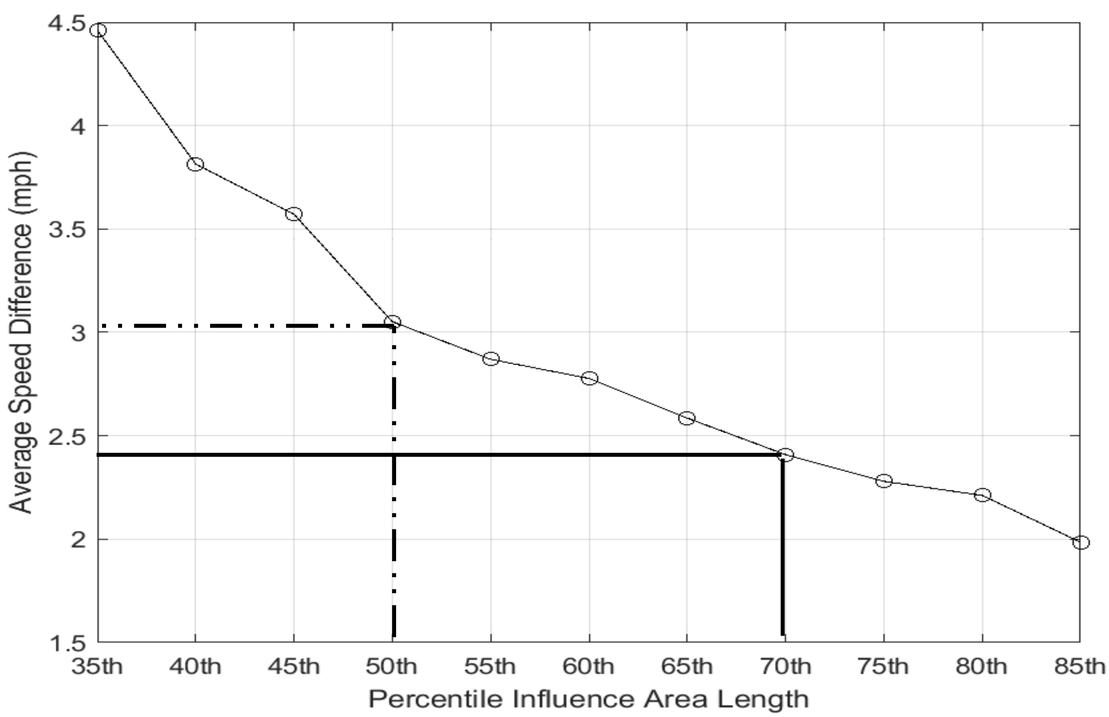


Figure 60. Roundabout: Average Speed Difference from Downstream Operating Speed

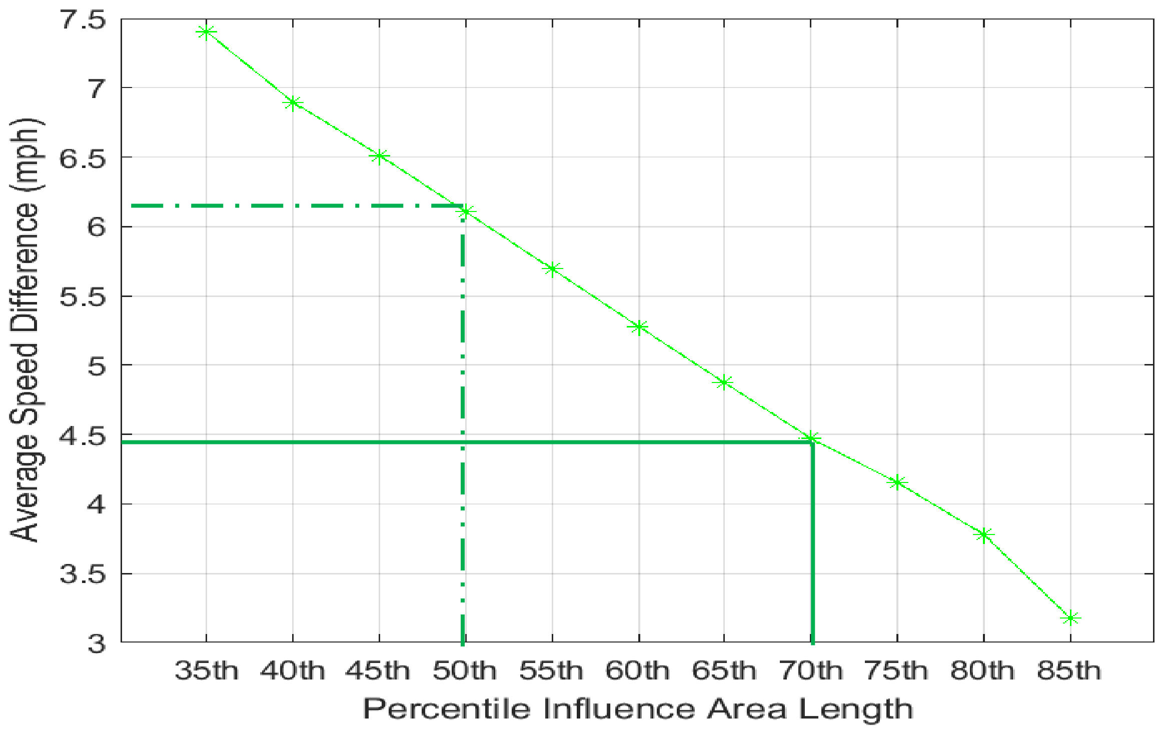


Figure 61. Signal: Average Speed Difference from Downstream Operating Speed

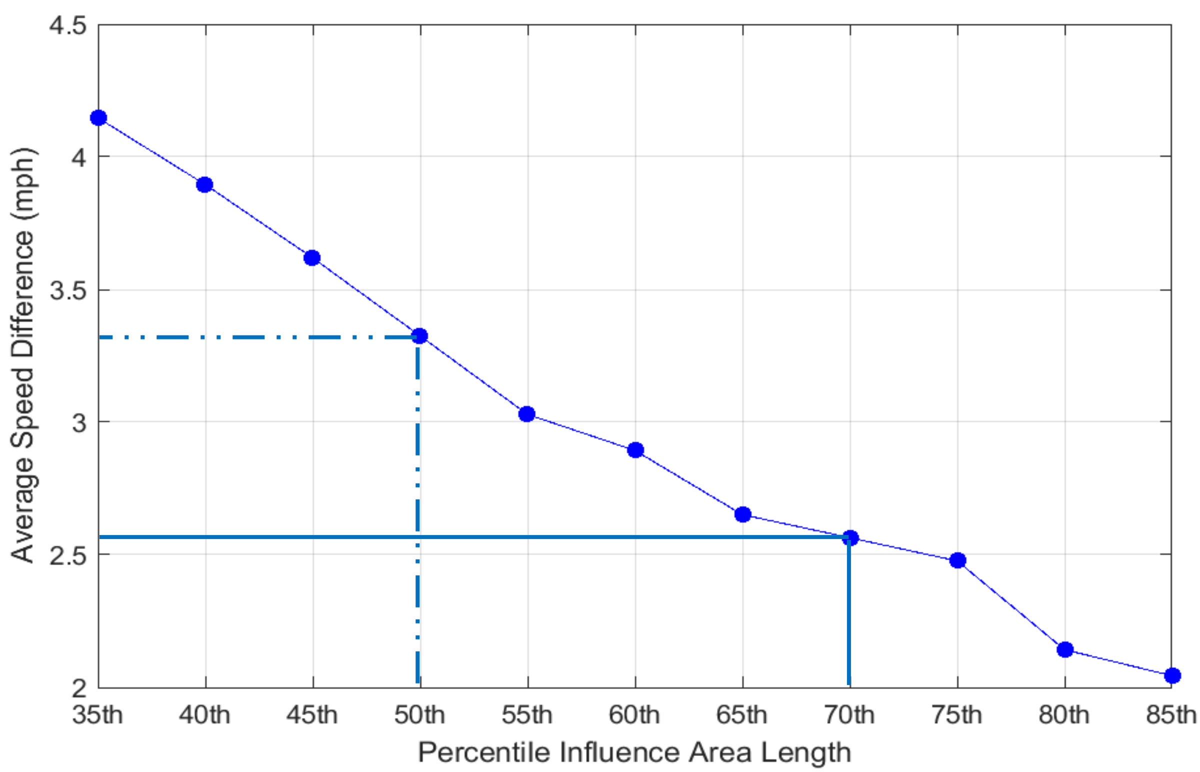


Figure 62. Stop: Average Speed Difference from Downstream Operating Speed

Instead of only focusing on the magnitude of speed difference from the operating speed of the downstream segment to the speed at the location of a specific percentile, the average percentage speed difference at different percentile influence area locations are calculated and illustrated as shown in **Figure 63** to **Figure 65**. For example, the speed at the 70th percentile downstream distance of the roundabout intersection is about 4.6% less on average than the operating speed on the downstream segment as indicated in **Figure 63**. Similarly, the speed at the 70th percentile downstream distance of signalized intersection is about 6.8% less on average than the operating speed on the downstream segment (see **Figure 64**).

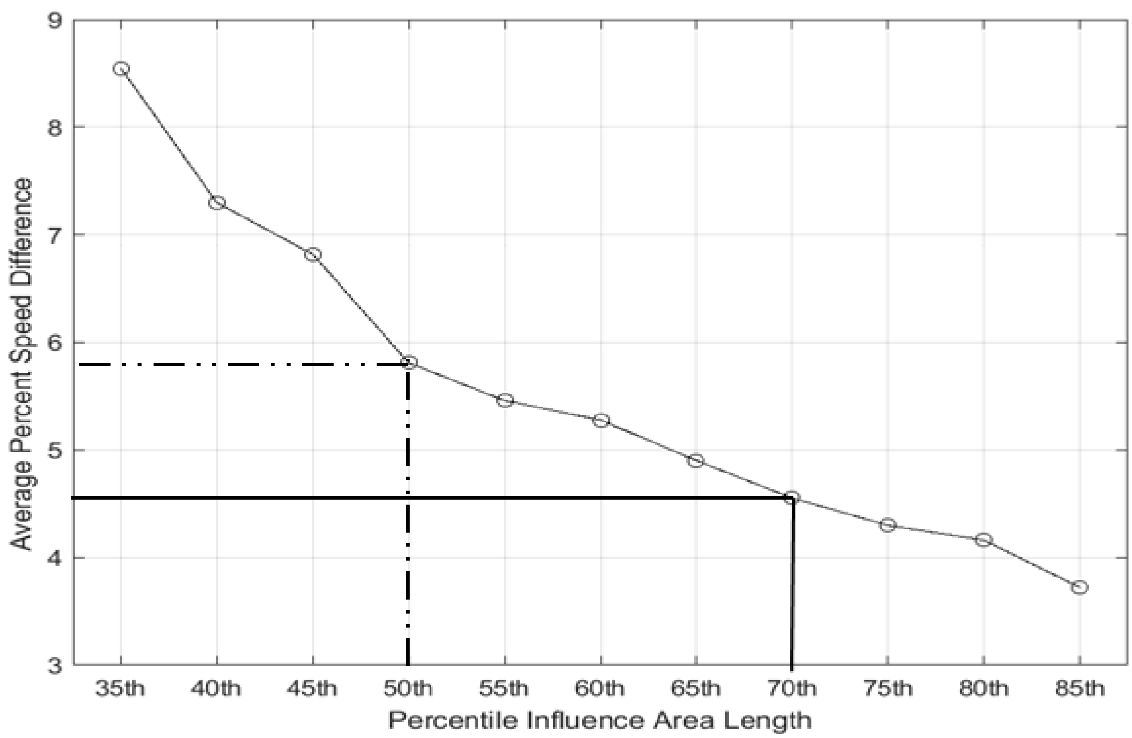


Figure 63. Roundabout: Average Percentage Speed Difference from Downstream Running Speed

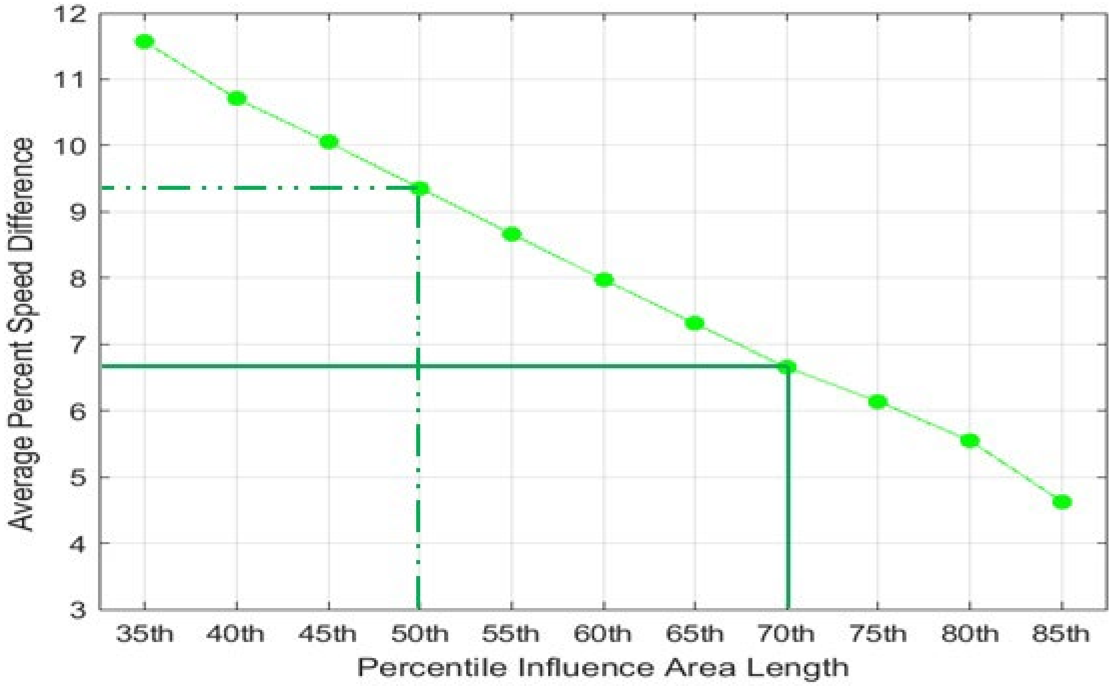


Figure 64. Signal: Average Percentage Speed Difference from Downstream Running Speed

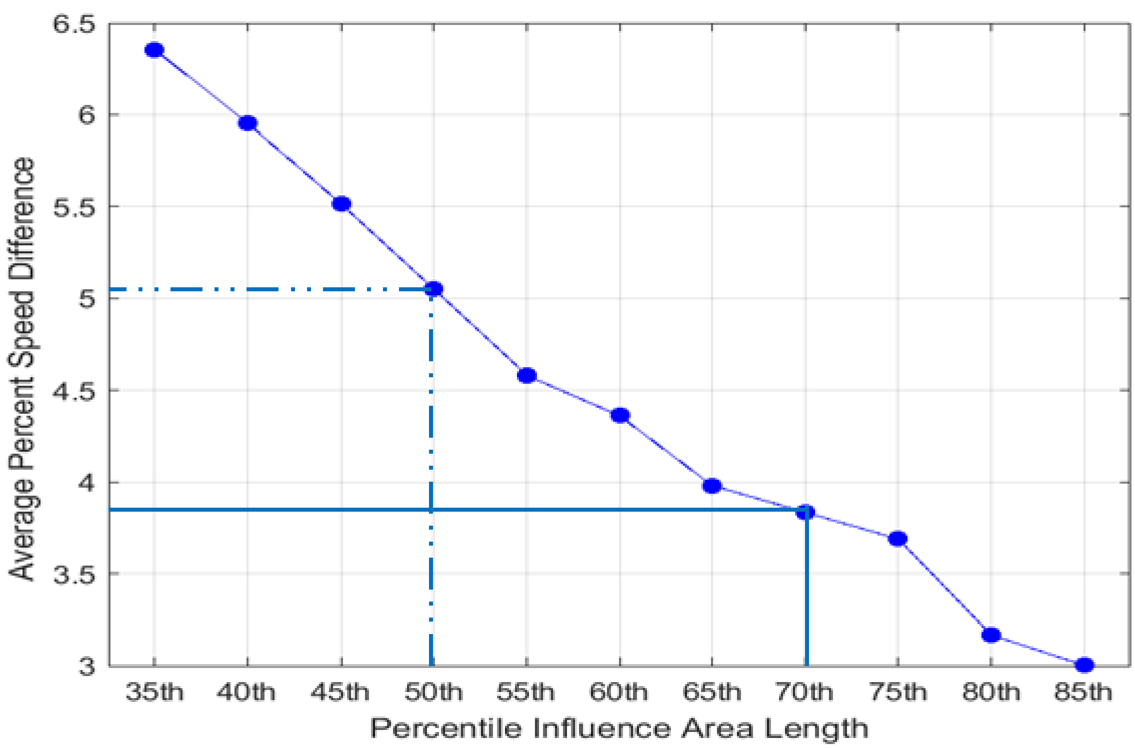


Figure 65. Stop: Average Percentage Speed Difference from Downstream Running Speed

Downstream Influence Area Selection. Like the upstream influence area selection, it was decided to adopt a 70th percentile of downstream influence area for signal and stop control intersections and a 50th percentile influence area length for roundabouts based on the criterion of substantial impact on traffic operation in the form of speed difference from the operating speed of the downstream segment. According to these recommendations of downstream influence areas, the speed at the 70th percentile of the downstream influence area of signal control intersection is more than 5% (>4 mi/h) below the operating speed of the downstream segment, and the speed at the 50th percentile of downstream influence area of a roundabout is about 6% (3 mi/h) below the operating speed of the downstream segment.

Statistical Modeling for Estimating Influence Areas

This section discusses the development of statistical models for estimating the upstream and downstream influence areas for the three types of intersection control. The objective is to estimate the influence area using variables that are thought to affect such distance and are readily available to the analyst. Several models were developed and evaluated with different regressors. However, only a few variables such as upstream and downstream segment operating speeds, roundabout circulating speed, percent heavy vehicles, and facility type (two-lane vs. multilane highway) were found to have statistically significant effects on the upstream and downstream influence areas.

The percentile analysis conducted in the previous section allowed us to understand the magnitude of operational impacts (in terms of speed discrepancy) at different influence area percentiles. Consistent with the percentile analysis, the regression models developed and presented in this section help to estimate multiple percentiles of influence area length using some explanatory variables. Specifically, Quantile Regression (QR) was adopted to model the influence area at the study sites using multiple percentiles. The models enumerate the relationship of predictors with a conditional quantile of an outcome variable without assuming any specific conditional distribution. As a result, it models the quantiles instead of the mean as done in standard linear regression (ordinary least squares or OLS). Similarly, QR does not make any assumptions about data distribution like the standard linear regression which makes it more robust to handle outliers and amenable to skewed distributions (Das et al., 2019).

In this study, QR was used to estimate the 50^{th}, 70^{th}, and 85^{th} percentiles of the upstream and downstream influence areas. Taking a comparable structure to the linear regression model, the quantile regression model equation in the context of this study for the τth quantile is:

$$Q_\tau(y_i) = \beta_0(\tau) + \beta_1(\tau)x_{i1} + \cdots + \beta_p(\tau)x_{ip} + \varepsilon_i \ , \qquad i = 1,2,\ldots,n \qquad (15)$$

Where, $Q_\tau(y_i)$ is the τth quantile of the influence area distribution, x_{ij}s are observed independent variables associated with observation i, $\beta_j(\tau)$ is the beta coefficient function of quantile level τ for variable j, and ε_i is a random error term with a mean equal to zero. The $\beta_j(\tau)$'s are estimated by solving the minimization problem as given in Equation (16):

$$\min_{\beta_0(\tau),\ldots,\beta_p(\tau)} \sum_{i=1}^{n} \rho_\tau\left(y_i - \beta_0(\tau) - \sum_{j=1}^{p} x_{ij}\,\beta_j(\tau)\right) \qquad (16)$$

where,

$$\rho_\tau(r) = \tau \max(r, 0) + (1-\tau)\max(-r, 0) \qquad (17)$$

The function $\rho_\tau(r)$ is referred to as the check loss which gives asymmetric weights to each of the individual error r for each data point, depending on the quantile and the sign of the error. For positive errors, the check function multiplies the error by τ, and by $(1 - \tau)$ if the error is negative. Minimizing equation (16) results in minimum median absolute deviation for the quantile model. For each quantile level τ, the solution to this minimization problem yields a distinct set of regression coefficients $\beta_0(\tau)$ and $\beta_j(\tau)$ (Koenker, 2005). In this study, the "quantreg" package (Koenker, 2021) in RStudio was used to estimate quantile regression models for the intersection influence areas.

Roundabout Influence Area Estimation

This section discusses the development of statistical models for estimating the roundabout upstream and downstream influence areas. Several different models were developed and tested with different regressors. However, only operating speed (OS) and the circulating speeds within the roundabout were found statistically significant in both models for the upstream and downstream influence areas. It is expected that a higher operating speed on the segment would result in longer upstream and downstream influence areas as the vehicle would need a longer distance for deceleration and acceleration upstream and downstream of the roundabout, respectively. Regarding circulating speed, it was assumed that the higher the circulating speed the shorter the distance required for deceleration and acceleration upstream and downstream of the roundabout, thus the shorter the influence areas. The roundabout circulating speed was estimated as an average speed of a 5-second interval while the vehicle is navigating within the roundabout.

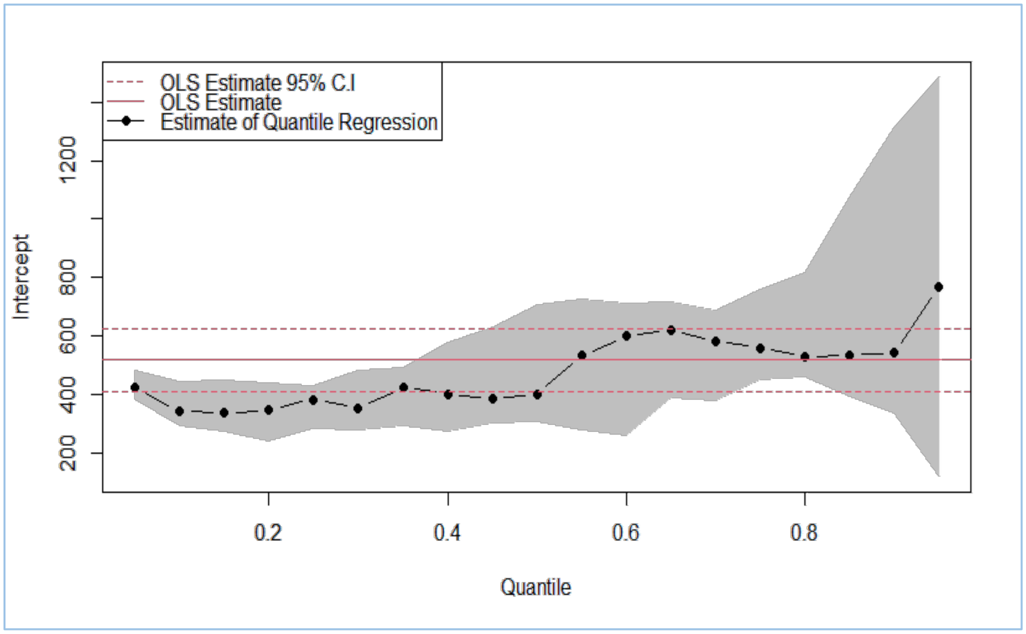
As the geometry including the diameter of roundabouts, the number of lanes in each approach, and the number of roundabout lanes, is similar for all study sites, these variables were not included in the statistical models. In traffic engineering, the 15th and 85th percentile estimates are often used in addition to the mean (or median) to study driving behaviors and traffic engineering parameters (e.g., speed, perception-reaction time, etc.).

The parameter estimates for the upstream and the downstream models are presented in **Table 20**. For each quantile model, parameter estimates are provided, along with standard errors and the p-value that corresponds to the t-statistic used to evaluate whether each of these parameters was significantly different from zero. The results imply that the length of the influence area is directly proportional to the operating speed and inversely proportional to the circulating speed.

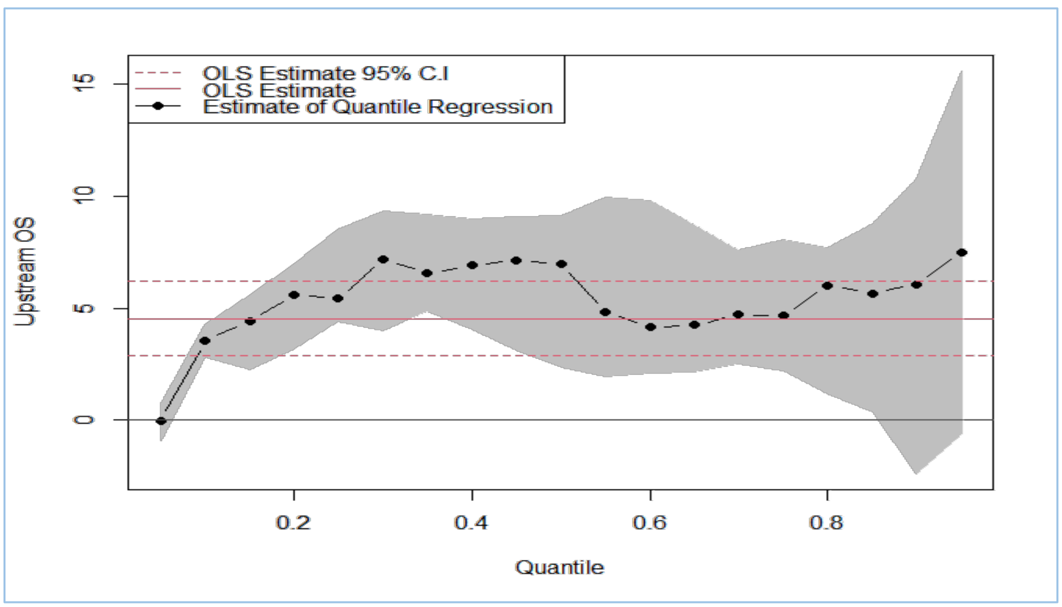
Table 20. Linear Quantile Regression Model for Influence Area

Dependent Variable: Upstream Influence Area Length (ft)						
	$\tau = 0.50$		$\tau = 0.70$		$\tau = 0.85$	
Parameters	**Estimate** ***(Std. Error)***	**p-value**	**Estimate** ***(Std. Error)***	**p-value**	**Estimate** ***(Std. Error)***	**p-value**
Intercept	402.15 *(86.63)*	<0.0001	581.69 *(28.91)*	<0.0001	536.85 *(73.20)*	<0.0001
Upstream OS (ft/s)	6.95 *(1.04)*	<0.0001	4.70 *(0.75)*	<0.0001	5.66 *(1.31)*	<0.0001
Circulating Speed (ft/s)	-10.38 *(1.21)*	<0.0001	-8.38 *(1.53)*	<0.0001	-6.99 *(2.30)*	<0.0001
Dependent Variable: Downstream Influence Area Length (ft)						
Parameters	$\tau = 0.50$		$\tau = 0.70$		$\tau = 0.85$	
	Estimate ***(Std. Error)***	**p-value**	**Estimate** ***(Std. Error)***	**p-value**	**Estimate** ***(Std. Error)***	**p-value**
Intercept	-313.80 *(46.57)*	<0.0001	-407.21 *(46.89)*	<0.0001	-499.17 *(42.18)*	<0.0001
Downstream OS (ft/s)	22.27 *(1.16)*	<0.0001	25.41 *(1.03)*	<0.0001	28.79 *(1.04)*	<0.0001
Circulating Speed (ft/s)	-18.37 *(2.08)*	<0.0001	-19.94 *(1.84)*	<0.0001	-22.71 *(1.80)*	<0.0001

Quantile Regression vs. OLS Comparison. For comparison purposes with OLS regression, **Figure 66** provides a graphical comparison of the parameter estimates of the upstream influence area model for each quantile (from the 5th percentile to the 100th percentile) along with the same estimates for an OLS model of mean influence area. When examining these plots, the OLS parameter estimates are reflected by a horizontal solid red line along with the associated 95% confidence intervals (C.I.) represented by a dashed red line. If the quantile regression parameter estimates fall outside of the 95% C.I. boundary, it implies that the difference between OLS estimates and quantile regression estimates is statistically significant at a 95% confidence level. **Figure 66** illustrates that the parameter estimates of the upstream influence area model at different quantiles lie generally within the boundaries of OLS parameter estimates. However, the parameter estimates of the downstream influence area model at different quantiles are mostly located outside of the 95% confidence boundary of OLS parameter estimates, as shown in **Figure 67**, and hence, are statistically significantly different than the OLS estimates. Thus, this analysis suggests that quantile regression is able to identify relationships in the data that would be otherwise not possible under the more typical OLS framework.

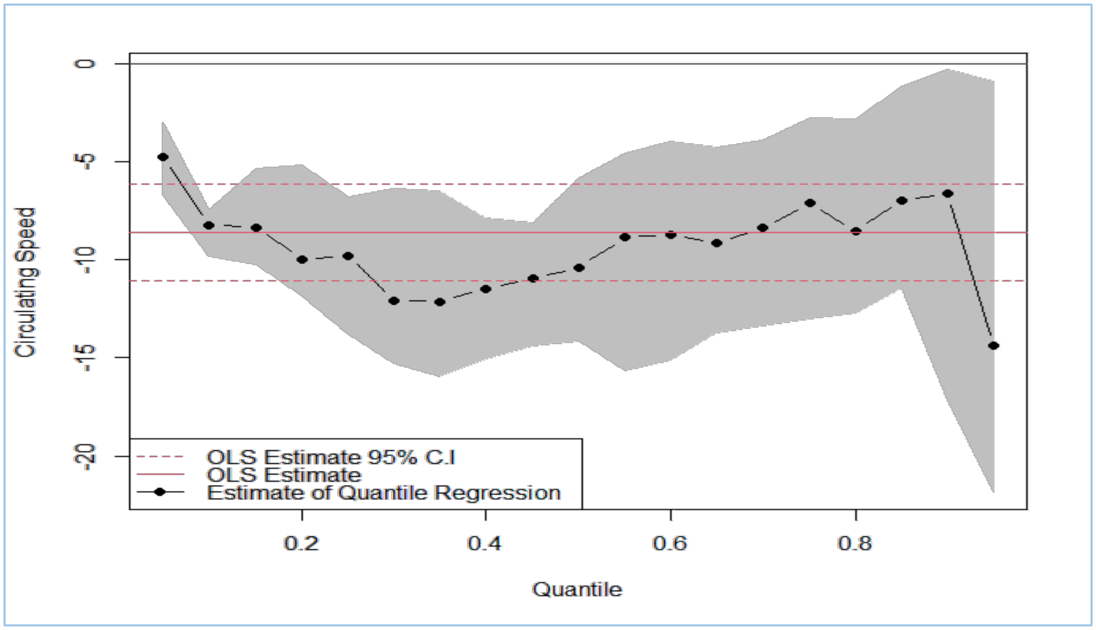


(a)



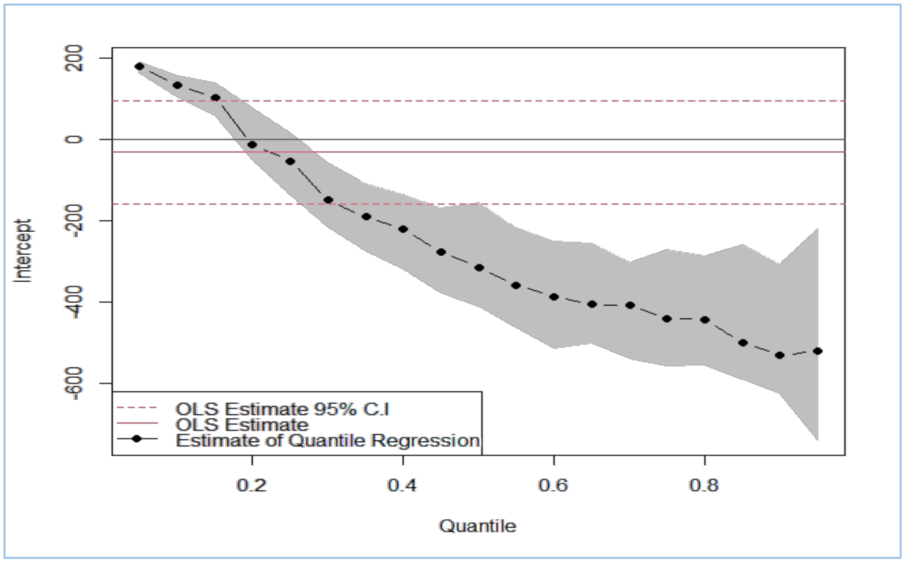
(b)

Figure 66. Upstream Influence Area Parameter Estimates – Quantile Regression

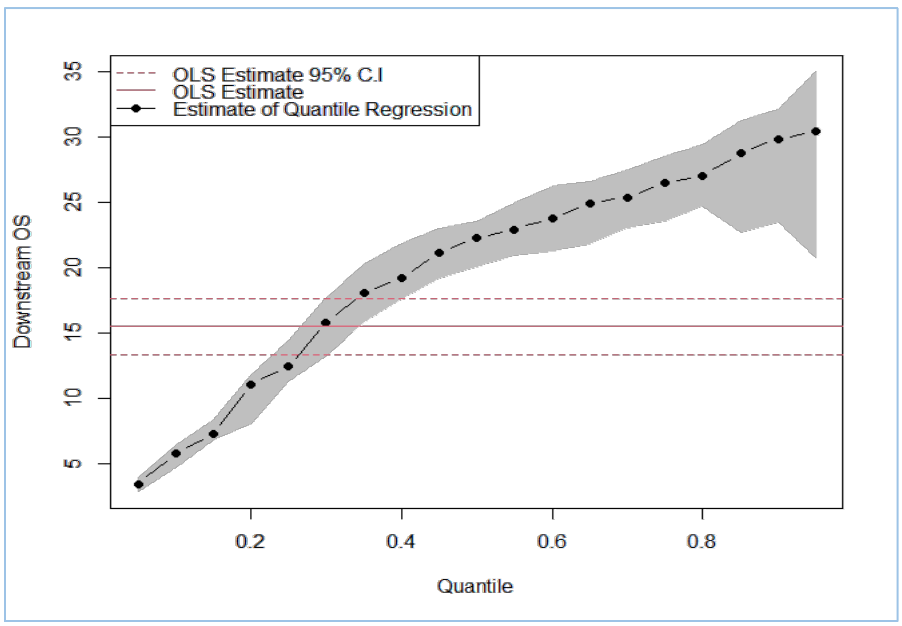


(c)

Figure 66 continued. Upstream Influence Area Parameter Estimates – Quantile Regression

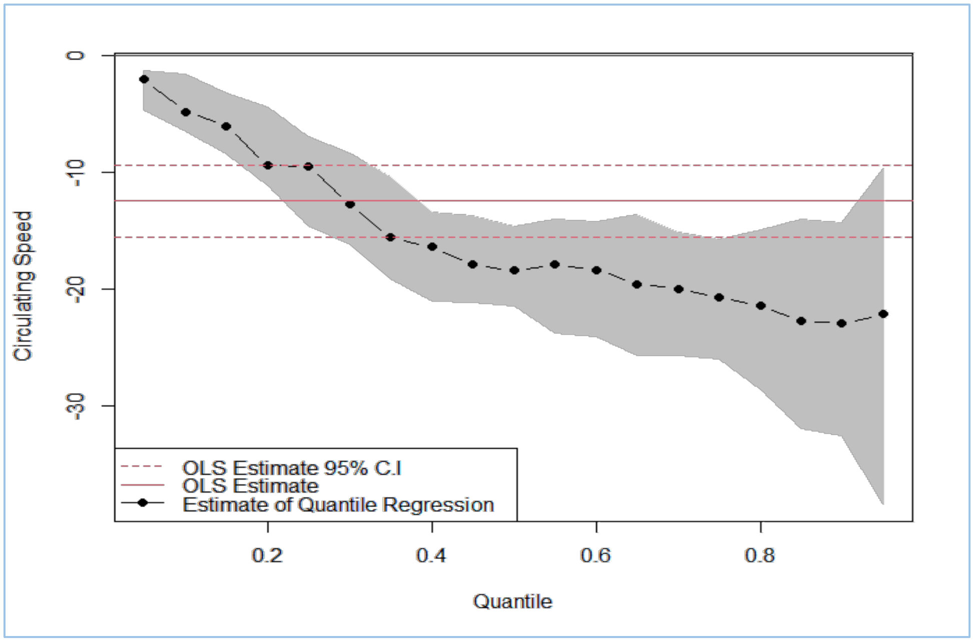


(a)



(b)

Figure 67. Downstream Influence Area Parameter Estimates – Quantile Regression



(c)

Figure 67 continued. Downstream Influence Area Parameter Estimates – Quantile Regression

Signal-Control Influence Area Estimation

This section discusses the development of statistical models for estimating the upstream and downstream influence areas for a signal-control intersection. Several models were developed and evaluated with different regressors. However, only a few variables such as upstream and downstream segment operating speeds, percent heavy vehicles, and facility type (two-lane vs. multilane highway) were found to have statistically significant effects on the upstream and downstream influence areas of signal-control intersection.

The parameter estimates for the signalized intersection upstream and downstream influence area models are presented in Table 21. For each quantile model, parameter estimates are provided, along with standard errors and the p-value that corresponds to the t-statistic used to evaluate whether each of these parameters was significantly different from zero. The results imply that the length of the upstream influence area at signalized intersections is directly related to the operating speed on the upstream segment and the percentage of trucks (heavy vehicles), while a multilane highway has a shorter influence area than the two-lane highway.

Quantile regression Vs. OLS Comparison. **Figure 68** and **Figure 69** provide a graphical comparison of the parameter estimates for each quantile along with the same estimates for an Ordinary Least Squares (OLS) regression model of the mean influence area. When examining these plots, the OLS parameter estimates are reflected by a horizontal solid red line along with the associated 95% confidence intervals (C.I.) represented by dashed red lines. If the quantile regression parameter estimates fall outside of the 95% C.I. boundary, it implies that the difference between the OLS parameter estimate and the quantile regression estimate is statistically significant at the 95% confidence level. For instance, **Figure 68** illustrates that the parameter estimates of the upstream operating speed (top right plot) are statistically significantly different than the parameter estimates of OLS for all percentiles except in the range of 45th to 55th percentiles (lie within the boundaries of 95% C.I. of OLS parameter estimates). Similarly, the parameter estimates of the downstream influence area model at different quantiles are mostly located outside of the 95% confidence boundary of OLS parameter estimates, as shown in **Figure 69**, and hence, are statistically significantly different than the OLS estimates. Thus, this analysis suggests that quantile regression is able to identify relationships in the data that would not be otherwise possible under the more typical OLS framework.

Table 21. Linear Quantile Regression Models for Influence Area at Signal-Control Study Sites

Dependent Variable: Upstream Influence Area Length (ft)						
	τ = 0.50		τ = 0.70		τ = 0.85	
Parameters	**Estimate *(Std. Error)***	**p-value**	**Estimate *(Std. Error)***	**p-value**	**Estimate *(Std. Error)***	**p-value**
Intercept	-364.59 (24.08)	<0.0001	-457.91 (36.44)	<0.0001	-480.58 (46.18)	<0.0001
Upstream Operating Speed (mi/h)	22.53 (0.41)	<0.0001	25.93 (0.62)	<0.0001	29.02 (0.81)	<0.0001
Heavy vehicle (%)	0.56* (0.48)	0.244	2.55 (0.64)	<0.0001	3.25 (0.74)	<0.0001
Segment Type (multilane)	-227.56 (10.70)	<0.0001	-209.38 (15.43)	<0.0001	-225.01 (19.56)	<0.0001
Dependent Variable: Downstream Influence Area Length (ft)						
Parameters	τ = 0.50		τ = 0.70		τ = 0.85	
	Estimate *(Std. Error)*	**p-value**	**Estimate *(Std. Error)***	**p-value**	**Estimate *(Std. Error)***	**p-value**
Intercept	-1439.59 (43.12)	<0.0001	-1407.53 (50.00)	<0.0001	-1364.49 (47.68)	<0.0001
Downstream Operating Speed (mi/h)	48.34 (0.75)	<0.0001	50.12 (0.87)	<0.0001	51.24 (0.83)	<0.0001
Heavy vehicle (%)	3.79 (0.69)	<0.0001	5.46 (0.78)	<0.0001	7.51 (0.72)	<0.0001
Segment Type (multilane)	-105.52 (14.76)	<0.0001	-70.56 (16.75)	<0.0001	-8.79* (17.02)	0.6057

Note: Segment Type: 1 if multilane, 0 if two-lane highway, * indicates not significant at 95% confidence

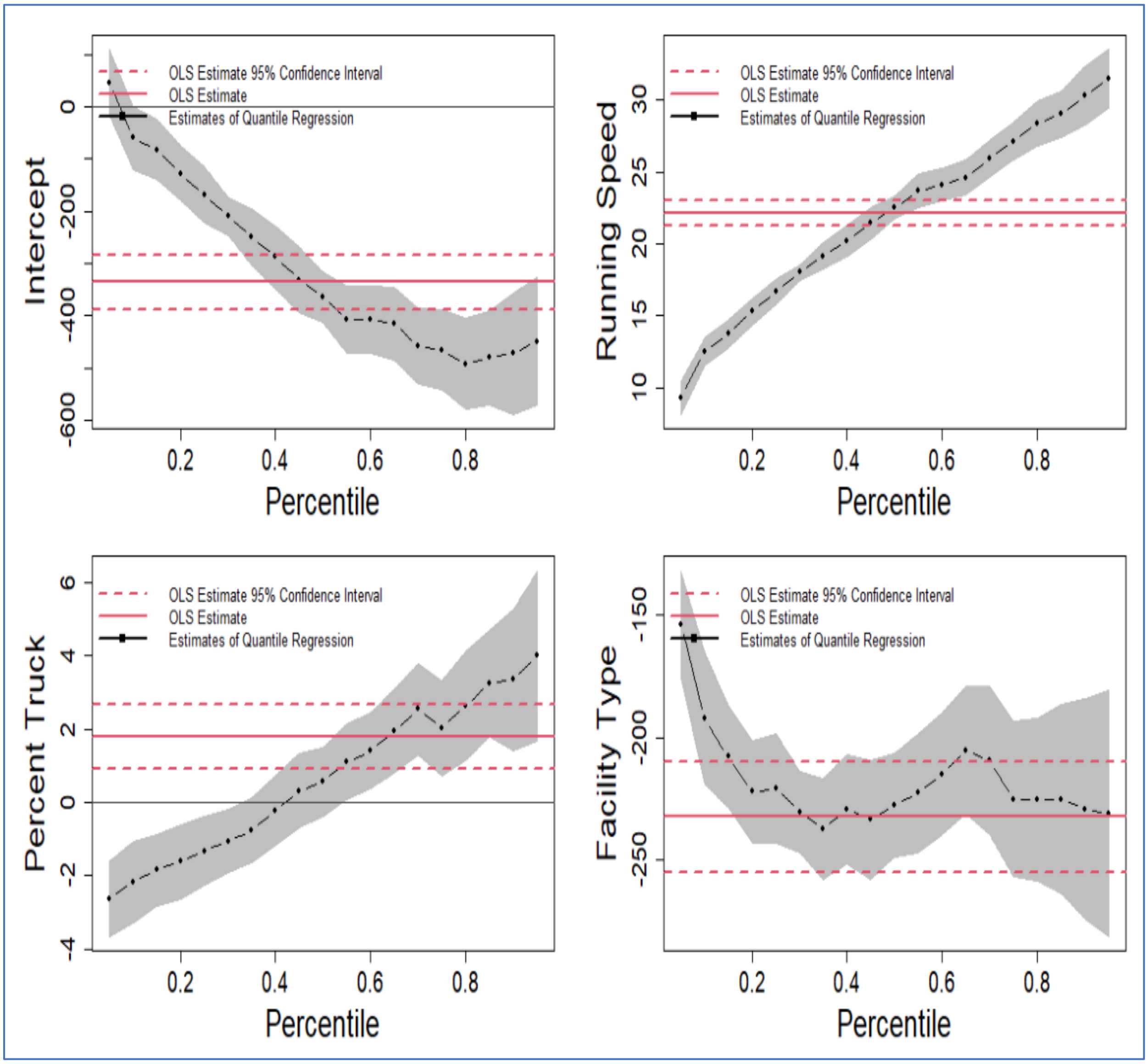


Figure 68. Comparison of Parameter Estimates – Quantile Regression vs. OLS for Upstream Influence Area at Signalized Intersections

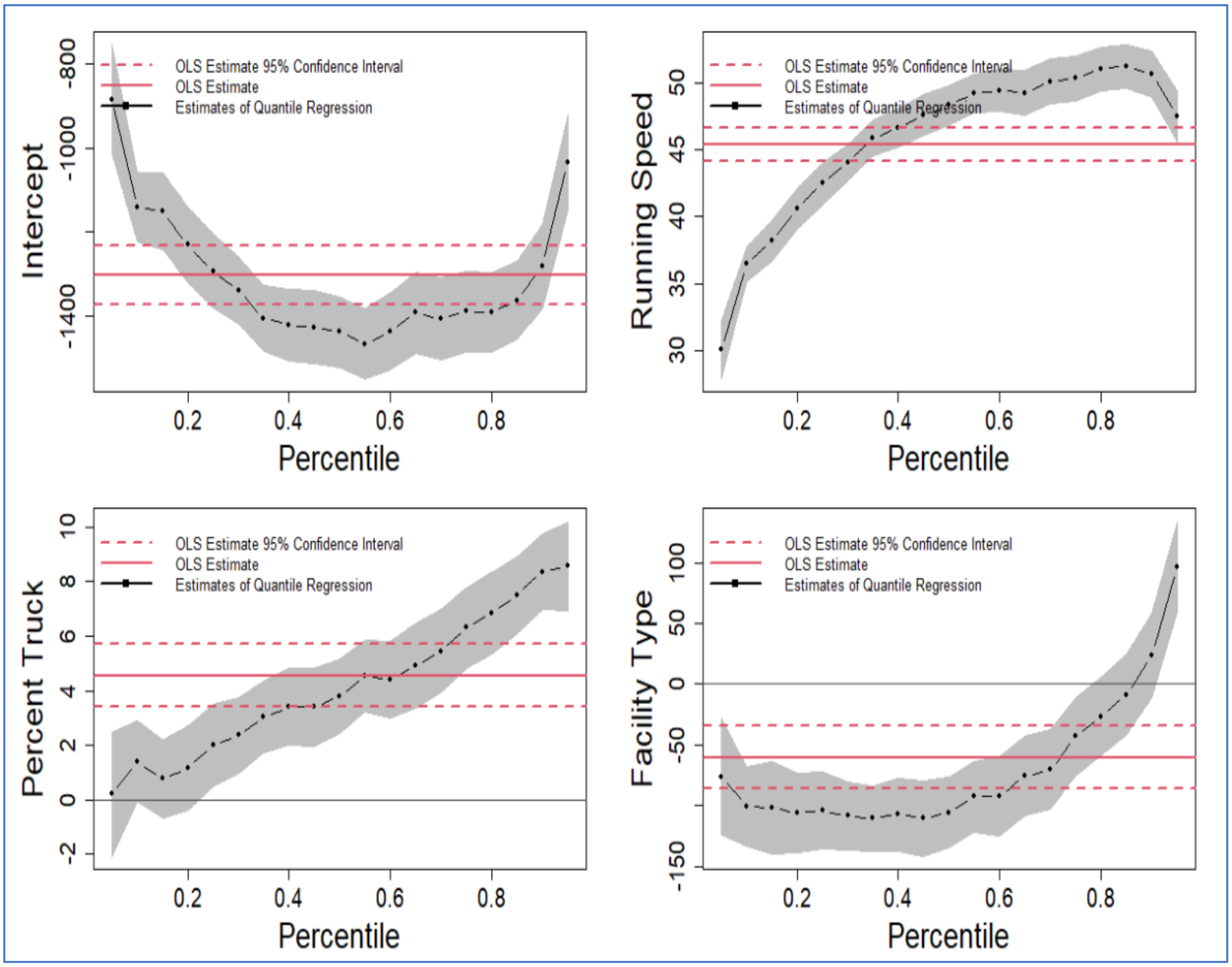


Figure 69. Comparison of Parameter Estimates – Quantile Regression vs. OLS for Downstream Influence Area at Signalized Intersections

<u>Stop-Control Influence Area Estimation</u>

For stop-control intersections, the quantile regression models were developed for the upstream and downstream influence areas and the parameter estimates are presented in **Table 22** and **Table 23**, respectively. Different variables were tested as regressors in the model such as AADT and heavy vehicle percentage. However, only the operating speed on the upstream and downstream segments was found statistically significant in the three models (50th, 70th, and 85th percentiles) presented in **Table 22** and **Table 23**.The probable reason is that roadways at the study sites, similar to most rural roadways, usually operate near free-flow conditions (well below capacity), besides the low percentage of heavy vehicles observed at the study sites. For each quantile (50^{th}, 70^{th}, and 85^{th}) model, parameter estimates are provided, along with standard errors and the p-value that corresponds to the t-statistic used to evaluate whether each of these parameters was significantly different from zero. The results imply that the length of the upstream influence areas at the stop-control intersection is directly related to the operating speed on the upstream segment. Similar, results were obtained for the downstream influence area of the stop-control intersection as presented in **Table 23**.

Table 22. Linear Quantile Regression Model for Upstream Influence Area of Stop-Control Intersection

Dependent Variable: Upstream Influence Area Length (ft)						
	τ = 0.50		τ = 0.70		τ = 0.85	
Parameters	**Estimate *(Std. Error)***	**p-value**	**Estimate *(Std. Error)***	**p-value**	**Estimate *(Std. Error)***	**p-value**
Intercept	-387.79 (38.74)	<0.0001	-408.91 (47.17)	<0.0001	-507.80 (72.95)	<0.0001
Upstream Operating Speed (mi/h)	21.47 (0.80)	<0.0001	23.90 (1.01)	<0.0001	27.80 (1.47)	<0.0001

Table 23. Linear Quantile Regression Model for Downstream Influence Area of Stop-Control Intersection

Dependent Variable: Downstream Influence Area Length (ft)		
	$\tau = 0.70$	
Parameters	**Estimate** ***(Std. Error)***	**p-value**
Intercept	-1067.63	<0.0001
Downstream Operating Speed (mi/h)	44.38	<0.0001

Quantile regression Vs. OLS Comparison. **Figure 70** provides a graphical comparison of the parameter estimates for each quantile (from percentile 5th to 95th by increment of 5) along with the same estimates for an Ordinary Least Squares (OLS) regression model of the mean influence area. When examining these plots, the OLS parameter estimates are reflected by a horizontal solid red line along with the associated 95% confidence intervals (C.I.) represented by dashed red lines. If the quantile regression parameter estimates fall outside of the 95% C.I. boundary, it implies that the difference between the OLS parameter estimate and the quantile regression estimate is statistically significant at the 95% confidence level. For instance, **Figure 70** illustrates that the parameter estimates of the upstream operating speed (top right plot) are statistically significantly different than the parameter estimates of OLS for all percentiles except in the range of 40th to 70th percentiles (lie within the boundaries of 95% C.I. of OLS parameter estimates).

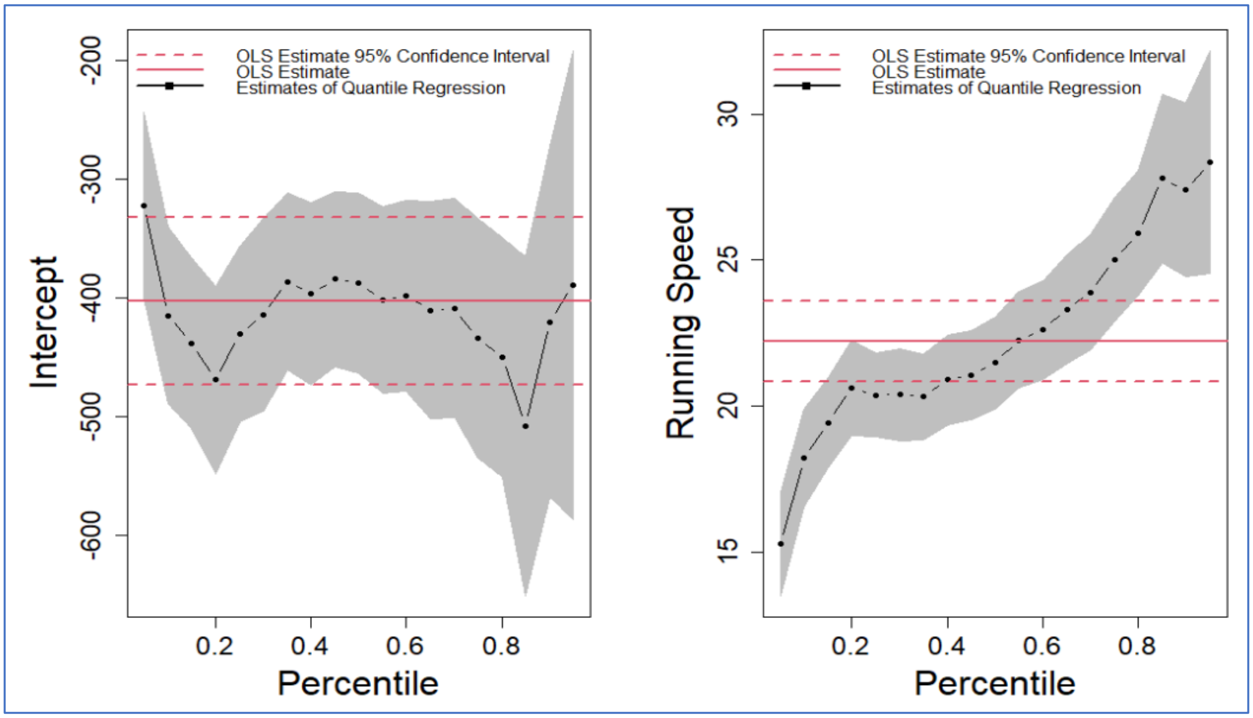


Figure 70. Comparison of Parameter Estimates – Quantile Regression vs. OLS for Upstream Influence Area at Stop-Control Intersection

Look-up Tables for Influence Areas

Considering that the proposed methodology for evaluating the quality of service is intended for use by transportation engineers in the field, it is more convenient to perform facility segmentation of rural highways using look-up tables rather than relying on statistical models. With this in mind, look-up tables for both upstream and downstream influence areas have been developed based on the statistical models presented in the preceding section on percentile analysis. These look-up tables provide transportation professionals with an accessible and efficient means of determining influence areas, thus facilitating the process of facility segmentation and operational analysis of rural highways.

The following sections briefly discuss the influence area look-up tables.

Roundabout Influence Area

Based on the detailed percentile analyses in the preceding section, the 50th percentile influence area was considered for roundabout intersections, as significant operational effects are observed at the 50th percentile distance of the influence area. Consequently, quantile regression models of the 50th percentiles were developed to estimate upstream and downstream influence areas of roundabouts. Equations 18 and 19 represent the 50th percentile models:

$$I.A._{Roundabout/Upstr} = 402.15 + 10.21 \times MeanOS_{Up} - 15.27 \times MeanCS \quad (18)$$

$$I.A._{Roundabout/Downstr} = -313.80 + 32.73 \times MeanOS_{Down} - 27.01 \times MeanCS \quad (19)$$

where,

- $\mathrm{I.A.}_{\mathrm{Roundabout/Upstr}}$ = upstream influence area of the roundabout (ft)
- $I.A._{Roundabout/Downstr}$ = downstream influence area of the roundabout (ft)
- $MeanOS_{Up}$ = upstream operating speed (mi/h)
- $MeanOS_{Dwn}$ = downstream operating speed (mi/h)
- CS = roundabout circulating speed (mi/h)

Utilizing the statistical models, influence area look-up tables have been developed, as shown in **Table 24** and **Table 25**. These tables enable the estimation of upstream and downstream influence areas using the mean operating speed and mean circulating speed inside the roundabout – thus providing a practical and efficient means of conducting facility segmentation for roundabout intersections.

Table 24. Upstream Influence Area at Roundabout Intersection

Mean Speed (mi/h)	**50th Percentile I.A. (ft)**			
	CS = 10 mi/h	**CS = 15 mi/h**	**CS = 20 mi/h**	**CS = 25 mi/h**
35	605	530	455	380
40	660	580	505	430
45	710	635	555	480
50	760	685	605	530
55	810	735	660	580
60	860	785	710	635

CS = circulating speed

Table 25. Downstream Influence Area at Roundabout Intersection

Mean Speed (mi/h)	**50th Percentile I.A. (ft)**			
	CS = 10 mi/h	**CS = 15 mi/h**	**CS = 20 mi/h**	**CS = 25 mi/h**
35	560	425	290	155
40	725	590	455	320
45	890	755	620	485
50	1050	920	780	650
55	1215	1080	945	810
60	1380	1245	1110	975

CS = circulating speed

Signal-Control Intersection

For signal-controlled intersections, the 70th percentile influence areas (encompassing both upstream and downstream) are deemed appropriate, as determined through percentile analyses of influence areas. It indicates that approximately 70% of drivers initiate deceleration within the length of the influence area, signifying that the signal-controlled system has a notable impact on traffic operations for about 70% of drivers. Conversely, only 30% of drivers begin deceleration at a farther upstream location than the specified 70th percentile influence area length.

To estimate the influence area at signal-control intersections, quantile regression models for the 70th percentile were formulated and are expressed in Equations 20 and 21:

$$I.A._{Signal/Upstr} = -923.89 + 35.92 \times MeanOS_{Up} + 1.23 \times \%HeavyVeh - 374.05 \times I_{multilane=1} \quad (20)$$

$$I.A._{Signal/Downstr} = -1929.64 + 60.25 \times MeanOS_{Down} + 7.23 \times \%HeavyVeh - 154.15 \times I_{multilane=1} \quad (21)$$

where,

- $\mathrm{I.A.}_{\mathrm{Signal/Upstr}}$ = upstream influence area of signal-control intersection (ft)
- $I.A._{Signal/Downstr}$ = downstream influence area of signal-control intersection (ft)
- $MeanOS_{Up}$ = upstream operating speed (mi/h)
- $MeanOS_{Down}$ = downstream operating speed (mi/h)
- $\%HeavyVeh$ = heavy vehicles in percentage
- $I_{multilane=1}$ = indicator variable of segment type: 1 if multilane and 0 if a two-lane highway

Based on these two equations, a set of four look-up tables (**Table 26** to **Table 29)** have been created to estimate the influence area at signal-control intersections on both multilane and two-lane highways. These tables are specifically designed to estimate the influence area, with two tables dedicated to upstream influence areas and two focusing on downstream influence areas.

Table 26. Upstream Influence Area at Signal-Control Intersection – Multilane Highway

Mean Speed (mi/h)	**70th Percentile I.A. (ft)**					
	H.V. 5%	H.V. 10%	H.V. 15%	H.V. 20%	H.V. 25%	H.V. 30%
45	325	330	335	345	350	355
50	505	510	515	520	530	535
55	685	690	695	700	710	715
60	865	870	875	880	890	895
65	1045	1050	1055	1060	1070	1075
70	1220	1230	1235	1240	1250	1255
75	1400	1410	1415	1420	1425	1430

*H.V. = heavy vehicle

Table 27. Upstream Influence Area at Signal-Control Intersection – Two-Lane Highway

Mean Speed (mi/h)	**70th Percentile I.A. (ft)**					
	H.V. 5%	H.V. 10%	H.V. 15%	H.V. 20%	H.V. 25%	H.V. 30%
45	700	705	710	720	725	730
50	880	885	890	895	900	910
55	1060	1065	1070	1075	1080	1090
60	1240	1245	1250	1255	1260	1270
65	1420	1425	1430	1435	1440	1450
70	1595	1600	1610	1615	1620	1630
75	1775	1780	1790	1795	1800	1810

*H.V. = heavy vehicle

Table 28. Downstream Influence Area at Signal-Control Intersection – Multilane Highway

Mean Speed (mi/h)	**70th Percentile I.A (ft)**					
	H.V. 5%	H.V. 10%	H.V. 15%	H.V. 20%	H.V. 25%	H.V. 30%
45	660	700	735	770	810	845
50	965	1000	1035	1070	1110	1145
55	1265	1300	1340	1345	1410	1445
60	1565	1600	1640	1675	1710	1750
65	1870	1900	1940	1975	2015	2050
70	2170	2205	2240	2280	2315	2350
75	2470	2505	2540	2580	2615	2650

*H.V. = heavy vehicle

Table 29. Downstream Influence Area at Signal-Control Intersection – Two Highway

Mean Speed (mi/h)	70th Percentile I.A (ft)					
	H.V. 5%	H.V. 10%	H.V. 15%	H.V. 20%	H.V. 25%	H.V. 30%
45	815	855	890	925	960	1000
50	1120	1155	1190	1225	1265	1300
55	1420	1455	1490	1530	1565	1600
60	1720	1755	1790	1830	1865	1900
65	2020	2060	2095	2130	2165	2200
70	2325	2360	2395	2430	2470	2505
75	2625	2660	2695	2730	2470	2805

*H.V. = heavy vehicle

Stop-Control Intersection

Similar to the signal-control intersections, the 70th percentile influence area was adopted for stop-control intersections as well. Two separate quantile regression models were developed: one representing the upstream influence area and the other representing the downstream influence area. These models are expressed in Equation 22 and Equation 23, respectively. Based on the 70th percentile models, two look-up tables were created, which are presented in **Table 30** and **Table 31.** This approach enables transportation engineers to easily and efficiently estimate influence areas based on the average operating speed of the segment.

$$I.A._{Stop/Upstr} = -1147.62 + 38.82 \times MeanOS_{Up} \quad (22)$$

$$I.A._{Stop/Downstr} = -1067.63 + 44.38 \times MeanOS_{Down} \quad (23)$$

where,

- $\mathrm{I.A.}_{\mathrm{Stop/Upstr}}$ = upstream influence area of stop-control intersection (ft)
- $I.A._{Stop/Downstr}$ = downstream influence area of stop-control intersection (ft)
- $MeanOS_{Up}$ = upstream operating speed (mi/h)
- $MeanOS_{Down}$ = downstream operating speed (mi/h)

Table 30. Upstream Influence Area at Stop-Control Intersections

Mean Speed (mi/h)	**70^{th} Percentile I.A (ft)**
45	570
50	760
55	950
60	1145
65	1335

Table 31. Downstream Influence Area at Stop-Control Intersections

Mean Speed (mph)	**70^{th} Percentile I.A (ft)**
45	930
50	1150
55	1370
60	1595
65	1815

CHAPTER FIVE

LEVEL-OF-SERVICE METHODOLOGY FOR RURAL HIGHWAY FACILITY

The primary objective of this research is to develop a comprehensive methodology for estimating the level of service (LOS) for rural facilities that consist of multiple segments and junctions. Segments may involve two-lane highways with and without passing constraints, passing lane sections, rural multilane highways, and urban street segments, whereas junctions may involve roundabouts, signal-control, and stop-control intersections. The prospective methodology is particularly significant as it allows transportation analysts to estimate the quality of service over an extended length of a rural highway that forms part of the primary route for the majority of traffic using the facility in question. This will ultimately lead to increased use of facility-level analysis and would allow local and state agencies to make informed decisions on operational improvements along rural highway facilities.

This chapter elaborates on the framework of the proposed methodology for quality of service assessment of a rural highway facility, as well as outlines the steps involved in implementing the proposed methodology. In the following discussions, the facility is used strictly to refer to an extended length of a rural highway comprising multiple segments and junctions, while individual segments and junctions of different types are referred to as components.

LOS-Based Methodology

This approach is based on the facility segmentation rules developed in this research (discussed in Chapter 4) as well as on the existing segment-level analysis methodologies in the most recent HCM edition (TRB, 2022). Specifically, it utilizes analysis methods for the following roadway segments and junctions:

- Multilane Highways (HCM Chapter # 12)
- Two-lane Highways (HCM Chapter # 15)
- Urban Streets (HCM Chapter # 18)
- Signalized Intersections (HCM Chapter # 19)
- Two-Way Stop-Control (TWSC) Intersections (HCM Chapter # 20)
- All-Way Stop-Control (AWSC) Intersections (HCM Chapter # 21)
- Roundabout Intersections (HCM Chapter # 22)

The proposed methodology does not attempt to adapt or validate any of the current procedures provided in the HCM, instead, outputs from these procedures will be used to assess the composite (global) facility-level LOS. The main advantage of adopting this approach is that it adheres strictly to the LOS concept as outlined in the HCM, without introducing any new measure or concept. A key requirement for an effective LOS performance measure is that the measure should be sensitive to the user’s perception of the quality of service. This approach utilizes the various performance measures in calculating the LOS for individual facility components, which are subsequently used in determining the composite facility-level LOS.

The current performance measures specific to each facility component for segment LOS determination are as follows:

- density (pc/mi/ln) for multilane highways
- follower density (followers/mi/ln) for two-lane highways
- control delay (s/veh) for intersections (signalized, stop control, roundabout)

- average speed (mi/h) for urban streets

Due to the lack of a homogeneous or common performance measure across rural highway components, the facility-level LOS determination cannot be accomplished using an aggregation method of any component-level performance measure (an approach that is used for urban and freeway facilities in HCM). To address this challenge, the proposed methodology converts heterogeneous performance measures into LOS rankings. Instead of employing the discrete and alphabetical order of LOS outlined in the HCM, this approach assigns numerical values on a continuous scale, derived from the specific service measure's numeric scale. Consequently, the determination of the rural highway facility-level LOS is achieved through an aggregation of segment-level LOS numerical values, providing a more nuanced and comprehensive evaluation of the facility's performance.

Methodology Approach

The facility-level LOS is estimated using the following five steps.

I. Implement the guidance developed in this research to perform facility segmentation, i.e., partitioning the facility into its distinct constituent components.

II. Apply the current HCM methodologies for the different components of the facility in order to estimate the performance measure for each component.

III. Convert the performance measures values to assign numerical LOS scores on a continuous scale that will subsequently be used in deriving the facility-level LOS.

IV. Aggregate the component LOS numerical values, weighted by travel time, into a composite (global) facility-level LOS numerical value. Facility-level LOS score is adjusted for variation using the LOS constancy adjustment factor.

V. Assign Facility LOS Letter Grade

Figure 71 illustrates the six steps required to determine the LOS of a rural highway facility.

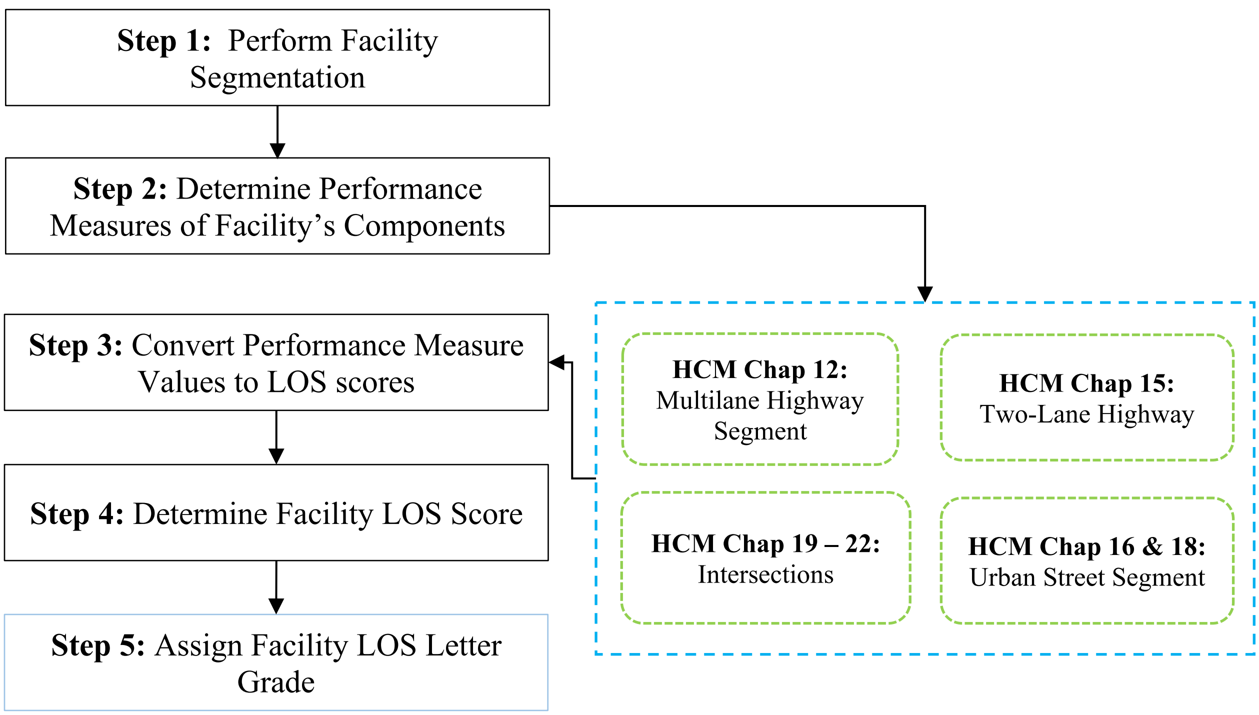


Figure 71. Rural Highway Facility Methodology

The following subsections provide a more in-depth discussion of the aforementioned steps.

Step I: Facility Segmentation

In order to apply the various segment-level HCM LOS methodologies, the rural facility has to be segmented into distinct components for which appropriate analysis procedures are provided in the HCM. For different segment types, the process of segmentation is relatively straightforward. For example, the start (or end) of passing lane sections or multilane highway sections roughly coincide at the location of lane addition (or lane drop). Similarly, pavement marking is used to delineate passing restricted sections and passing zones. However, at intersections (signal-control, roundabout, stop-control), the quality-of-service assessment should not only include the physical junction area but also the lengths along all approaches that are affected by the junction, commonly known as the "influence area." Moreover, it is essential that the analysis segment exhibits uniform characteristics such as geometry, grade, posted speed limit, traffic demand, and other pertinent attributes. Any change in any of the attributes necessitates the creation of a new segment to ensure accurate representation and application of the respective segment-level analysis. In Chapter 4 of this research, comprehensive guidelines for facility segmentation are provided, delineating the necessary steps and factors to be considered when partitioning transportation facilities into their constituent components.

Step II: Apply HCM Procedures for Facility Components

In this step, performance measures for all components of the facility are estimated using the HCM procedures outlined in their respective chapters and also briefly discussed in Chapter 2. This ensures that each facility component's analysis is carried out in accordance with the established procedures in the HCM, thereby ensuring consistency with the HCM component-level methodologies. By utilizing the HCM methodologies for segment-level analyses, this step provides a solid foundation for the subsequent steps of the facility-level LOS determination process.

Step III: Convert Performance Measures to Numerical LOS Value

Because of disparate performance measures across facility components (density, follower density, control delay, travel speed), and the range of uncertainty involved with the step-function nature of LOS, we propose a modification to the LOS value for the purpose of aggregating into a facility value.

LOS, on a letter scale, is a step function that means that different ranges of a performance measure of a component (segment or intersection) define specific LOS rankings as shown in **Table 32** (an example of a multilane highway with a density as a performance measure). For instance, two traffic conditions may result in performance measure values that are very close, yet they may be assigned two different LOSs (e.g., $density_1$ of 26 pc/mi/ln is LOS C, while $density_2$ = 27 pc/mi/ln is LOS D). Likewise, two traffic conditions that are significantly different may end up being assigned the same LOS (one near the lower limit and another near the upper limit of the LOS range). Similarly, **Figure 72** illustrates the step function nature of LOS based on traffic signal control delay (performance measure for intersections). It indicates that a 12-s increase in average control delay at a traffic signal may results in no change of LOS, however, a small increase (i.e., 2-s) in average control delay at the same traffic signal may results in a change from one LOS to another, as it depends on the starting value of delay (performance measure). A change in LOS indicates that the roadway performance has transitioned from one range of operational conditions to another range.

Table 32. LOS Scheme for Multilane Highway Segments (TRB, 2022)

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	Demand exceeds capacity OR density > 45

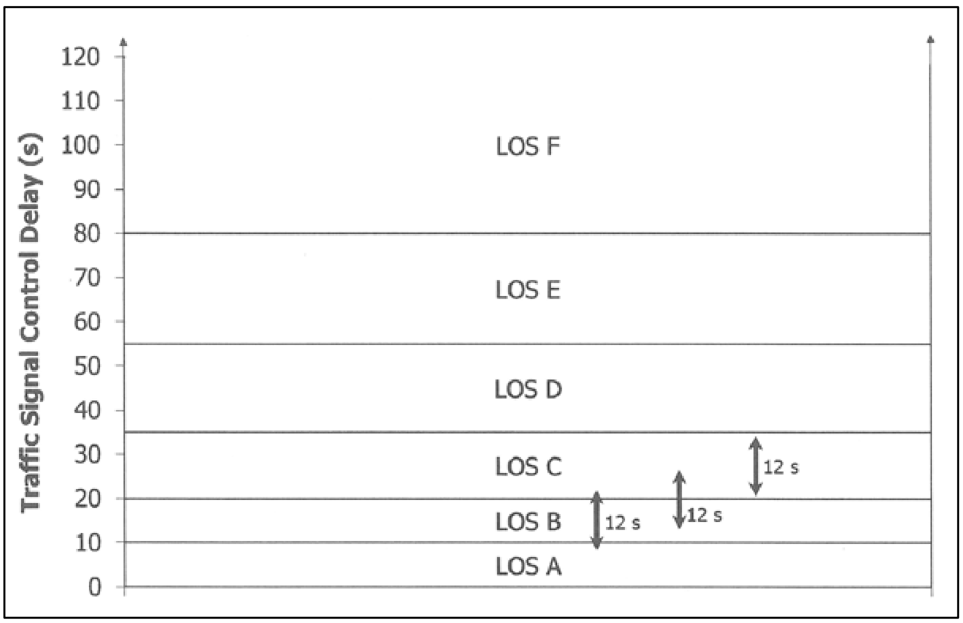


Figure 72. Example of the Step Function Nature of LOS (HCM, 2022)

While the current LOS approach seems simple and straightforward, it involves a good deal of approximation. However, the proposed modification in this research consists of treating the LOS as a continuous variable, with the exact value determined using the component-specific service measure. To address the different ranges assigned to various LOSs, these ranges are normalized to represent a 1.0-unit increment each on the LOS scale. **Figure 73** illustrates the continuous LOS function for two-lane highway segments using the follower density as a service measure. Functions for the other segment types are developed in a similar manner. For example, the LOS numeric value, referred to hereafter as LOS score, for a two-lane highway segment with a follower density of 6 followers/mi/ln would be 2.5. Whereas on a letter grade scale, the follower density of 4 to 8 followers/mi/ln is LOS C.

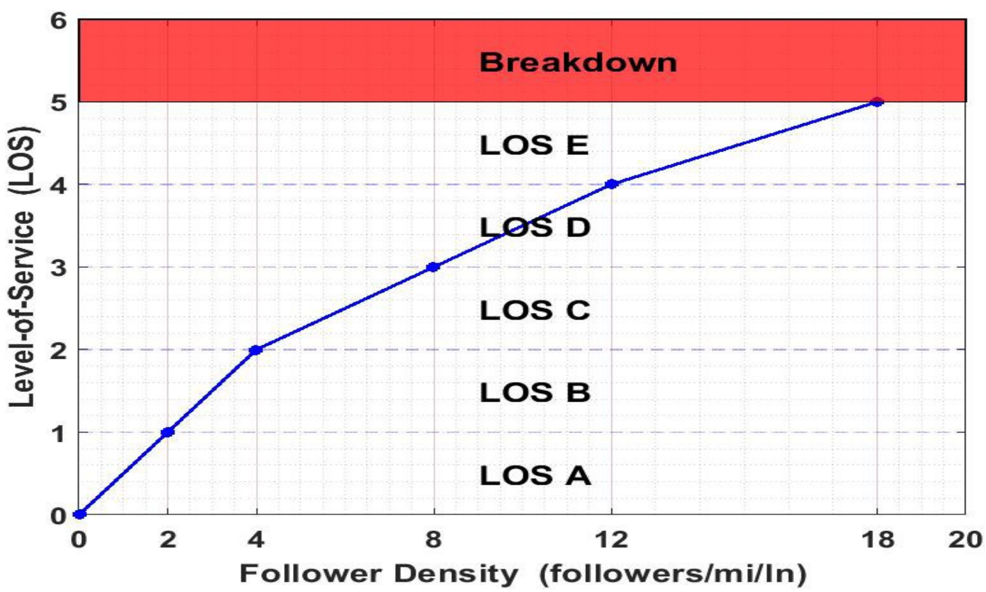
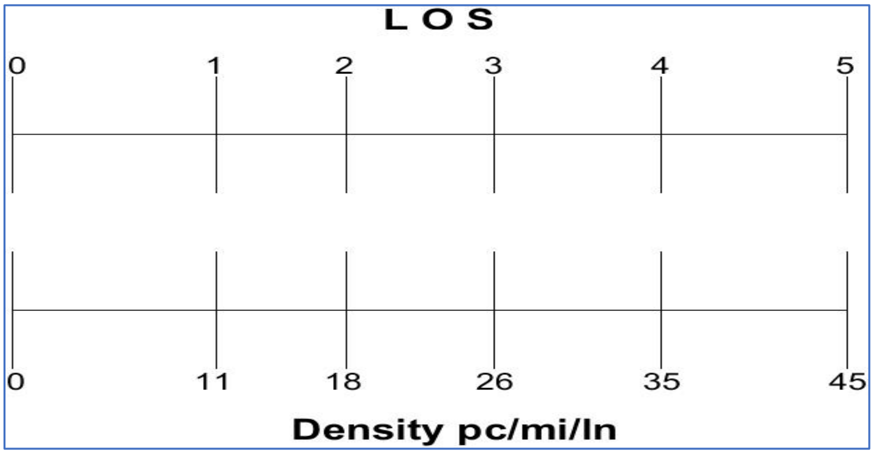
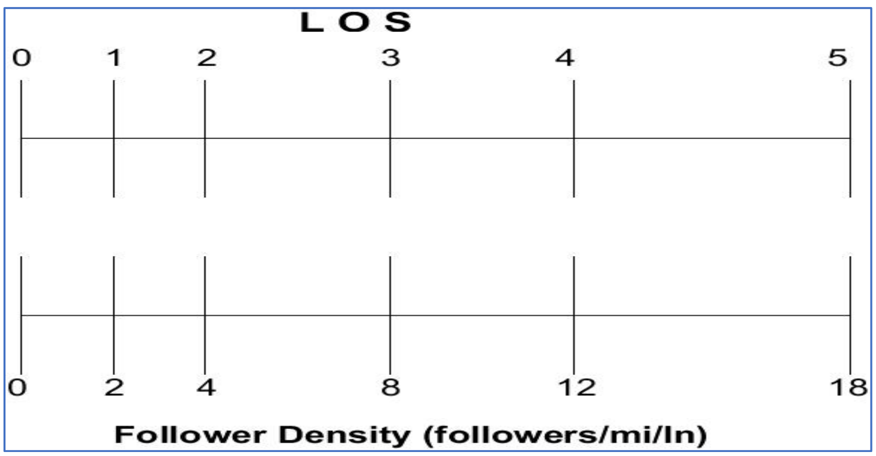


Figure 73. LOS Service Measure Value Conversion to Continuous LOS Numeric Value for Rural Two-Lane Highway (as an example)

Figure 74 illustrates the conversion of the letter grade LOS scale into a continuous numerical LOS score for different types of facility components, based on their respective performance measures. This approach has the advantage of assessing the quality of service at the facility level more accurately by treating the LOS as a continuous variable. By adopting a continuous scale, the methodology acknowledges the subtle variations in the quality of service that may not be captured by the traditional letter-grade LOS scale (step function). Thus, this conversion allows for a more nuanced evaluation of the facility components, ultimately contributing to a more accurate assessment of the overall facility-level LOS.

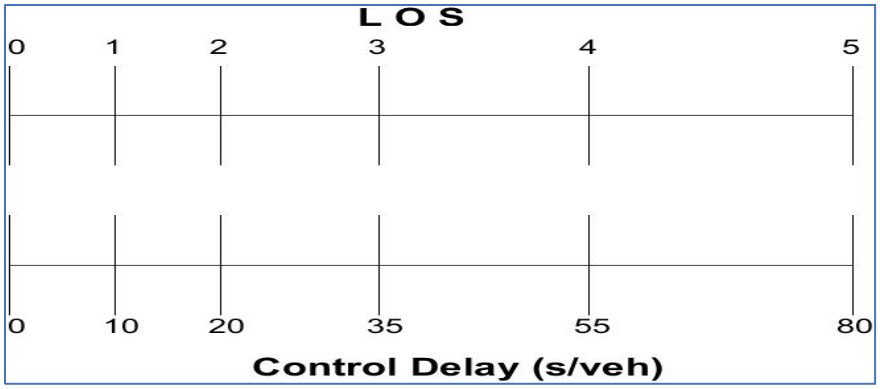


(a)

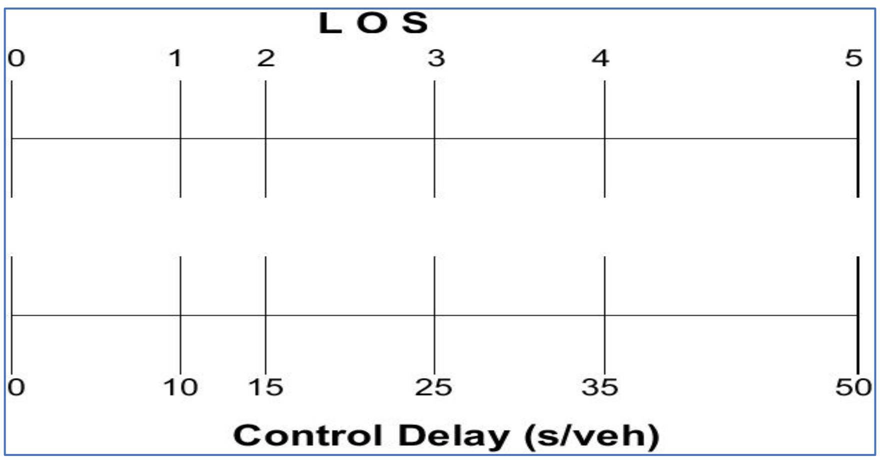


(b)

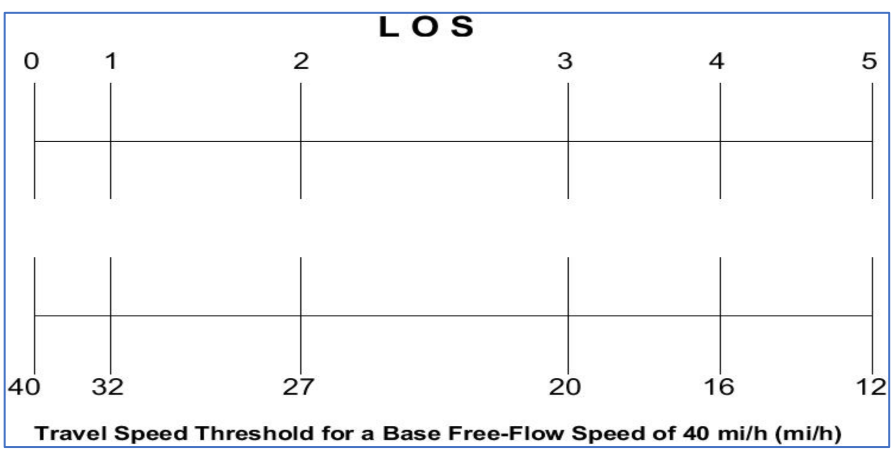
Figure 74. LOS Service Measure Value Conversion to Continuous LOS Numeric value for: (a)multilane highway segment, (b) two-lane highway segment, (c) signalized intersection, (d) unsignalized intersection, and (e) urban street segment (using 40 mi/h base free-flow



(c)



(d)



(e)

Figure 74 continued.

Step IV: Calculating the Facility-Level LOS Score

In this step, the LOS scores of individual components, obtained from Step III, are used to estimate a composite (global) LOS for the rural highway facility. This composite LOS facilitates the assessment of the quality of service on the rural highway facility in question. The aggregation of LOS scores for different components, resulting in a single composite LOS for the facility, can be achieved as follows:

In the proposed approach, LOS scores, weighted by the travel time of each component, are averaged to obtain composite LOS for the rural highway facility. Weighting by travel time is more realistic and aligns more closely with driver perceptions than using a straight arithmetic mean of segment LOS scores, resulting in a more accurate reflection of the overall user experience. The calculation for the facility LOS is expressed by the following equations:

$$LOS_{Faci} = \alpha_c \times \left[\frac{\sum_{i=1}^{n} LOS_{score_i} \times TravelTime_i}{\sum_{i=1}^{n} TravelTime_i}\right] \tag{24}$$

where,

LOS_{Faci} = average LOS score of the facility

α_c = constancy adjustment factor

LOS_{score_i} = LOS score for component i

n = number of components in the facility

$TravelTime_i$ = travel time for component i (s)

It is important to note that the facility-level quality of service is sensitive to the abrupt changes in LOSs of contiguous components. For example, a facility that consists of multiple components all operating at LOS C with one or two components operating at LOS B or D, is better from a quality of service perspective compared to the same facility with the same composite LOS but with abrupt changes in component LOSs, such as the majority of components operating at either LOS B or D. Similarly, a LOS that remains steady across multiple components before transitioning to a different LOS is more favorable from a quality of service perspective than frequent changes in component LOS, even when the facility-level LOS remains the same.

To account for the fluctuations in component-level LOS, both in terms of frequency and magnitude, a new measure is introduced, referred to as the "LOS Constancy" factor. The LOS Constancy factor can be defined using the following equation:

$$LOS\ Constancy = \frac{\sum_{i=2}^{n} |LOS_i - LOS_{i-1}|}{n-1} \tag{25}$$

Where,

$LOS\ Constancy$ = Steadiness of LOS across facility components

LOS_i = Level-of-service for component i

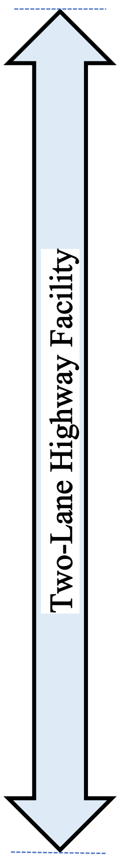
LOS_{i-1} = Level-of-service for preceding component $i-1$

n = Number of components in the facility

While the standard deviation (or variance) captures the variability in LOS scores of components within the facility, the LOS constancy captures not only the variability in LOS but also the frequency of the change. This concept can be demonstrated through a hypothetical example provided in . To simplify the example, the LOS score was expressed as a discrete variable (though using a continuous variable should provide a more precise estimation).

Both Scenario 1 and Scenario 2 have the same number of components (14 components) and share identical LOS scores of components (3xB, 7xC, and 4xD). However, the change in LOS for contiguous components differs, with Scenario 2 exhibiting higher fluctuations in LOSs across the facility. Thus, while the variability in LOSs across the facility is the same (equal standard deviations) for the two facilities, the LOS constancy factor is different and higher for Scenario 2. This highlights the difference in the frequency of change in LOS for contiguous components, emphasizing the importance of considering the LOS constancy factor in evaluating the overall quality of service for rural highway facilities.

Table 33. Example Illustrating the Concept of LOS Constancy along a Directional Two-Lane Highway Facility



Component	**LOS (Letter)**	**LOS (Score)**	**LOS Change**	**Component**	**LOS (Letter)**	**LOS (Score)**	**LOS Change**
1	B	2	---	1	C	3	---
2	B	2	0	2	C	3	0
3	B	2	0	3	B	2	-1
4	C	3	1	4	C	3	1
5	C	3	0	5	B	2	-1
6	C	3	0	6	D	4	2
7	C	3	0	7	C	3	-1
8	C	3	0	8	D	4	1
9	C	3	0	9	C	3	-1
10	C	3	0	10	B	2	-1
11	D	4	1	11	C	3	1
12	D	4	0	12	D	4	1
13	D	4	0	13	C	3	-1
14	D	4	0	14	D	4	1
Scenario A	LOS Std Deviation = 0.73			**Scenario B**	LOS Std Deviation = 0.73		
	LOS Constancy = 0.154				LOS Constancy = 1.0		

This aspect of the facility-level quality of service can potentially be incorporated into the analysis by adjusting the composite facility-level LOS using a multiplier (constancy adjustment factor α_c) to account for LOS constancy along the facility. This constancy adjustment factor is determined using a scale (0.9 to 1.1) which means that this adjustment factor can enhance or degrade facility LOS up to a maximum of 10 percent. The constancy adjustment factor is a function of the LOS Constancy of component LOSs as motorists traverse the facility in any given direction. This multiplier adjustment factor, represented by 'α_c', is set according to **Table 34** and is also illustrated in **Figure 75**.

Table 34. LOS Constancy Adjustment Factor for Facility LOS

Adjustment Factor Value (α)	**LOS Constancy Value**
α_c = 0.9	LOS Constancy ≤ 0.2
α_c = 0.25 × LOS Constancy Value + 0.85	0.2 < LOS Constancy < 1.0
α_c = 1.1	LOS Constancy ≥ 1.0

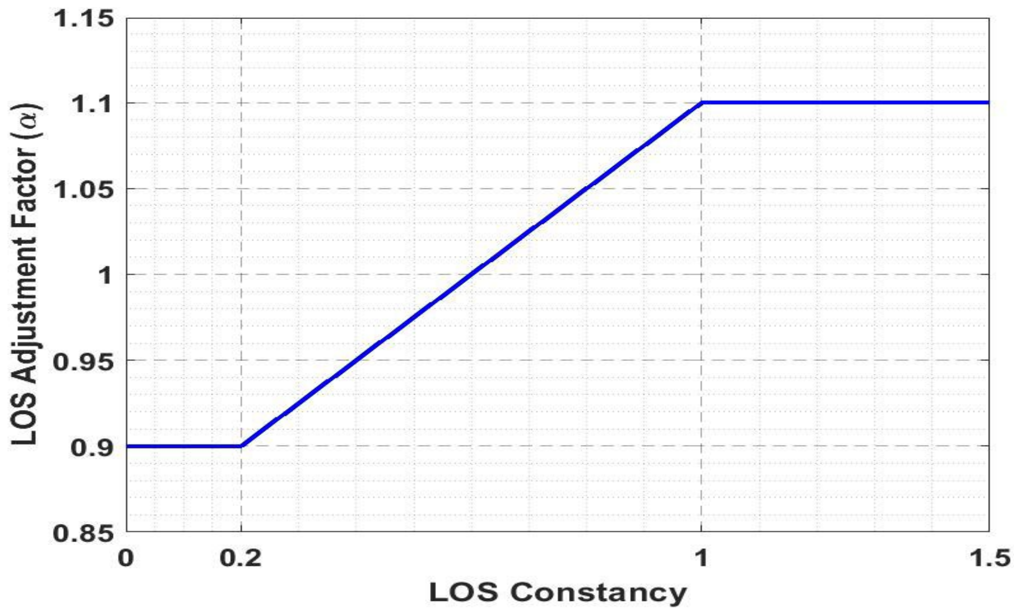


Figure 75. LOS Adjustment Factor Function of LOS Constancy

Step VI: Convert Facility LOS Score to Letter Grade LOS

In this step, the facility LOS score, computed in Step V, is converted to LOS (a letter grade). **Table 35** lists the LOS score ranges established for this purpose. It is important to note that the LOS descriptor for a rural highway facility should be considered differently from that at the component level, as drivers expect a higher quality of service (higher LOS) for their entire journey across the facility in comparison to their expectations of the quality of service (LOS) for a single component. For example, an LOS D on a single segment might be acceptable to drivers; however, an LOS D for an extended length of a facility may lead to driver frustration and may be deemed unacceptable. As a result, when converting the facility LOS score to a letter grade, transportation analysts and decision-makers should take into account the unique expectations and perceptions of drivers in relation to the overall facility, rather than merely considering individual components.

Table 35. LOS Criteria for Rural Highway Facility

Facility LOS Grade	Facility LOS Score
A	0 – 1
B	>1 – 2
C	>2 – 3
D	>3 – 4
E	>4 – 5
F	>5

Furthermore, the LOS for the overall rural highway facility should be interpreted with caution. It is imperative to report the LOS for individual components constituting the facility as well. Since the overall LOS represents an average, it may hide or obscure critical issues within individual segments of the facility, thereby leading to an inaccurate understanding of the facility's performance and potential challenges. In case any component of the rural highway facility exhibits a LOS F or a demand-to-capacity ratio greater than 1.0 (v/c >1.0), the applicability of the facility LOS becomes limited. In such cases, a more detailed assessment of the specific component is necessary to accurately understand and address the underlying issues impacting the quality of service.

In order to ensure a comprehensive assessment, it is essential to consider both the overall and component-level LOS in parallel, as this approach provides a more accurate depiction of the quality of service within the facility.

CHAPTER SIX

FACILITY-LEVEL RURAL HIGHWAY ANALYSIS: CASE STUDIES

This chapter presents a computational engine specifically developed to implement the proposed methodology for analyzing rural highway facilities. Moreover, it provides an examination of two case studies, which serve to illustrate the practical application of the quality of service analysis method proposed in this research.

Computational Engine for LOS Analysis

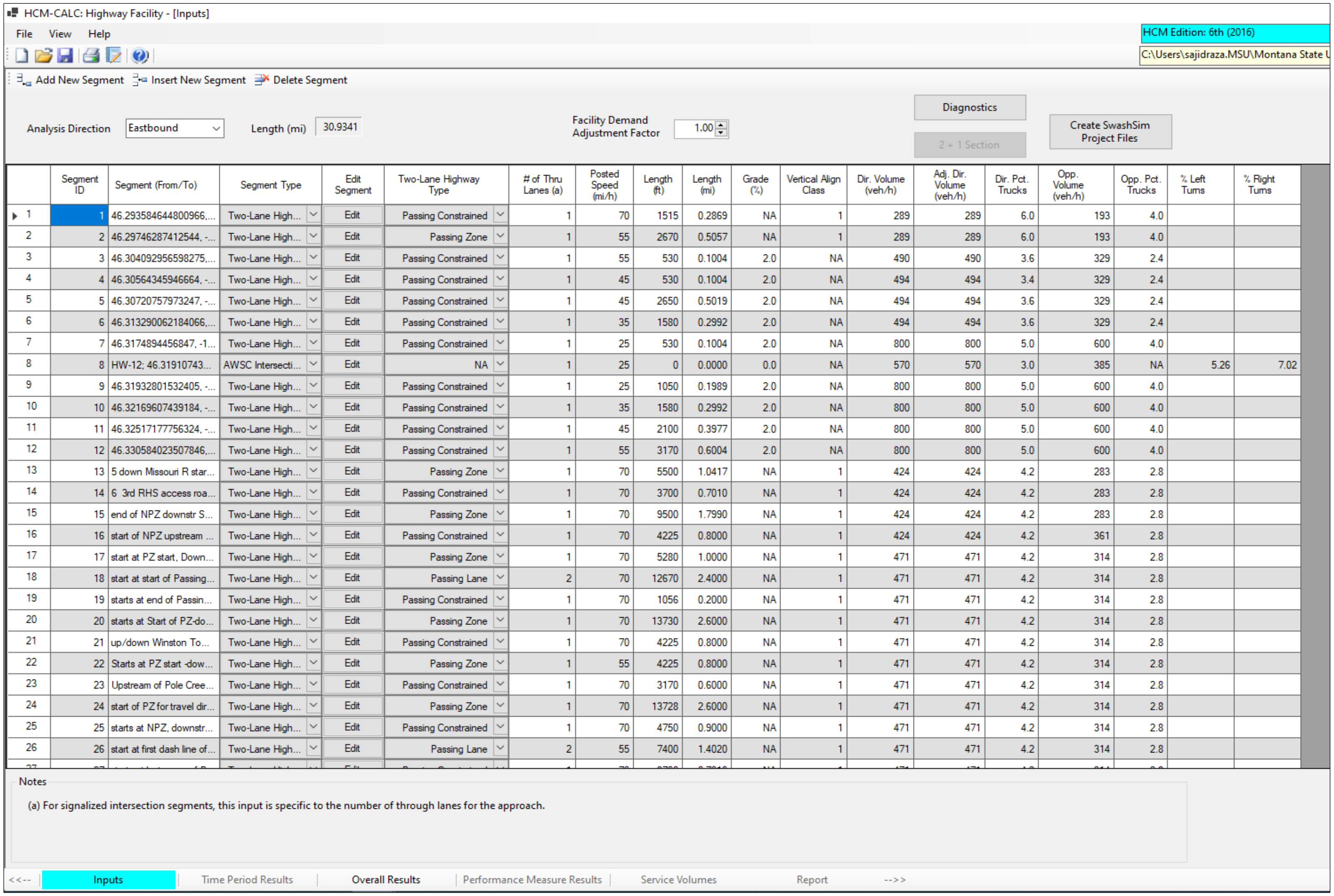
The proposed rural highway facility analysis methodology necessitates a comprehensive and extensive set of calculations to conduct the quality of service assessments. In order to facilitate the process and enhance efficiency for transportation analysts, a computational engine, known as HCM-Calc, is developed to perform facility-level analysis of rural highways. Developed by Scott Washburn, Ph.D., at the University of Florida, HCM-Calc is freely available for download and can be accessed via the provided link.

HCM-Calc encompasses calculations for the following roadway components, including:

- Multilane highway segments
- Two-lane highway segments
- Signalized intersections
- Roundabout intersections
- All-way stop-controlled intersections
- Urban streets (featuring signalized or uncontrolled intersections; all-way stop-controlled intersections and roundabouts are currently in progress)

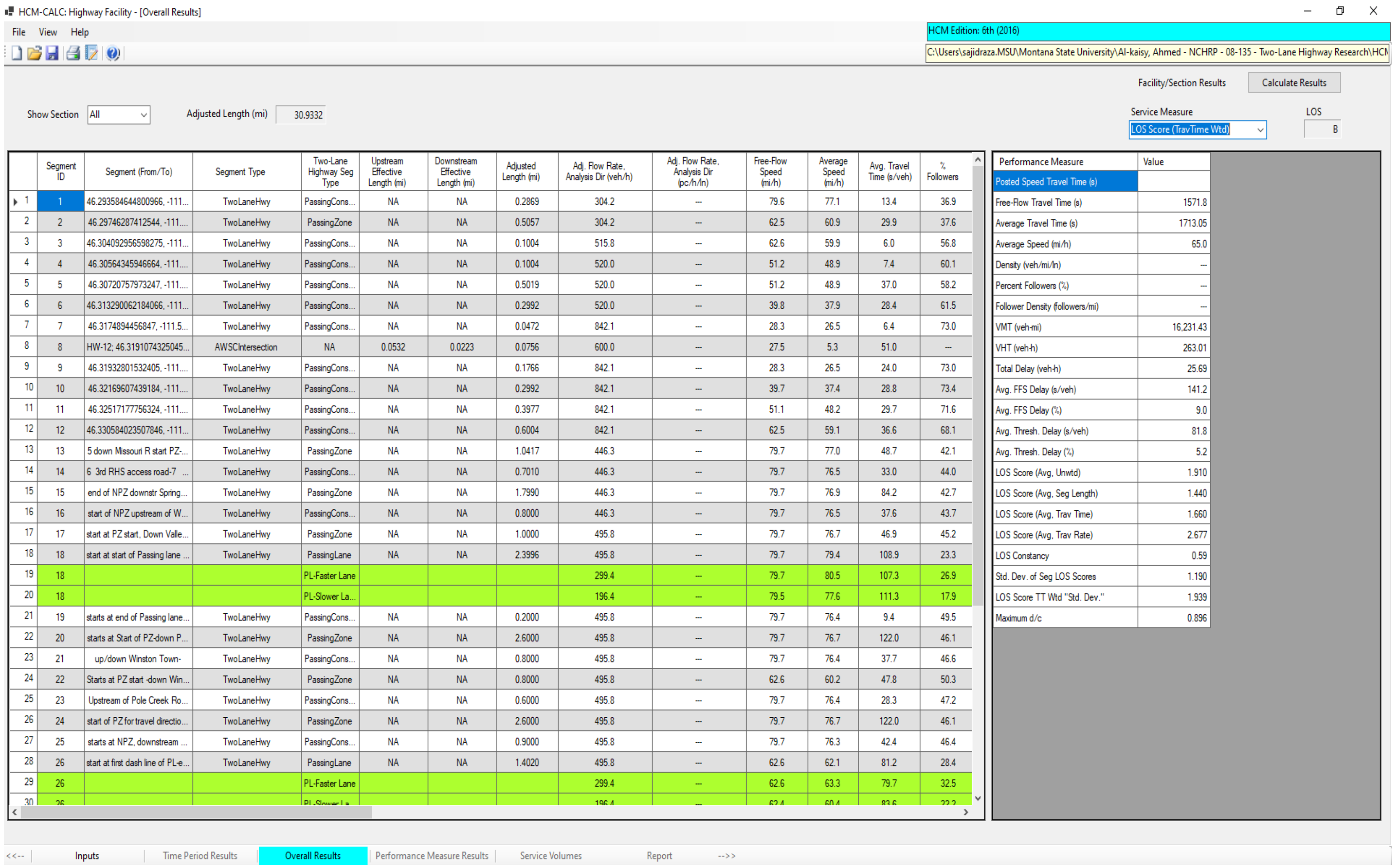
These calculations are based on methodologies outlined in the respective chapters of the most recent edition of the HCM. To conduct an analysis of rural highway facilities using the HCM-Calc software, it is essential to input the necessary data for each component of the facility, as specified in the HCM. This data must be entered into the input interface of HCM-Calc, which is illustrated in **Figure 76**. The input data interface for each component is designed to be user-friendly and intuitive, enabling transportation analysts to easily adjust or modify variables such as traffic volume, segment length, intersection control, and more. Upon completion of the data input process, the analyst can generate the results of the analysis with a single click.

A notable advantage of the HCM-Calc software is its ability to provide not only facility-level LOS results, but also LOS for individual components within the facility. In addition to LOS, HCM-Calc presents various other performance measures, such as travel time, demand-to-capacity ratio, vehicle miles traveled, total delays, and average travel speed. The output screen is shown in **Figure 77**.



	Segment ID	Segment (From/To)	Segment Type	Edit Segment	Two-Lane Highway Type	# of Thru Lanes (a)	Posted Speed (mi/h)	Length (ft)	Length (mi)	Grade (%)	Vertical Align Class	Dir. Volume (veh/h)	Adj. Dir. Volume (veh/h)	Dir. Pct. Trucks	Opp. Volume (veh/h)	Opp. Pct. Trucks	% Left Turns	% Right Turns
1	1	46.293584644800966,...	Two-Lane High...	Edit	Passing Constrained	1	70	1515	0.2869	NA	1	289	289	6.0	193	4.0		
2	2	46.29746287412544, -...	Two-Lane High...	Edit	Passing Zone	1	55	2670	0.5057	NA	1	289	289	6.0	193	4.0		
3	3	46.304092956598275,...	Two-Lane High...	Edit	Passing Constrained	1	55	530	0.1004	2.0	NA	490	490	3.6	329	2.4		
4	4	46.30564345946664, -...	Two-Lane High...	Edit	Passing Constrained	1	45	530	0.1004	2.0	NA	494	494	3.4	329	2.4		
5	5	46.30720757973247, -...	Two-Lane High...	Edit	Passing Constrained	1	45	2650	0.5019	2.0	NA	494	494	3.6	329	2.4		
6	6	46.313290062184066,...	Two-Lane High...	Edit	Passing Constrained	1	35	1580	0.2992	2.0	NA	494	494	3.6	329	2.4		
7	7	46.3174894456847, -1...	Two-Lane High...	Edit	Passing Constrained	1	25	530	0.1004	2.0	NA	800	800	5.0	600	4.0		
8	8	HW-12; 46.31910743...	AWSC Intersecti...	Edit	NA	1	25	0	0.0000	0.0	NA	570	570	3.0	385	NA	5.26	7.02
9	9	46.31932801532405, -...	Two-Lane High...	Edit	Passing Constrained	1	25	1050	0.1989	2.0	NA	800	800	5.0	600	4.0		
10	10	46.32169607439184, -...	Two-Lane High...	Edit	Passing Constrained	1	35	1580	0.2992	2.0	NA	800	800	5.0	600	4.0		
11	11	46.32517177756324, -...	Two-Lane High...	Edit	Passing Constrained	1	45	2100	0.3977	2.0	NA	800	800	5.0	600	4.0		
12	12	46.330584023507846,...	Two-Lane High...	Edit	Passing Constrained	1	55	3170	0.6004	2.0	NA	800	800	5.0	600	4.0		
13	13	5 down Missouri R star...	Two-Lane High...	Edit	Passing Zone	1	70	5500	1.0417	NA	1	424	424	4.2	283	2.8		
14	14	6 3rd RHS access roa...	Two-Lane High...	Edit	Passing Constrained	1	70	3700	0.7010	NA	1	424	424	4.2	283	2.8		
15	15	end of NPZ downstr S...	Two-Lane High...	Edit	Passing Zone	1	70	9500	1.7990	NA	1	424	424	4.2	283	2.8		
16	16	start of NPZ upstream ...	Two-Lane High...	Edit	Passing Constrained	1	70	4225	0.8000	NA	1	424	424	4.2	361	2.8		
17	17	start at PZ start, Down...	Two-Lane High...	Edit	Passing Zone	1	70	5280	1.0000	NA	1	471	471	4.2	314	2.8		
18	18	start at start of Passing...	Two-Lane High...	Edit	Passing Lane	2	70	12670	2.4000	NA	1	471	471	4.2	314	2.8		
19	19	starts at end of Passin...	Two-Lane High...	Edit	Passing Constrained	1	70	1056	0.2000	NA	1	471	471	4.2	314	2.8		
20	20	starts at Start of PZ-do...	Two-Lane High...	Edit	Passing Zone	1	70	13730	2.6000	NA	1	471	471	4.2	314	2.8		
21	21	up/down Winston To...	Two-Lane High...	Edit	Passing Constrained	1	70	4225	0.8000	NA	1	471	471	4.2	314	2.8		
22	22	Starts at PZ start -dow...	Two-Lane High...	Edit	Passing Zone	1	55	4225	0.8000	NA	1	471	471	4.2	314	2.8		
23	23	Upstream of Pole Cree...	Two-Lane High...	Edit	Passing Constrained	1	70	3170	0.6000	NA	1	471	471	4.2	314	2.8		
24	24	start of PZ for travel dir...	Two-Lane High...	Edit	Passing Zone	1	70	13728	2.6000	NA	1	471	471	4.2	314	2.8		
25	25	starts at NPZ, downstr...	Two-Lane High...	Edit	Passing Constrained	1	70	4750	0.9000	NA	1	471	471	4.2	314	2.8		
26	26	start at first dash line of...	Two-Lane High...	Edit	Passing Lane	2	55	7400	1.4020	NA	1	471	471	4.2	314	2.8		

Figure 76. Main Inputs Screen for Components of the Facility



	Segment ID	Segment (From/To)	Segment Type	Two-Lane Highway Seg Type	Upstream Effective Length (mi)	Downstream Effective Length (mi)	Adjusted Length (mi)	Adj. Flow Rate, Analysis Dir (veh/h)	Adj. Flow Rate, Analysis Dir (pc/h/ln)	Free-Flow Speed (mi/h)	Average Speed (mi/h)	Avg. Travel Time (s/veh)	% Followers
1	1	46.293584644800966, -111...	TwoLaneHwy	PassingCons...	NA	NA	0.2869	304.2	---	79.6	77.1	13.4	36.9
2	2	46.29746287412544, -111....	TwoLaneHwy	PassingZone	NA	NA	0.5057	304.2	---	62.5	60.9	29.9	37.6
3	3	46.304092956598275, -111...	TwoLaneHwy	PassingCons...	NA	NA	0.1004	515.8	---	62.6	59.9	6.0	56.8
4	4	46.30564345946664, -111....	TwoLaneHwy	PassingCons...	NA	NA	0.1004	520.0	---	51.2	48.9	7.4	60.1
5	5	46.30720757973247, -111....	TwoLaneHwy	PassingCons...	NA	NA	0.5019	520.0	---	51.2	48.9	37.0	58.2
6	6	46.313290062184066, -111...	TwoLaneHwy	PassingCons...	NA	NA	0.2992	520.0	---	39.8	37.9	28.4	61.5
7	7	46.3174894456847, -111.5...	TwoLaneHwy	PassingCons...	NA	NA	0.0472	842.1	---	28.3	26.5	6.4	73.0
8	8	HW-12; 46.3191074325045...	AWSCIntersection	NA	0.0532	0.0223	0.0756	600.0	---	27.5	5.3	51.0	---
9	9	46.31932801532405, -111....	TwoLaneHwy	PassingCons...	NA	NA	0.1766	842.1	---	28.3	26.5	24.0	73.0
10	10	46.32169607439184, -111....	TwoLaneHwy	PassingCons...	NA	NA	0.2992	842.1	---	39.7	37.4	28.8	73.4
11	11	46.32517177756324, -111....	TwoLaneHwy	PassingCons...	NA	NA	0.3977	842.1	---	51.1	48.2	29.7	71.6
12	12	46.330584023507846, -111...	TwoLaneHwy	PassingCons...	NA	NA	0.6004	842.1	---	62.5	59.1	36.6	68.1
13	13	5 down Missouri R start PZ-...	TwoLaneHwy	PassingZone	NA	NA	1.0417	446.3	---	79.7	77.0	48.7	42.1
14	14	6 3rd RHS access road-7 ...	TwoLaneHwy	PassingCons...	NA	NA	0.7010	446.3	---	79.7	76.5	33.0	44.0
15	15	end of NPZ downstr Spring...	TwoLaneHwy	PassingZone	NA	NA	1.7990	446.3	---	79.7	76.9	84.2	42.7
16	16	start of NPZ upstream of W...	TwoLaneHwy	PassingCons...	NA	NA	0.8000	446.3	---	79.7	76.5	37.6	43.7
17	17	start at PZ start, Down Valle...	TwoLaneHwy	PassingZone	NA	NA	1.0000	495.8	---	79.7	76.7	46.9	45.2
18	18	start at start of Passing lane ...	TwoLaneHwy	PassingLane	NA	NA	2.3996	495.8	---	79.7	79.4	108.9	23.3
19	18			PL-Faster Lane				299.4	---	79.7	80.5	107.3	26.9
20	18			PL-Slower La...				196.4	---	79.5	77.6	111.3	17.9
21	19	starts at end of Passing lane...	TwoLaneHwy	PassingCons...	NA	NA	0.2000	495.8	---	79.7	76.4	9.4	49.5
22	20	starts at Start of PZ-down P...	TwoLaneHwy	PassingZone	NA	NA	2.6000	495.8	---	79.7	76.7	122.0	46.1
23	21	up/down Winston Town-	TwoLaneHwy	PassingCons...	NA	NA	0.8000	495.8	---	79.7	76.4	37.7	46.6
24	22	Starts at PZ start -down Win...	TwoLaneHwy	PassingZone	NA	NA	0.8000	495.8	---	62.6	60.2	47.8	50.3
25	23	Upstream of Pole Creek Ro...	TwoLaneHwy	PassingCons...	NA	NA	0.6000	495.8	---	79.7	76.4	28.3	47.2
26	24	start of PZ for travel directio...	TwoLaneHwy	PassingZone	NA	NA	2.6000	495.8	---	79.7	76.7	122.0	46.1
27	25	starts at NPZ, downstream ...	TwoLaneHwy	PassingCons...	NA	NA	0.9000	495.8	---	79.7	76.3	42.4	46.4
28	26	start at first dash line of PL-e...	TwoLaneHwy	PassingLane	NA	NA	1.4020	495.8	---	62.6	62.1	81.2	28.4
29	26			PL-Faster Lane				299.4	---	62.6	63.3	79.7	32.5
30	26			PL-Slower La...				196.4	---	62.4	60.4	83.6	22.2

Performance Measure	Value
Posted Speed Travel Time (s)	
Free-Flow Travel Time (s)	1571.8
Average Travel Time (s)	1713.05
Average Speed (mi/h)	65.0
Density (veh/mi/ln)	---
Percent Followers (%)	---
Follower Density (followers/mi)	---
VMT (veh-mi)	16,231.43
VHT (veh-h)	263.01
Total Delay (veh-h)	25.69
Avg. FFS Delay (s/veh)	141.2
Avg. FFS Delay (%)	9.0
Avg. Thresh. Delay (s/veh)	81.8
Avg. Thresh. Delay (%)	5.2
LOS Score (Avg, Unwtd)	1.910
LOS Score (Avg, Seg Length)	1.440
LOS Score (Avg, Trav Time)	1.660
LOS Score (Avg, Trav Rate)	2.677
LOS Constancy	0.59
Std. Dev. of Seg LOS Scores	1.190
LOS Score TT Wtd "Std. Dev."	1.939
Maximum d/c	0.896

Figure 77. Facility Result (Outputs) Screen

The selected case studies encompass extended stretches of rural highway facilities, situated in two different states, Montana and Oregon, and feature a variety of configurations. These examples have been chosen to provide a comprehensive understanding of the proposed methodology's applicability and effectiveness in addressing real-world challenges related to rural highway facility analysis. The selected case studies are as follows:

i. US-20 Sisters City Corridor, Oregon

ii. US-287 Townsend Corridor, Montana

US-20 Sisters City Corridor, Oregon

Route Description

This corridor of rural highway is an approximately 26 miles stretch of US-20 in central Oregon. The route generally extends from the Jefferson County line to Cline Falls Hwy/OB Riley Rd in Tumalo [44.399010616037145, -121.68160872108665; 44.12954543870768, -121.32386641302361]. The route is shown in **Figure 78**, as well as the linked online map.

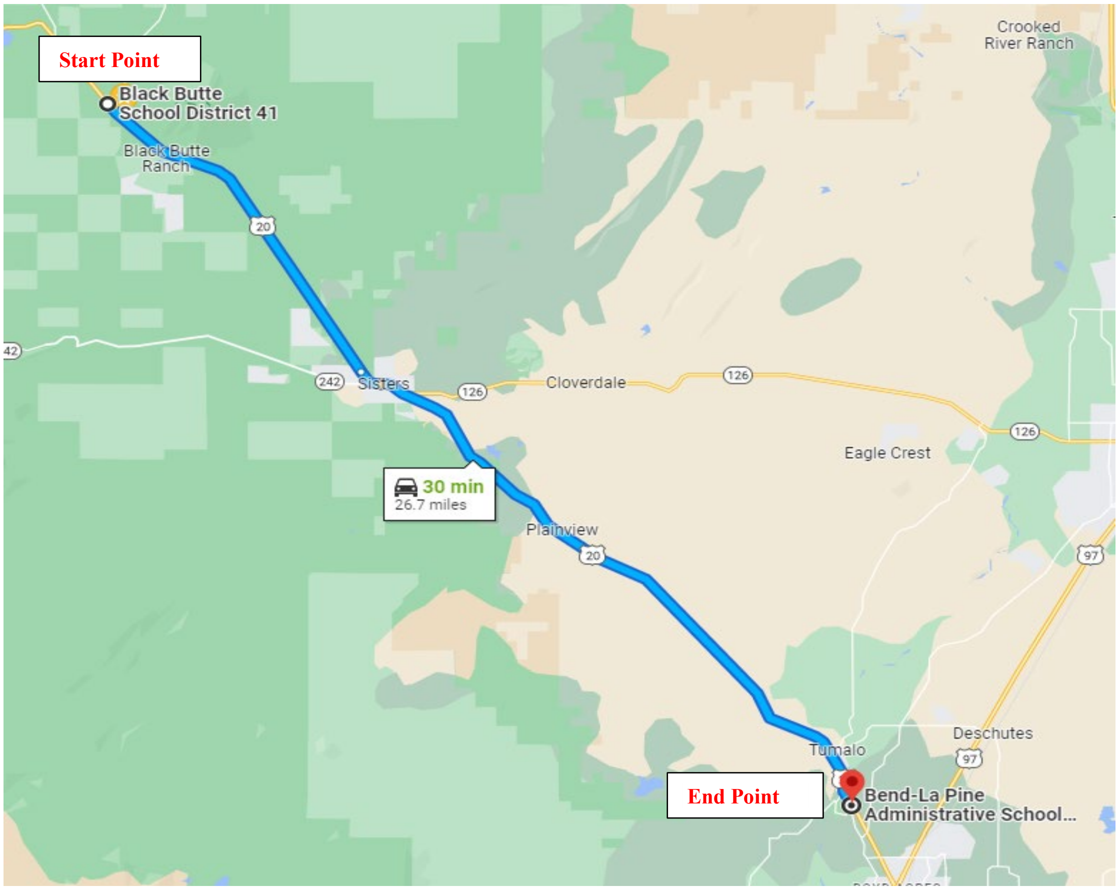


Figure 78. US-20 Sisters City Corridor, Oregon

This route serves as a connection between western Oregon cities such as Salem and Eugene and the western-central city of Bend, Oregon. This route serves heavy recreational and truck traffic as all traffic to central Oregon from the central and southern Willamette Valley travels through this area. The facility runs through the small town of Sisters, Oregon. There is a roundabout, several hotels, lodges, shopping complexes, and tourist attractions located along the route. At the regional level, Sisters City, Oregon is a popular tourist destination and provides access to several national parks, hiking, and other outdoor sporting activities. The Mt. Bachelor resort is in the nearby Bend area.

Facility Segmentation

This rural highway facility consists of sections of two-lane highways, with passing constrained, passing zone, and passing lane segments, as well as an arterial street section that passes through the small city of Sisters, Oregon. The arterial section includes a roundabout intersection and several two-way stop-controlled intersections (control only on the minor street). The analysis direction is the southeast direction of travel as shown in **Figure 78**.

The initial step in the segmentation process involved identifying segments based on cross-sectional characteristics and passing configurations (specifically for two-lane highways). Subsequently, locations where posted speed limits change are determined to further refine the segmentation. Following this, the corridor section passing through Sisters City is divided into urban arterial and rural segments to account for the varying characteristics and operational requirements of these distinct areas. By conducting a thorough segmentation process, a total of 32 segments including a roundabout intersection were created as summarized in **Table 36**.

Table 36. Initial Facility Segmentation for US-20 Corridor, Oregon

Seg ID	Hwy Seg Type	Two-Lane Seg Type	#Dir Lanes	Length (ft)	Grade (%)	Vert Align Class	# Horiz Curves	Posted Speed (mi/h)
1	TwoLaneHwy	PassingConstrained	1	1007	0	1	0	55
2	TwoLaneHwy	PassingZone	1	8276	0	1	0	55
3	TwoLaneHwy	PassingConstrained	1	13045	0	1	0	55
4	TwoLaneHwy	PassingConstrained	1	2779	-5	3	0	55
5	TwoLaneHwy	PassingConstrained	1	18620	0	1	0	55
6	TwoLaneHwy	PassingZone	1	5109	0	1	0	55
7	TwoLaneHwy	PassingConstrained	1	2567	0	1	0	35
8	Roundabout	---	1	100	0	0	0	35
9	TwoLaneHwy	PassingConstrained	1	1802	0	1	0	35
10	Urban Arterial	---	1	3105	0	1	0	20
11	TwoLaneHwy	PassingConstrained	1	1640	0	1	0	35
12	TwoLaneHwy	PassingConstrained	1	944	0	1	0	45
13	TwoLaneHwy	PassingZone	1	1750	0	1	0	55
14	TwoLaneHwy	PassingConstrained	1	2984	0	1	0	55
15	TwoLaneHwy	PassingZone	1	5235	0	1	0	55
16	TwoLaneHwy	PassingConstrained	1	4148	0	1	1	55
17	TwoLaneHwy	PassingZone	1	4039	0	1	0	55
18	TwoLaneHwy	PassingConstrained	1	6695	0	1	0	55
19	TwoLaneHwy	PassingZone	1	1542	0	1	0	55
20	TwoLaneHwy	PassingConstrained	1	674	0	1	0	55
21	TwoLaneHwy	PassingZone	1	1991	0	1	0	55
22	TwoLaneHwy	PassingConstrained	1	1231	-3	1	0	55
23	TwoLaneHwy	PassingLane	2	6116	0	1	0	55
24	TwoLaneHwy	PassingConstrained	1	3120	0	1	0	55
25	TwoLaneHwy	PassingZone	1	7688	0	1	0	55
26	TwoLaneHwy	PassingConstrained	1	4540	0	1	0	55
27	TwoLaneHwy	PassingLane	2	6783	2.5	2	0	55
28	TwoLaneHwy	PassingConstrained	1	7416	0	1	0	55
29	TwoLaneHwy	PassingZone	1	2178	0	1	0	55
30	TwoLaneHwy	PassingConstrained	1	5468	-3.5	3	0	55
31	TwoLaneHwy	PassingConstrained	1	674	0	1	0	55
32	TwoLaneHwy	PassingConstrained	1	1373	0	1	0	45

Influence Area and Adjusted Length Calculations. The upstream and downstream influence areas were calculated for the roundabout based on the statistical models proposed in this research (Chapter 4). Based on these values, adjusted segment lengths were calculated for the roundabout (component) and the upstream/downstream segments connected to the roundabout.

The length of upstream and downstream segments (Segments # 7 & 9) of the roundabout are adjusted as shown in **Table 37**.

Roundabout (Segment #8)

Upstream Influence Area, per Eq. (18)

$$I.A._{Roundabout/Upstr} = 402.15 + 10.21 \times MeanOS_{Up} - 15.27 \times MeanCS$$

$$= 402.15 + 10.21 \times 37.7 - 15.27 \times 15$$

$$= 558.0 \text{ ft}$$

Downstream Influence Area, per Eq. (19)

$$I.A._{Roundabout/Downstr} = -313.80 + 32.73 \times MeanOS_{Down} - 27.01 \times MeanCS$$

$$= -313.80 + 32.73 \times 37.54 - 27.01 \times 15$$
$$= 515.0 \text{ ft}$$

Adjusted roundabout segment Length: 100.0 + 558.0 + 515.0 = 1173.0 ft (0.2221 mi)

The upstream and downstream influence areas (558, 515) affect the adjusted lengths of the upstream and downstream connecting segments, as follows:

Upstream Segment #7

Input length = 2567 ft (0.4862 mi) → Adjusted length = 2567-558 = 2009 ft (0.3804)

Downstream Segment #9

Input length= 1802 ft (0.3412 mi) → Adjusted length = 1802-515 = 1287ft (0.2437)

The urban street segment is not bounded by intersections that require the major through movement to stop or yield; thus, influence area calculations are not necessary for this segment.

Table 37. Final Facility Segmentation for US-20 Corridor, Oregon

Seg ID	Hwy Seg Type	Two-Lane Seg Type	#Dir Lanes	Length (ft)	Upstr. Inf. (ft)	Downstr . Inf. (ft)	Adj. Len (mi)	Posted Speed (mi/h)
1	TwoLaneHwy	PassingConstrained	1	1007	---	---	1007	55
2	TwoLaneHwy	PassingZone	1	8276	---	---	8276	55
3	TwoLaneHwy	PassingConstrained	1	13045	---	---	13045	55
4	TwoLaneHwy	PassingConstrained	1	2779	---	---	2779	55
5	TwoLaneHwy	PassingConstrained	1	18620	---	---	18620	55
6	TwoLaneHwy	PassingZone	1	5109	---	---	5109	55
7	TwoLaneHwy	PassingConstrained	1	**2567**	---	---	**2009**	35
8	Roundabout	---	1	**100**	**558**	**515**	**1173**	35
9	TwoLaneHwy	PassingConstrained	1	**1802**	---	---	**1287**	35
10	Urban Arterial	---	1	3105	---	---	3105	20
11	TwoLaneHwy	PassingConstrained	1	1640	---	---	1640	35
12	TwoLaneHwy	PassingConstrained	1	944	---	---	944	45
13	TwoLaneHwy	PassingZone	1	1750	---	---	1750	55
14	TwoLaneHwy	PassingConstrained	1	2984	---	---	2984	55
15	TwoLaneHwy	PassingZone	1	5235	---	---	5235	55
16	TwoLaneHwy	PassingConstrained	1	4148	---	---	4148	55
17	TwoLaneHwy	PassingZone	1	4039	---	---	4039	55
18	TwoLaneHwy	PassingConstrained	1	6695	---	---	6695	55
19	TwoLaneHwy	PassingZone	1	1542	---	---	1542	55
20	TwoLaneHwy	PassingConstrained	1	674	---	---	674	55
21	TwoLaneHwy	PassingZone	1	1991	---	---	1991	55
22	TwoLaneHwy	PassingConstrained	1	1231	---	---	1231	55
23	TwoLaneHwy	PassingLane	2	6116	---	---	6116	55
24	TwoLaneHwy	PassingConstrained	1	3120	---	---	3120	55
25	TwoLaneHwy	PassingZone	1	7688	---	---	7688	55
26	TwoLaneHwy	PassingConstrained	1	4540	---	---	4540	55
27	TwoLaneHwy	PassingLane	2	6783	---	---	6783	55
28	TwoLaneHwy	PassingConstrained	1	7416	---	---	7416	55
29	TwoLaneHwy	PassingZone	1	2178	---	---	2178	55
30	TwoLaneHwy	PassingConstrained	1	5468	---	---	5468	55
31	TwoLaneHwy	PassingConstrained	1	674	---	---	674	55
32	TwoLaneHwy	PassingConstrained	1	1373	---	---	1373	45

Performance Measures and LOS Scores for Individual Components

Upon completing the facility segmentation, each individual component was analyzed using the methodologies offered by HCM. To conduct these analyses, the computational engine HCM-Calc was employed, ensuring an efficient and reliable assessment of performance measures for each segment. The resulting performance measure values were then converted to numerical LOS Scores, as summarized in **Table 38**, following the scale defined in Chapter 5 of this thesis. This conversion allows for a more accurate and continuous representation of the LOS, facilitating the subsequent aggregation of component LOS Scores in order to determine the overall facility-level LOS.

Table 38. Performance Measures and LOS Scores for Components Using HCM-Calc

Seg ID	Hwy Seg Type	Two-Lane Seg Type	Avg Travel Time (s)	Follower Density (veh/mi/ln)	Adj. Follower Density (veh/mi/ln)	Avg. Thresh. Delay (s/veh)	Avg. FFS Delay (s/veh)	LOS	LOS Value	TT × LOS Score
1	TwoLane Hwy	PassingConstrained	11.55	8.2	8.2	0	0.6	D	3.06	35.34
2	TwoLane Hwy	PassingZone	94.64	7.7	7.7	0	4.6	C	2.93	277.29
3	TwoLane Hwy	PassingConstrained	150.21	8.1	8.1	0	8	D	3.02	453.63
4	TwoLane Hwy	PassingConstrained	33.29	8.6	8.6	0	2.6	D	3.15	104.86
5	TwoLane Hwy	PassingConstrained	214.45	8.3	8.3	0	11.4	D	3.06	656.22
6	TwoLane Hwy	PassingZone	58.4	7.7	7.7	0	2.8	C	2.93	171.11
7	TwoLane Hwy	PassingConstrained	37.26	13.6	13.6	0	2.1	D	3.72	138.61
8	Roundabout	---	36.46	---	---	15.6	17.5	C	2.25	82.03
9	TwoLaneHwy	PassingConstrained	24.19	13.8	13.8	0	1.3	D	3.76	90.95
10	Urban Arterial	---	74.95	---	---	0	5		0.93	69.70
11	TwoLaneHwy	PassingConstrained	26.41	13.8	13.8	0	1.5	D	3.75	99.03
12	TwoLaneHwy	PassingConstrained	13.25	10.5	10.5	0	0.7	D	3.1	41.01
13	TwoLaneHwy	PassingZone	20.04	8	8	0	1	C	3	60.12
14	TwoLaneHwy	PassingConstrained	34.32	8	8	0	1.8	D	3	102.96
15	TwoLaneHwy	PassingZone	59.85	7.7	7.7	0	2.9	C	2.92	174.76

Table 38 continued.

Seg ID	Hwy Seg Type	Two-Lane Seg Type	Avg Travel Time (s)	Follower Density (veh/mi/ln)	Adj. Follower Density (veh/mi/ln)	Avg. Thresh. Delay (s/veh)	Avg. FFS Delay (s/veh)	LOS	LOS Value	TT × LOS Score
16	TwoLaneHwy	PassingConstrained	48.72	8.1	8.1	0	3.5	D	3.03	147.62
17	TwoLaneHwy	PassingZone	46.17	7.7	7.7	0	2.2	C	2.94	135.73
18	TwoLaneHwy	PassingConstrained	77.04	7.9	7.9	0	4	C	2.97	228.80
19	TwoLaneHwy	PassingZone	17.66	8	8	0	0.9	D	3.01	53.15
20	TwoLaneHwy	PassingConstrained	7.75	8.3	8.3	0	0.4	D	3.07	23.79
21	TwoLaneHwy	PassingZone	22.81	8	8	0	1.1	C	2.99	68.20
22	TwoLaneHwy	PassingConstrained	14.15	8.3	8.3	0	0.7	D	3.07	43.44
23	TwoLaneHwy	PassingLane	68.08	2.3	2.3	0	1.4	B	1.16	78.97
24	TwoLaneHwy	PassingConstrained	35.88	8	6.3	0	1.9	C	2.58	92.57
25	TwoLaneHwy	PassingZone	87.92	7.7	6.6	0	4.3	C	2.64	232.11
26	TwoLaneHwy	PassingConstrained	52.23	7.9	7	0	2.7	C	2.74	143.11
27	TwoLaneHwy	PassingLane	75.6	2.2	2.2	0	1.4	B	1.11	83.92
28	TwoLaneHwy	PassingConstrained	85.34	7.9	6.6	0	4.5	C	2.65	226.15
29	TwoLaneHwy	PassingZone	24.89	7.9	6.7	0	1.2	C	2.68	66.71
30	TwoLaneHwy	PassingConstrained	66.4	8.7	7.7	0	6	C	2.91	193.22
31	TwoLaneHwy	PassingConstrained	7.75	8.3	7.3	0	0.4	C	2.83	21.93
32	TwoLaneHwy	PassingConstrained	19.33	10.5	9.4	0	1	C	2.88	55.67

LOS Constancy for the Facility

The LOS constancy factor serves as a measure to capture the fluctuation in component-level LOS, accounting for both the frequency and magnitude of changes across contiguous segments. Based on the LOS scores obtained in the previous step, the LOS constancy factor was computed using the following equation:

$$LOS\ Constancy = \frac{\sum_{i=2}^{n} |LOS_i - LOS_{i-1}|}{n-1}$$

$$= \frac{18.36}{32-1} = 0.592$$

The above calculated LOS constancy factor was used to estimate the LOS Adjustment factor (α_c) based on the function defined in Chapter 5 of this thesis and also provide below in **Table 39**:

$$\alpha_c = 0.25 \times \text{LOS Constancy Value} + 0.85$$

$$= 0.25 \times 0.592 + 0.85 = 0.998$$

Table 39. LOS Adjustment Factor for Facility LOS

Adjustment Factor Value (α)	**LOS Constancy Value**
α_c = 0.9	LOS constancy ≤ 0.2
α_c = 0.25 × LOS Constancy Value + 0.85	0.2 < LOS Constancy < 1.0
α_c = 1.1	LOS Constancy ≥ 1.0

Facility-Level LOS Score

The facility-level LOS score was calculated for the complete facility by taking into consideration the average travel time of each segment, the LOS score (both provided in **Table 38**), and the LOS adjustment factor. The following equation was employed to compute the facility-level LOS score:

$$LOS_{Faci} = \alpha_c \times \left[\frac{\sum_{i=1}^{n} LOS_{score_i} \times TravelTime_i}{\sum_{i=1}^{n} TravelTime_i}\right]$$

$$= 0.998 \times \frac{4452.84}{1646.99} = 2.698$$

Assign LOS Letter-Grade to Facility

To determine the facility LOS letter-grade, the facility LOS score (LOS_{Faci} = 2.698) was converted based on the criteria presented in **Table 40**. As a result, the overall facility LOS was assigned a letter-grade of C, indicating satisfactory performance. It should be noted that all the components within the facility operate at a LOS of D or better, which is considered acceptable in the context of this analysis.

Table 40. LOS Criteria for Rural Highway Facility

Facility LOS Grade	Facility LOS Score
A	0 – 1
B	>1 – 2
C	>2 – 3
D	>3 – 4
E	>4 – 5
F	>5

This conversion allows for a clear and concise representation of the overall quality of service experienced by users on the rural highway facility. By assigning a letter-grade to the facility-level LOS score, the assessment of the facility's performance can be easily communicated to the public and policymakers, enabling informed decision-making regarding the management and improvement of the rural highway facility.

US-287 Townsend Corridor, Montana

Route Description

This corridor is mainly comprised of a two-lane rural highway that extends from 1.0 mile south of Townsend (a small rural town) to the center of East Helena, Montana. The coordinates of the start and end points of the corridor are [46.293584644800966, -111.50420836367195] and [46.59039324407053, -111.93775081845547], respectively. The highest posted speed limit is 70 mi/h for the rural parts of the corridor (majority distance by length) and the lowest posted speed limit is 25 mi/h in the town of Townsend. The route is shown in **Figure 79**, as well as the linked online map.

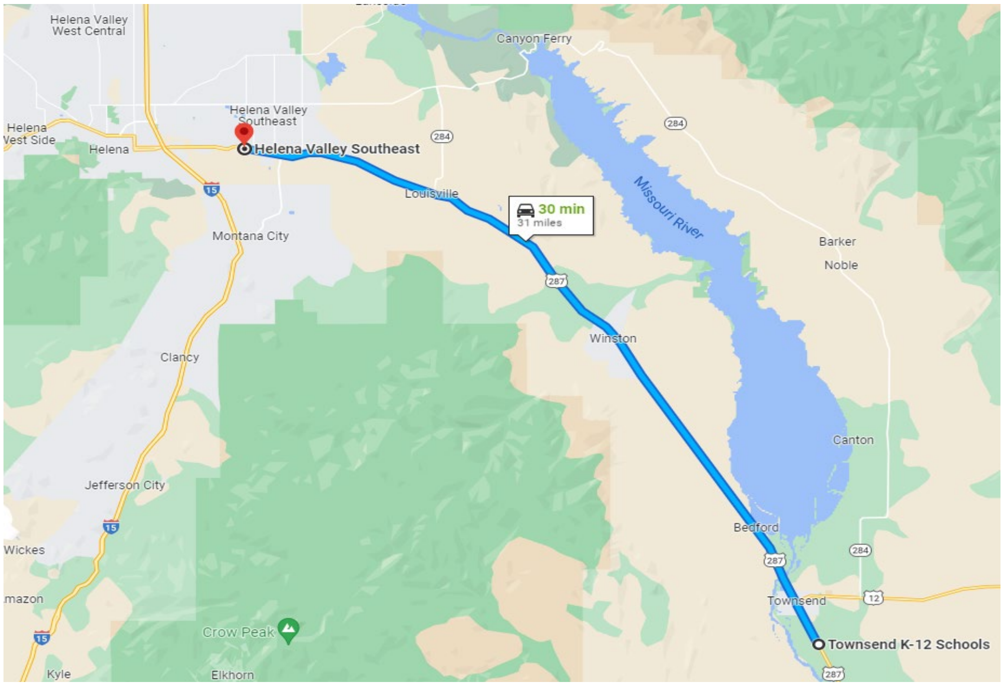


Figure 79. US-287 Townsend Corridor, Montana

Facility Segmentation

The facility segmentation for this corridor was performed based on the change in cross-section, change in passing restrictions, and change in the posted speed limit. This resulted in a total of 38 segments including two passing lane segments, seven segments (with different speed limits) through the town of Townsend, two signal-control intersections, two-multilane highway segments, and one All-Way Stop-Control (AWSC) intersection in Townsend. The remaining segments are two-lane highways (with passing or no-passing restrictions) as shown in **Table 41**.

Table 41. Facility Segmentation of US-287 Townsend Corridor, MT

Seg ID	Hwy Seg Type	Two-Lane Seg Type	# Dir Lanes	Length (ft)	Grade (%)	Vertical Align Class	# Horiz Curves	Posted Speed (mi/h)
1	Two-Lane Highway	PassingConstrained	1	1515	<2	1	R>3000 ft	70
2	Two-Lane Highway	PassingZone	1	2670	<2	1	R>3000 ft	55
3	Two-Lane Highway	PassingConstrained	1	530	<2	1	R>3000 ft	55
4	Two-Lane Highway	PassingConstrained	1	530	<2	1	R>3000 ft	45
5	Two-Lane Highway	PassingConstrained	1	2650	<2	1	R>3000 ft	45
6	Two-Lane Highway	PassingConstrained	1	1580	<2	1	R>3000 ft	35
7	Two-Lane Highway	PassingConstrained	1	530	<2	1	R>3000 ft	25
8	AWSC	NA	1	85	<2	1	R>3000 ft	25
9	Two-Lane Highway	PassingConstrained	1	965	<2	1	R>3000 ft	25
10	Two-Lane Highway	PassingConstrained	1	1580	<2	1	R>3000 ft	35
11	Two-Lane Highway	PassingConstrained	1	2100	<2	1	R>3000 ft	45
12	Two-Lane Highway	PassingConstrained	1	3170	<2	1	R>3000 ft	55
13	Two-Lane Highway	PassingZone	1	5500	<2	1	R>3000 ft	70
14	Two-Lane Highway	PassingConstrained	1	3700	<2	1	R>3000 ft	70
15	Two-Lane Highway	PassingZone	1	9500	<2	1	R>3000 ft	70
16	Two-Lane Highway	PassingConstrained	1	4225	<2	1	R>3000 ft	70
17	Two-Lane Highway	PassingZone	1	5280	<2	1	R>3000 ft	70
18	Two-Lane Highway	PassingLane	2	12670	<2	1	R>3000 ft	70
19	Two-Lane Highway	PassingConstrained	1	1056	<2	1	R>3000 ft	70
20	Two-Lane Highway	PassingZone	1	13730	<2	1	R>3000 ft	70
21	Two-Lane Highway	PassingConstrained	1	4225	<2	1	R>3000 ft	70
22	Two-Lane Highway	PassingZone	1	4225	<2	1	R>3000 ft	55
23	Two-Lane Highway	PassingConstrained	1	3170	<2	1	R>3000 ft	70
24	Two-Lane Highway	PassingZone	1	13728	<2	1	R>3000 ft	70
25	Two-Lane Highway	PassingConstrained	1	4750	<2	1	R>3000 ft	70
26	Two-Lane Highway	PassingLane	2	7400	<2	1	R>3000 ft	55
27	Two-Lane Highway	PassingConstrained	1	3700	<2	1	R>3000 ft	70
28	Two-Lane Highway	PassingZone	1	4750	<2	1	R>3000 ft	70
29	Two-Lane Highway	PassingConstrained	1	1590	<2	1	R>3000 ft	70
30	Two-Lane Highway	PassingZone	1	2100	<2	1	R>3000 ft	55
31	Two-Lane Highway	PassingConstrained	1	3170	<2	1	R>3000 ft	70
32	Two-Lane Highway	PassingZone	1	19536	<2	1	R>3000 ft	70
33	Two-Lane Highway	PassingConstrained	1	4752	<2	1	R>3000 ft	40
34	Two-Lane Highway	PassingConstrained	1	5800	<2	1	R>3000 ft	55
35	Signalized Intersection	NA	2	120	<2	1	R>3000 ft	45
36	Multilane Highway	NA	2	3580	<2	1	R>3000 ft	45
37	Signalized Intersection	NA	2	120	<2	1	R>3000 ft	45
38	Multilane Highway	NA	2	3050	<2	1	R>3000 ft	55

Segmentation Through the Town of Townsend, MT. Townsend is a small rural town on US-287 Highway, about 32 miles southeast of Helena. The total population of Townsend is 2080 people (according to 2020 census data). The stretch of road through the town of Townsend is comprised of 8 segments as indicated in **Table 42** (starting at the southeast end of the town).

Table 42. Segments through Townsend, MT (US-87)

Seg ID	Hwy Seg Type	Two-Lane Seg Type	# Dir Lanes	Length (ft)	Grade (%)	Vertical Align Class	# Horiz Curves	Posted Speed (mi/h)
1	Two-Lane Highway	PassingConstrained	1	530	0	1	0	45
2	Two-Lane Highway	PassingConstrained	1	2650	0	1	0	45
3	Two-Lane Highway	PassingConstrained	1	1580	0	1	0	35
4	Two-Lane Highway	PassingConstrained	1	530	0	1	0	25
5	AWSC	NA	1	85	0	1	0	25
6	Two-Lane Highway	PassingConstrained	1	965	0	1	0	25
7	Two-Lane Highway	PassingConstrained	1	1580	0	1	0	35
8	Two-Lane Highway	PassingConstrained	1	2100	0	1	0	45

The total length of the roadway stretch through the town is about 1.9 mi as shown in **Figure 80**.

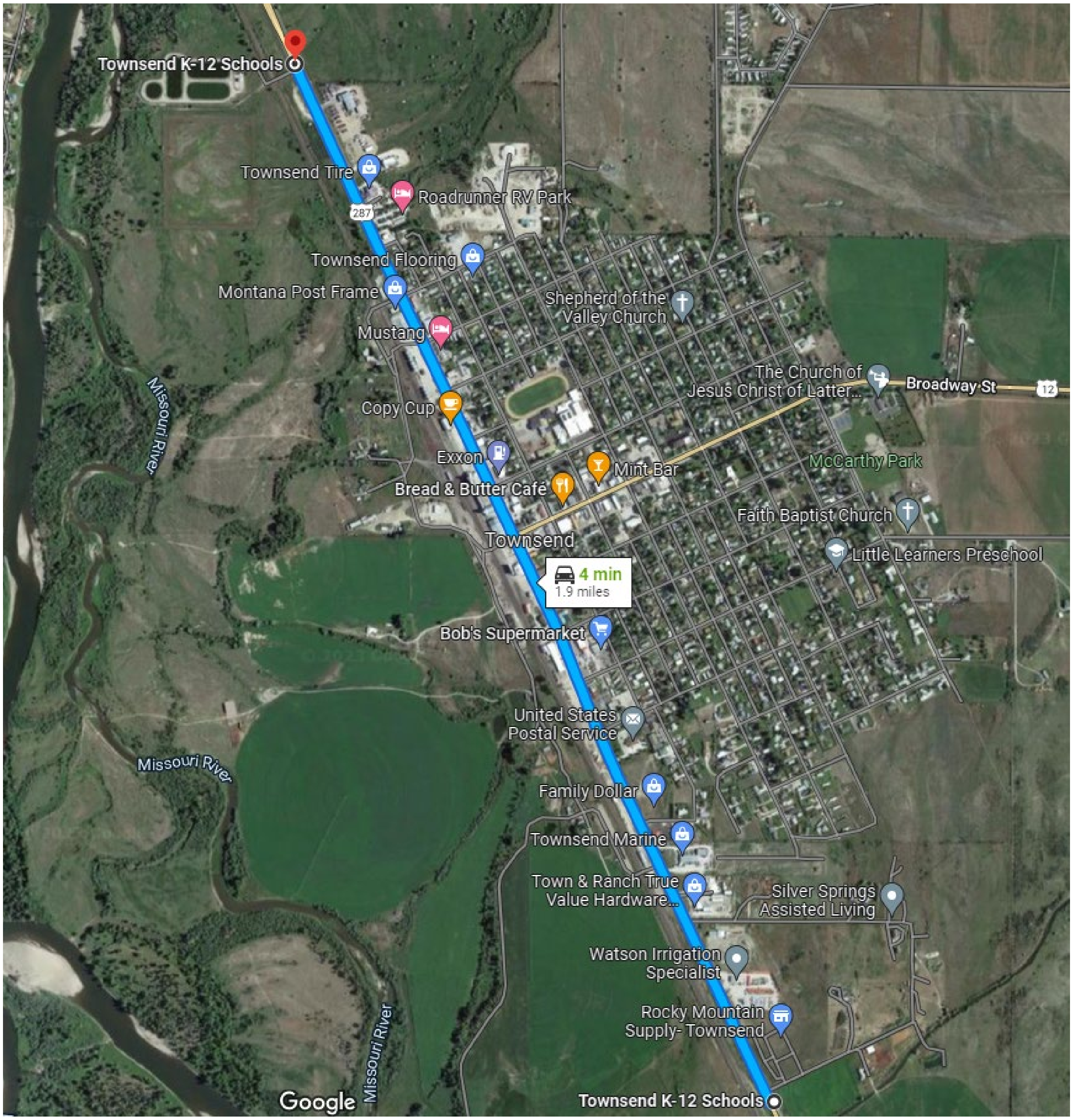


Figure 80. US-287 Stretch Through Townsend, MT

The speed limits are 45, 35, and 25 mi/h entering the town and in the reverse order exiting the town. The roadway characteristics through the town are as follows:

- 1 lane in the analysis direction
- Two-way left-turn lane in the center
- AWSC intersection
- No curb and gutter at the beginning of town, and then curb on both sides (starts at E-street)
- Sidewalk on the east side of the roadway only
- Numerous driveways and access roads within the town limits
- 25 mi/h zone in Townsend, MT is about 0.32 mi (1700 ft) long

The connecting roadways to the US-287, with the exception of Broadway St. (AWSC intersection), exhibit very low traffic volumes. Consequently, the analysis focused on the link traversing Townsend as a two-lane highway segment (passing constrained), the AWSC intersection, and a two-lane highway segment (passing constrained).

To determine the influence areas for both the AWSC and signal-control intersections, equations provided in Chapter 4 were used and HCM-Calc was utilized for computation. The final segmentation, inclusive of the influence areas of intersections, is presented in **Table 43**.

Table 43. Final Segmentation of US-287 Townsend Corridor, Montana

Seg ID	Hwy Seg Type	Two-Lane Seg Type	Length (mi)	Upstr. Inf. (mi)	Downstr. Inf. (mi)	Adj. Length (mi)
1	TwoLaneHwy	PassingConstrained	0.2869	---	---	0.2869
2	TwoLaneHwy	PassingZone	0.5057	---	---	0.5057
3	TwoLaneHwy	PassingConstrained	0.1004	---	---	0.1004
4	TwoLaneHwy	PassingConstrained	0.1004	---	---	0.1004
5	TwoLaneHwy	PassingConstrained	0.5019	---	---	0.5019
6	TwoLaneHwy	PassingConstrained	0.2992	---	---	0.2992
7	TwoLaneHwy	PassingConstrained	0.1004	---	---	0.0472
8	AWSCIntersection	---	0.0161	0.0532	0.0223	0.0916
9	TwoLaneHwy	PassingConstrained	0.1827	---	---	0.1604
10	TwoLaneHwy	PassingConstrained	0.2992	---	---	0.2992
11	TwoLaneHwy	PassingConstrained	0.3977	---	---	0.3977
12	TwoLaneHwy	PassingConstrained	0.6004	---	---	0.6004
13	TwoLaneHwy	PassingZone	1.0417	---	---	1.0417
14	TwoLaneHwy	PassingConstrained	0.701	---	---	0.701
15	TwoLaneHwy	PassingZone	1.799	---	---	1.799
16	TwoLaneHwy	PassingConstrained	0.8	---	---	0.8
17	TwoLaneHwy	PassingZone	1	---	---	1
18	TwoLaneHwy	PassingLane	2.4	---	---	2.4
19	TwoLaneHwy	PassingConstrained	0.2	---	---	0.2
20	TwoLaneHwy	PassingZone	2.6	---	---	2.6
21	TwoLaneHwy	PassingConstrained	0.8	---	---	0.8
22	TwoLaneHwy	PassingZone	0.8	---	---	0.8
23	TwoLaneHwy	PassingConstrained	0.6	---	---	0.6
24	TwoLaneHwy	PassingZone	2.6	---	---	2.6
25	TwoLaneHwy	PassingConstrained	0.9	---	---	0.9
26	TwoLaneHwy	PassingLane	1.402	---	---	1.402
27	TwoLaneHwy	PassingConstrained	0.701	---	---	0.701
28	TwoLaneHwy	PassingZone	0.9	---	---	0.9
29	TwoLaneHwy	PassingConstrained	0.301	---	---	0.301
30	TwoLaneHwy	PassingZone	0.398	---	---	0.398
31	TwoLaneHwy	PassingConstrained	0.6	---	---	0.6
32	TwoLaneHwy	PassingZone	3.7	---	---	3.7
33	TwoLaneHwy	PassingConstrained	0.9	---	---	0.9
34	TwoLaneHwy	PassingConstrained	1.098	---	---	0.8671
35	SigIntersection	---	0.0227	0.2309	0.2369	0.4905
36	MultilaneHwy	---	0.6774	---	---	0.3280
37	SigIntersection	---	0.0227	0.1125	0.211	0.3462
38	MultilaneHwy	---	0.5773	---	---	0.3663

Performance Measures and LOS Scores for Individual Components

In this section, performance measures for individual components of the facility were determined, based on current methodologies outlined in HCM, using the computational engine HCM-Calc. The performance measures for both segments and intersections are summarized in columns 5 and 6 of **Table 44**, respectively. Additionally, the table also presents the LOS Scores for each component in column 9. The LOS scores are determined based on scales of performance measures defined in Chapter 5 of this thesis.

LOS Constancy for the Facility

Based on the LOS scores obtained in the previous step, the absolute differences in LOS scores between the contiguous segments were computed and are presented in the last column of **Table 44**. The LOS constancy factor for the facility was determined using the following equation:

$$LOS\ Constancy = \frac{\sum_{i=2}^{n} |LOS_i - LOS_{i-1}|}{n-1}$$

$$= \frac{21.85}{38-1} = 0.591$$

With the calculated LOS constancy factor, the LOS Adjustment factor (α_c) was estimated based on the function proposed in Chapter 5 of this thesis, as well as the following:

$$\alpha_c = 0.25 \times \text{LOS Constancy Value} + 0.85$$

$$= 0.25 \times 0.591 + 0.85 = 0.998$$

Table 44. Performance Analysis and LOS for Individual Components of Facility US-287 Corridor

Seg ID	Hwy Seg Type	Two-Lane Seg Type	Avg Travel Time (s)	Follower Density (veh/mi/ln)	Avg. Thresh. Delay (s/veh)	Avg. FFS Delay (s/veh)	LOS	LOS Score	TT × LOS Score	Abs. LOS Diff.
1	TwoLane Hwy	Passing Constrained	13.39	1.5	0	0.4	A	0.73	9.77	-
2	TwoLane Hwy	Passing Zone	29.87	1.9	0	0.7	A	0.94	28.08	0.21
3	TwoLane Hwy	Passing Constrained	6.04	4.9	0	0.3	C	2.22	13.41	1.28
4	TwoLane Hwy	Passing Constrained	7.39	6.4	0	0.3	C	2.28	16.85	0.06
5	TwoLane Hwy	Passing Constrained	36.97	6.2	0	1.7	C	2.24	82.81	0.04
6	TwoLane Hwy	Passing Constrained	28.4	8.4	0	1.3	C	2.69	76.40	0.45
7	TwoLane Hwy	Passing Constrained	6.4	23.2	0	0.4	E	5	32.00	2.31
8	AWSC	---	50.97	---	40.1	41.1	E	4.41	224.78	0.59
9	TwoLane Hwy	Passing Constrained	23.96	23.2	0	1.5	E	5	119.80	0.59
10	TwoLane Hwy	Passing Constrained	28.82	16.5	0	1.7	E	4.31	124.21	0.69
11	TwoLane Hwy	Passing Constrained	29.69	12.5	0	1.7	D	3.5	103.92	0.81
12	TwoLaneHwy	Passing Constrained	36.59	9.7	0	2	D	3.43	125.50	0.07
13	TwoLane Hwy	Passing Zone	48.72	2.4	0	1.6	B	1.22	59.44	2.21
14	TwoLane Hwy	Passing Constrained	32.97	2.6	0	1.3	B	1.28	42.20	0.06
15	TwoLane Hwy	Passing Zone	84.17	2.5	0	2.9	B	1.24	104.37	0.04
16	TwoLane Hwy	Passing Constrained	37.63	2.6	0	1.5	B	1.28	48.17	0.04
17	TwoLane Hwy	Passing Zone	46.91	2.9	0	1.7	B	1.46	68.49	0.18
18	TwoLane Hwy	Passing Lane	108.87	0.7	0	0.4	A	0.36	39.19	1.1
19	TwoLane Hwy	Passing Constrained	9.43	2.6	0	0.4	B	1.29	12.16	0.93
20	TwoLane Hwy	Passing Zone	122	2.6	0	4.5	B	1.31	159.82	0.02
21	TwoLane Hwy	Passing Constrained	37.72	2.7	0	1.6	B	1.35	50.92	0.04
22	TwoLane Hwy	Passing Zone	47.81	3.7	0	1.8	B	1.87	89.40	0.52
23	TwoLane Hwy	Passing Constrained	28.29	2.8	0	1.2	B	1.39	39.32	0.48

24	TwoLane Hwy	Passing Zone	122	2.8	0	4.5	B	1.39	169.58	0
25	TwoLane Hwy	Passing Constrained	42.44	2.8	0	1.8	B	1.42	60.26	0.03
26	TwoLane Hwy	Passing Lane	81.22	1.1	0	0.5	A	0.56	45.48	0.86
27	TwoLane Hwy	Passing Constrained	33.05	2.4	0	1.4	B	1.22	40.32	0.66
28	TwoLane Hwy	Passing Zone	42.21	2.5	0	1.5	B	1.23	51.92	0.01
29	TwoLane Hwy	Passing Constrained	14.19	2.7	0	0.6	B	1.35	19.16	0.12
30	TwoLane Hwy	Passing Zone	23.78	3.7	0	0.9	B	1.85	43.99	0.5
31	TwoLane Hwy	Passing Constrained	28.21	2.2	0	1.1	B	1.11	31.31	0.74
32	TwoLane Hwy	Passing Zone	173.59	2.7	0	6.4	B	1.37	237.82	0.26
33	TwoLane Hwy	Passing Constrained	42.42	2.8	0	1.8	B	1.4	59.39	0.03
34	TwoLane Hwy	Passing Constrained	52.43	6.6	0	2.6	C	2.64	138.42	1.24
35	SigInter-section	---	55.12	---	17.7	21.1	C	2.07	114.10	0.57
36	Multilane Hwy	---	24.11	---	0	0	A	0.8	19.29	1.27
37	SigInter-section	---	48.64	---	22.8	25.1	C	2.34	113.82	1.54
38	Multilane Hwy	---	26.67	---	1.2	0	B	1.04	27.74	1.3
Sum			1713.09						2843.62	21.85

Facility-Level LOS Score

The facility-level LOS score was calculated for the entire facility through a weighted average approach, incorporating the LOS scores and travel time associated with each component of the facility. **Table 44** presents the average travel times and LOS scores for each component. The facility-level LOS score was determined using the following equation:

$$LOS_{Faci} = \alpha_c \times \left[\frac{\sum_{i=1}^{n} LOS_{score_i} \times TravelTime_i}{\sum_{i=1}^{n} TravelTime_i}\right]$$

$$= 0.998 \times \frac{2843.62}{1713.09} = 1.66$$

Facility LOS Score to Facility LOS Letter-Grade

In order to assign the LOS letter-grade to the facility, the facility LOS score (LOS_{Faci} = 1.66) was translated based on the criteria presented in **Table 45** (discussed in Chapter 5). Consequently, the overall facility LOS was assigned a letter-grade of B, signifying a highly satisfactory performance at the facility level.

It is important to note that the majority of individual components within the facility operate at LOS C or better, with only a few exceptions functioning at LOS D or E. The components with lower quality of service (LOS D or E) are primarily located within the stretch of highway passing through the small rural town of Townsend. Given that users' expectations regarding the quality of service on a short stretch of roadway through a town may be relatively lower, due to reduced posted speed limits and increased interruptions in flow from side streets and driveways, the performance on this specific stretch may not significantly influence users' perceptions of the overall quality of service of the rural highway facility.

Table 45. LOS Criteria for Rural Highway Facility

Facility LOS Grade	Facility LOS Score
A	0 – 1
B	>1 – 2
C	>2 – 3
D	>3 – 4
E	>4 – 5
F	>5

This conversion allows for a clear and concise representation of the overall quality of service experienced by users on the rural highway facility. By assigning a letter-grade to the facility-level LOS score, the assessment of the facility's performance can be easily communicated to the public and policymakers, enabling informed decision-making regarding the management and improvement of the rural highway facility.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this research was to develop a comprehensive methodology for evaluating the quality of service of rural highway facilities, taking into account the diverse roadway components and operational conditions that characterize these complex transportation systems. Rural highway facilities encompass extended lengths of rural highways consisting of various combinations of multilane highways, two-lane highways, intersections (signal-control, stop-control, and roundabout), and occasionally urban street segments for highways passing through small towns. In order to develop and implement a rural highway facility analysis methodology, it is imperative to segment the facility into its constituent components, a process referred to as facility segmentation. This chapter summarizes the most pertinent findings of the study and discusses the limitations associated with the proposed methodology, providing valuable insights for future research and practical applications regarding the quality of service analysis for rural highway facilities.

Findings of Facility Segmentation / Influence Area of Intersections

In order to delineate the spatial extent of the operational effects of intersections on traffic operation, upstream and downstream influence areas at roundabout, signal control, and stop control intersections were examined using vehicle trajectory data. The key findings from the influence area analyses are summarized below:

- Preliminary analysis of influence area data revealed that the intersection downstream influence areas are significantly longer than the upstream influence areas. Moreover, there is a strong association between the length of the influence area and the operating speed of the connecting roadway segment. It was observed that the upstream influence areas for signalized intersections are longer than those for stop-control and roundabout intersections even for comparable operating speeds of the segments. This is likely due to the presence of queues during the red signal phase and the fact that most vehicles don't need to reach a complete stop at rural roundabouts.

- Deceleration rates at upstream of intersections are greater in magnitude compared to acceleration rates at downstream of intersections.
- Quantile regression models, developed for estimating the influence areas, revealed that the segment operating speed (upstream/downstream) significantly impacts the influence areas.
- Traffic flow levels were found to have a significant effect on the influence areas of signal-control intersections, but not on the influence areas of roundabouts and stop-control intersections. This is primarily expected due to low traffic flows on rural roadways with roundabouts and stop-control intersections, resulting in negligible impacts on speed (i.e., no queues at intersection entries and no discernible effect on mid-segment operating speeds).
- The influence area at signal-control intersections on multilane highways is smaller than that on two-lane highways. Additionally, heavy vehicles significantly affect the influence area length at signal-control intersections.
- The circulating speed within the roundabout has a significant impact on the influence area of the roundabout.

- Higher posted speed limits and operating speeds, fewer access points, and low traffic levels all contribute to longer influence areas in rural settings compared to their urban counterparts.
- Based on the percentile analyses and the observed operational impacts, the decision was made to consider the 70th percentile influence areas for signal-control and stop-control intersections, while the 50th percentile was deemed appropriate for roundabout intersections. Utilizing these criteria, quantile regression models were developed to facilitate the estimation of intersection influence areas. These models, built on empirical data, provide a robust and reliable approach for determining the influence areas for various intersection types. The incorporation of these models into the facility-level analysis framework enhances the accuracy of the quality-of-service assessment.
- Influence areas look-up tables were established based on the quantile regression models, offering an efficient and practical tool for transportation engineers to perform facility segmentation for rural highway facilities.

The findings from the intersection influence area analysis provide critical insights into the spatial extent of the operational effects of intersections on connecting approaches. These findings contribute to not only the facility-level operational analysis but would also have some implications on traffic safety, as many intersection-related crashes are associated with deceleration on upstream approaches (e.g., rear-end collisions). Consequently, it is recommended that future research be conducted using empirical data gathered from a wide variety of locations with a wide range of traffic conditions and roadway features. Additionally, such research endeavors may also lead to the identification of new factors or relationships that could further improve the accuracy and precision of intersection influence area estimation, ultimately contributing to a more comprehensive understanding of the operational and safety impacts of intersections within rural highway facilities.

Findings of Facility-Level LOS Methodology

After an extensive evaluation of various performance measures and methodologies, this research proposed a comprehensive analytical framework for assessing the quality of service of rural highway facilities. The proposed methodology is characterized by the following salient aspects:

- A crucial aspect of the proposed methodology is its strict adherence to the LOS concept, as outlined in the HCM, without introducing any new measures or concepts.
- It relies on the existing analysis methods for individual components (segments and intersections) of the facility as described in the latest edition of the Highway Capacity Manual (TRB, 2022). This fulfills the key requirement for an effective LOS performance measure – that the measure should be sensitive to the user's perception of the quality of service.
- The methodology accommodates a wide range of rural highway components, including multilane highway segments, two-lane highway segments, urban street segments (rural town), and intersections (signal-control, stop-control, and roundabout). This versatility enables the framework to accurately capture the performance of complex rural highway facilities, providing a holistic view of the operational performance.

- The proposed approach utilizes the HCM-recommended performance measures to calculate the LOS score for individual components of the facility, which are subsequently used to determine the composite facility-level LOS.
- To address the limitations in the LOS scale due to its step-function nature, LOS scores on a continuous numerical scale are estimated for individual components of the facility based on their performance measures. This conversion to continuous numerical scores results in a more accurate assessment of the overall facility-level assessment.
- In order to aggregate the components' LOS scores, a thorough evaluation and in-depth consultation with transportation professionals and researchers were conducted. It was decided to use travel time as a measure for weighting the component's LOS score. Travel times align closely with users' perceptions of the quality of service on highways.
- A highly significant and intriguing feature of the proposed methodology is the LOS constancy factor, which accounts for fluctuations in component-level LOS in terms of both frequency and magnitude. Specifically, frequent changes in LOS between contiguous components across the facility are deemed detrimental to the quality of service from the users' (drivers') perspective. To account for this in the overall facility LOS, an adjustment factor is used.
- Another important aspect of the proposed LOS methodology is that it not only provides a holistic view of the rural highway facility but also offers detailed insights into the performance of individual components of the facility. This microscopic perspective offers a more comprehensive understanding of the quality of service of the rural

highway, enabling better-informed decision-making and resource allocation in instances where specific components may fail under high traffic demand.

- It is essential to note that the LOS of a rural highway facility should be considered differently from that of the individual component level, as drivers expect a higher quality of service (higher LOS) for their entire journey across the facility compared to their expectations of the quality of service (LOS) for a single segment. For example, an LOS D on a single segment might be acceptable to drivers; however, an LOS D for an extended length of a facility may lead to driver frustration and be deemed unacceptable.
- This proposed methodology effectively addresses a limitation and gap in the current edition of the HCM. Specifically, the current edition of the HCM lacks a methodology for analyzing extended lengths of two-lane highways with any type of intersection (signalized, stop control, or roundabouts) or segments of multilane cross sections (TRB, 2022). The inability to perform such an analysis using the current edition of the HCM leaves a substantial gap in the assessment of rural highway facilities, which often feature a combination of various intersection and segment types. By integrating intersection controls that require traffic to stop or yield into the analysis framework, the proposed methodology offers a more comprehensive and accurate evaluation of the performance along rural highway routes with diverse operational environments. Consequently, transportation agencies can better understand the quality of service experienced by users on such highways.

In summary, the proposed methodology offers a robust and comprehensive framework for assessing the quality of service on rural highway facilities. By integrating diverse roadway components, sophisticated segmentation techniques, and advanced performance measure computation methods, the framework provides an accurate and detailed evaluation of facility performance.

Limitations of the Proposed Methodology

While the proposed methodology for rural highway facility analysis offers a comprehensive and robust framework for assessing the quality of service on rural highway facilities, it is important to recognize and acknowledge its inherent limitations. This section discusses the limitations associated with the proposed methodology, which should be considered when interpreting the results and implementing the framework in practice.

- One of the potential limitations of the proposed methodology stems from its reliance on the performance measures estimated by segment and intersection methods in HCM Chapters 12, 15-16, and 19-22 (TRB, 2022). Consequently, the proposed methodology inherently incorporates any limitation that might exist in any of these methods. This means that any inaccuracies, assumptions, or simplifications made in the underlying HCM methods may directly affect the accuracy of the proposed rural highway facility analysis. Therefore, users should exercise caution when interpreting the results and consider the potential impact of these limitations on the overall assessment.

- Generally, rural highways experience relatively low traffic demand; however, under certain circumstances such as alternative route closures or natural disasters, traffic demand can significantly increase. One limitation of the proposed methodology lies in its ability to effectively manage situations where the demand-to-capacity ratio for any given segment exceeds 1.00. In such instances, the completeness of the analysis may be compromised, as the methodology may not fully capture the performance implications of congestion, queue formation, and other operational issues resulting from demand exceeding the capacity of the segment. This may lead to an underestimation of the negative impacts on the quality of service experienced by users in these conditions. To address this limitation, users should carefully assess the demand-to-capacity ratios of the segments under analysis and consider additional investigation or alternative methods if necessary (e.g., traffic simulation) to better understand the performance of the facility in situations where demand exceeds capacity.

Additionally, although the influence area analyses conducted in this research were detailed and based on microscopic data from the field, there are some recommendations for further research to enhance the generalizability and applicability of the findings:

- The roundabouts included in this research shared similar geometric characteristics (e.g., number of lanes, diameter, etc.). To better understand the effect of roundabout geometries on the influence areas, it is recommended that future research should collect and analyze data on a diverse range of roundabouts located in different states, with varying geometric configurations.

- This research utilized data from 11 signal-control and stop-control intersections in central Florida, all of which were in relatively flat terrain. To account for any potential effects of different driver populations (driver behavior) and varying terrain on the intersection influence areas, it would be valuable to examine intersection influence areas in other regions as well. The impact of grades, which are directly related to acceleration and deceleration distances, should also be investigated to develop a more comprehensive understanding of the factors influencing intersection influence areas.
- Apart from rural intersections, this study lays a foundation for conducting similar investigations into influence areas of intersections in urban environments. By extending the analysis to urban settings, the findings could be made more applicable to a wider range of traffic conditions and roadway features, ultimately leading to a more versatile and useful methodology for assessing the facility-level quality of service.

In summary, while the influence area analyses in this research offer valuable insights into the operational effects of intersections on connecting approaches, further research is needed to expand the scope and applicability of these findings. By incorporating data from diverse locations, varying geometric configurations, and different traffic conditions, future research can contribute to a more comprehensive understanding of intersection influence areas and their implications for facility-level analysis and decision-making.

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