DEPARTMENT OF TRANSPORTATION

Complete Streets Speed Impacts

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June 2024

Research Project
Final Report 2024-13

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Final Report

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List of Abbreviations

MnDOT	Minnesota Department of Transportation
VRU	Vulnerable road users
SRF	Speed reduction factors
TAP	Technical advisory panel
FHWA	Federal Highway Administration
CSS	Context Sensitive Solution
MUTCD	Manual on Uniform Traffic Control Devices
NTSB	National Transportation Safety Board
TWLTL	Two-Way Left-Turn Lanes
DSFS	Dynamic Speed Feedback Sign
CMF	Crash Modification Factor
PBPD	Performance-Based Practical Design

Executive Summary

Recently, speed management practices have shifted away from an historical focus on the 85th percentile speed toward a safe systems approach that is focused on promoting safer speeds in all roadway environments through a combination of thoughtful, equitable, context-appropriate roadway design, appropriate speed-limit setting, targeted education, outreach campaigns, and enforcement. These approaches include performance-based practical design, context-sensitive solutions, and Complete Streets. The shift toward safer and more accessible transportation infrastructure is particularly noteworthy in Minnesota as Statute §174.75 requires the Minnesota Department of Transportation (MnDOT) to follow a Complete Streets approach "to address the safety and accessibility needs of users of all ages and abilities." However, an area of particular concern for Complete Streets is designing in consideration of speed outcomes because highways and streets have been traditionally designed for a maximum safe speed in consideration of controlling criteria such as horizontal/vertical alignment and stopping sight distance. This is particularly true in environments where vulnerable road users (VRU), such as people biking and walking, are present. To that end, MnDOT and other agencies have adopted a design approach that instead emphasizes target speed in consideration of the needs of anticipated road users. Consequently, this study aims to examine the relationship between travel speeds and various design elements within the context of Complete Streets to develop speed-reduction factors (SRFs). SRFs provide an estimate of the average reduction in travel speeds that is experienced in the presence of a specific feature. To obtain these SRFs, the study sought to answer the following research questions: (1) How much do drivers reduce their speeds when entering speed-reduction zones, such as those entering communities located along high-speed rural highways? (2) How do these speed reductions vary based on the cross-sectional elements of the highway, as well as the upstream and downstream speed limits? (3) How do drivers adjust their speeds in response to specific cross-sectional elements of the highway, and over what distance are any changes in travel speeds maintained?

To achieve the objectives of this study, the research team worked in conjunction with the Technical Advisory Panel (TAP) to identify and select sites across different combinations of contexts (rural town vs. urban/suburban), roadway types (multilane divided vs. multilane undivided vs. two-lane undivided), posted speed limits, traffic volume ranges, and in the presence (absence) of specific features (e.g., bike lanes, raised median). Nineteen corridors and 48 sites were identified in this manner for detailed field data collection across Minnesota. Fourteen of the corridors were speed-transition zones entering small communities, while the remaining five were located within the urban/suburban core. The field studies involved the collection of data on: (1) the speed profiles of vehicles as they travel into and within Complete Streets; (2) the road corridor dimension (lane width, shoulder width, and median width); (3) the road context; and (4) the geometric features present within the corridors. Speed trajectory data were collected using handheld lidar guns during weekday, off-peak periods on free-flowing vehicles. Generally, speed reduction was generally found to vary with the posted speed limit, the type of vehicle, and the geometric feature present.

Multiple linear regression was used in the analysis to estimate SRFs. The models were estimated such that the highest speed limit (60 mph speed limit on a rural, two-lane highway) serves as the baseline/default condition. The average speed on these segments (i.e., in the absence of any of the geometric features associated with speed reductions) was approximately 64.5 mph. In terms of how average speed varies when vehicles travel through different speed limit reduction, a 5-mph speed limit reduction corresponded with a reduction in mean speed of 3 to 5 mph. In addition, when examining mean speed reduction, heavy vehicles were found to travel at 1.5 mph slower than passenger cars. Turning to the geometric characteristics, single-lane roundabouts within 500 ft upstream or downstream were found to have the strongest influence on speed as they were associated with an average speed reduction of 7 mph. In terms of median type, raised medians and depressed medians were associated with speed reductions of 3.1 mph and 1.3 mph, respectively, when compared to an undivided facility. However, the presence of a two-way, left-turn lane was associated with a speed reduction below 1 mph.

The presence of on-street parking was associated with a mean speed reduction of 1.7 mph. Similar reductions were observed in the case of marked crosswalks (1.3 mph) or where curb and gutter were present (1.0 mph) when compared to paved shoulders. The presence of stop control on the minor approach did not have a substantive impact on speeds (less than 0.2 mph). Similarly, speeds were marginally higher (0.5 mph) where bicycle lanes were present. The analysis of spatial trends showed that drivers started to reduce their speeds at distances of up to 1000 ft upstream of the speed limit reduction. The rate of reduction increased more rapidly the nearer a vehicle was to the upcoming speed limit sign. Once a vehicle was within 400 ft of the speed sign, speeds were reduced by about 1 mph for every 100 ft a vehicle got nearer to the sign. The overall reduction from 1000 ft to 100 ft upstream of the sign was approximately 5.7 mph on average. Vehicles continued to reduce their speeds once they passed the speed limit sign, up to a distance of approximately 400 ft downstream. Beyond this distance, speeds remained relatively constant. Consequently, this study led to the development of SRF, which transportation agencies can use to prioritize treatments and interventions, especially in areas where high speed is a concern or where there is a high number of vulnerable road users.

In contrast, certain geometric features showed marginal impacts on travel speeds. These included lane width, shoulder width, and the presence of bike lanes. Several other features, including upstream horizontal curvature and isolated median islands, were examined as part of this study and found to have effects, but these results could not be generalized due to a limited number of sites at which the features were present. It should be noted that the research team finding minimal impacts of these geometric features did not imply that they do not influence travel speed. Instead, such areas present opportunities for further research to gain further insights.

Additional analyses were also undertaken to bolster the robustness of SRFs. The speeding behavior of drivers along the study corridors was investigated through logistic regression to discern the factors that increase or decrease the likelihood of speeding under various contexts. The variability across vehicle speeds on the study corridors was also evaluated by estimating a linear regression model for the standard deviation in vehicle speeds as a function of the same roadway features of interest. The results from both of these supplemental analyses corroborated the trends observed with respect to operating speeds, providing additional empirical support for application of the SRFs.

Overall, single-lane roundabouts were found to be a very effective speed-control measure, making them a potential solution in the transition areas from high-speed roadways into Complete Streets environments, especially at locations where there was an expectation of heavy non-motorized traffic. It should be noted that this study exclusively evaluated single-lane roundabouts, and speed reduction impacts may vary for multilane roundabouts. The introduction of medians was also found to consistently reduce speeds. Raised medians were particularly effective and could be used as a traffic-calming measure with the added benefit of serving as a refuge for pedestrians and bicyclists crossing the road. Also, the presence of on-street parking and crosswalks was associated with reduced speeds. Transportation agencies could use marked crosswalks as traffic-calming measures at locations with high pedestrian flow, such as school zones, malls, etc. Likewise, when feasible, on-street parking could be implemented as part of Complete Streets configuration.

Finally, as drivers did not typically reduce their speeds until they were approximately 1000 ft upstream of a speed limit reduction, road agencies could consider traffic control devices, such as dynamic speed feedback signs (DSFS) or reduced speed limit ahead signs, to enhance driver awareness of impending speed limit reductions.

Chapter 1: Introduction

Traditionally, in transportation planning and engineering, highways and streets have been designed with an emphasis on the movement of motor vehicles, particularly fom an operational and safety perspective. This approach has resulted in transportation systems that are generally well designed for such vehicles but which may present inherent challenges for other road users, such as people walking and biking. Recently, there has been a substantive shift in design practices toward approaches that are more inclusive, flexible, and context-appropriate. These approaches include performance-based practical design, context-sensitive solutions, and Complete Streets. These approaches are able to better accommodate all users, promoting equity and solutions that are right-sized rather than standards-driven. Given recent increases in the number of pedestrian and bicyclist fatalities that have corresponded with the onset of the COVID-19 pandemic, these solutions have become increasingly important. This is particularly pertinent in Minnesota as Minnesota Statute §174.75 requires the Minnesota Department of Transportation (MnDOT) to follow a Complete Streets approach “to address the safety and accessibility needs of users of all ages and abilities.” MnDOT assesses user needs at several stages of planning, project scoping and designing, construction, operation, and maintenance” (MnDOT, 2023).

Recognizing the importance of these design principles, the Federal Highway Administration (FHWA) has designated Complete Streets as the default approach for funding and designing federally funded roadways around the US (FHWA, 2022).

1.1 Problem Statement and Study Objectives

The National Complete Street Coalition describes “Complete Streets as a means by which streets are made safer and accessible to all road users through the explicit incorporation of design features to create hospitable environments for pedestrians, bicyclists, and transit riders of all ages and abilities” (Smart Growth, 2022). Motor vehicles are not considered the priority in a complete street environment. Complete Streets seek to transform the traditional approach to roadway design with the sole aim of creating a safer and more accessible environment for all road users. To "complete a street," roads are either built from scratch with features that encourage the use of the facility by all users or retrofitted in what is known as a roadway reallocation. When converting from a legacy urban street, roadway reallocation typically involves lane reduction, the addition of a median, the introduction of bicycle lanes, and enlarging sidewalks, among other changes, as illustrated in Figure 1 and Figure 2, which show a roadway before and after conversion. In this example, a four-lane roadway with two vehicle lanes in each direction is converted to a facility with two vehicle lanes, a median, and space allocated for people walking and biking as well.

Figure 1 Before Conversion in Richfield, Minnesota (Source: Minnesota Department of Transportation)

Figure 2 After Conversion in Richfield, Minnesota (Source: Minnesota Department of Transportation)

However, an area of particular concern for Complete Streets is designing in consideration of speed outcomes. This is particularly true in environments where there are large numbers of people walking and biking. Highways and streets have been traditionally designed for a maximum safe speed in consideration of curve radius/superelevation and stopping sight distance. However, the 2018 *Green Book* (*A Policy on Geometric Design of Highways*) has introduced an increased emphasis on flexibility in design (AASTHO, 2018). This train of thought is consistent with the adoption of context sensitive solutions (CSS) in streets where design speed is not the most important factor (Hui et al., 2018). A notable initiative supporting this change in design philosophy is the National Association of City Transportation Officials (NACTO) 2017 policy statement advocating for the removal of rules or laws that require that speed limits be set at the 85th percentile speed and promote the concept that cities should be permitted to set their own speed limits (NACTO, 2017). Furthermore, a 2017 National Transportation Safety Board (NTSB) study included recommendations for the *Manual on Uniform Traffic Control Devices* (MUTCD) to change the factors used in engineering studies (e.g., crash statistics) from optional to required and require an expert system as a validation tool for speed limit selection (NTSB, 2017). This requires that factors such as crash statistics be used in speed limit selection to ensure that safe speeds for all users are selected on the roadway, and this is one of the main goals of a complete street.

To that end, MnDOT and other agencies have adopted a design approach that instead emphasizes target speed in consideration of the needs of anticipated road users. As such, this research focuses on the following questions:

1. How much do drivers reduce their speeds when entering speed-reduction zones, such as those entering communities located along high-speed rural highways?
2. How do these speed reductions vary based on the cross-sectional elements of the highway, as well as the upstream and downstream speed limits?
3. How do drivers adjust their speeds in response to specific cross-sectional elements of the highway, and over what distance are any changes in travel speeds maintained?

The primary focus is on the impact of Complete Streets on travel speeds. Specific attention is paid to the relationship between speeds and various design elements associated with Complete Streets.

1.2 Task Summary

To achieve the above-stated research objectives, the following tasks were performed. A detailed description of these tasks has been provided in the subsequent chapters of this report.

- <u>Literature Review</u>: A comprehensive state-of-the-art literature review was carried out to document established findings as to the relationship between travel speeds and roadway characteristics, particularly as they relate to Complete Streets
- <u>Site Selection</u>: The chapter provides insight on the collaborative effort between the research team and the Technical Advisory Panel (TAP) to identify suitable sites for field data collection activities.
- <u>Field Data Collection</u>: This chapter provides a comprehensive overview of the procedures employed to conduct field data collection of vehicle operating speeds at the designated sites selected as part of the site-selection task.

- Data Analysis: This section details the statistical analysis methodology used to discern the relationship between operating speeds and site characteristics. Details on the data extraction process is also provided.
- Research Benefits and Implementation Steps: This chapter documents the estimated benefits that would be derived from this project. Details on the key steps needed to implement these benefits are also provided.
- Conclusion and Recommendations: This chapter presents the conclusion and recommendations of the research, followed by the limitations and opportunities for future work.

Chapter 2: Literature Review

The impact of geometric features on travel speeds within Complete Streets corridors is being studied in this project (or something to complete this sentence). Therefore, there is a need to synthesize existing literature to enhance our understanding of this important aspect of transportation engineering. To this end, this chapter provides an extensive summary of previous research literature as it relates to the impact of changes to the road cross section on traffic safety and travel speeds. This section builds upon insights from prior studies by identifying key trends, emerging areas, and gaps in the research literature.

2.1 Road Diets/Roadway Conversions

Road diets/roadway conversions can be described as a low-cost countermeasure that adds or removes from the existing pavement cross-section to provide benefits for safety, accessibility, and mobility for all categories of users (Zhou et al., 2022). A report by the FHWA in 2014 describes road diet/roadway conversions as removing travel lanes from the roadway and utilizing the resultant space for other travel modes and road users (Knapp et al., 2014). Another study in 2001 frames it as simply the conversion of four lanes undivided roadways to three lanes (TWLTL) with the extra lane converted to bicycle lanes, pedestrian facilities, and/or on-street parking (Huang et al., 2002). Different configurations of conversion are from four lanes to five lanes TWLTL, two lanes to three lanes TWLTL, and five lanes TWLTL to three lanes TWLTL (Knapp et al., 2014). However, the most common is the four to three lanes TWLTL conversion. Roads suitable for conversion are usually four-lane roads, pedestrian-at-risk roadways, traffic volume between 11,000 -25,000, roads that experience overspeeding, and roads with a high number of bicyclists (Burden & Lagerwey, 1999).

2.1.1 Safety Benefits of Road Diets/Roadway Conversions

The safety benefits of roadway conversions have been quantified by crash modification factors (CMFs), which express the average change in crash frequency that is associated with the conversion of a "traditional" design (e.g., four-lane undivided facility) through a roadway conversion (e.g., reduction to one lane in each direction with a two-way left-turn lane).

Ultimately, different studies have generated varying quantitative benefits of roadway conversions. A study by the University of North Carolina completed in 2001 that used data collected in Washington and California on sites converted from 4 – 3 lanes TWLTL concluded that a 6% reduction in crash frequency could be achieved on roadway conversions when each site was compared to one or more similar site (Huang et al., 2002). In contrast, a similar study carried out in Iowa in 2005 did not show any meaningful crash reduction in its analysis of monthly crash data using Poisson models (Pawlovich et al., 2006), though it should be noted that the roadway conversion sites in Iowa were roads with very low ADT. A study of 24 sites in Michigan in 2012 that examined the safety impact and operational effects of roadway conversions reported an average CMF from all sites of 0.91, implying that average crashes on all were reduced by 9%. It should be noted that this result was found not to be statistically different from 1.0 (Lyles et al., 2012).

When examining differences in CMFs across studies, crash reduction ranges from as low as 19% to as high as 44%. For example, CMFs developed using the Empirical Bayes (EB) method on 39 segments and 39 intersection sites in Virginia that had undergone conversions reported a 38% total crash reduction and a 64% reduction in fatal and injury crashes on suburban/urban arterials (Lim & Fontaine, 2022). One limitation of the research, however, was the short segment lengths and the relatively sparse after-treatment data. In another study in Rhode Island in 2022, a safety effectiveness analysis was carried out on 11 treatment roadway conversion sites and 17 reference sites where a 4-lane undivided roadway was converted to 3 lanes TWLTL, finding a 29% reduction in total crashes and a 37% reduction in fatal and injury crashes (Zhou et al., 2022). A Texas study explored the relationship between operating speed, roadway characteristics, and crashes on city streets using a negative binomial model and reported that the presence of conversion elements such as median, curb and gutter caused a reduction in fatal and injury crashes (Park et al., 2021).

A study in California that analyzed the safety and speed effects of roadway conversions with high-volume traffic in 2022 showed that the conversion of a 4-lane roadway to a 3-lane TWLTL reduced speeds by 6% (Venegas, 2022). An FHWA informational guide reports 3-to-5 mph reductions in average and 85th percentile speeds when roadway conversions are introduced (Knapp et al., 2014). On a related note, a study that examined the yielding behavior of drivers to pedestrians at unsignalized crossings based on the 85th percentile speed in Boston reports that the yielding rate was inversely proportional to the operating speed; the faster a vehicle was traveling, the less likely it was that the driver chose to yield. This is seen from a 78% yield rate for a 20 mph speed to a 9% yield rate at a 38 mph speed (Bertulis & Dulaski, 2014). This suggests that roadway conversions may both reduce speeds and increase vehicle yielding in Complete Street environment.

Lastly, the impacts of roadway conversions and Complete Streets features on travel delay were explored in a study of 25 mph speed limit with 3 lanes TWLTL sites in New Brunswick, Canada. Speed limit was used as a surrogate of operating speed, with Vissim and Synchro-8 used for the simulation. The results showed that conversions might introduce delays and increased travel time. However, this has been offset by the economic cost of the crashes that could have resulted if these conversions had not been introduced (Noland et al., 2015).

2.2 Impact of Design Choices and Geometric Elements on Safety and Travel Speed

The following sections summarize research literature related to Complete Streets/roadway reallocations and cross-sectional features of roadways and their impact on driver speeds and safety of the facility.

2.2.1 Relationship with Travel Speeds

Many states and road agencies establish speed limits in a non-statutory speed zone, such as Complete Streets location, based on the results of a traffic and engineering study. The MUTCD guidance for setting speed limits in speed zones is to use the 85th percentile speed. However, evidence showing that the 85th

(NTSB, 2017) percentile speed is the speed for the lowest crash involvement rate for all types of vehicles is limited, and adopting it on a Complete Street may not yield the speed and safety outcome for all road users.

Ultimately, various factors are considered when establishing speed limits. Using philosophies set forth in Vision Zero, and Safe Systems, the establishment of speed limits in urban areas by using different approaches in urban areas as compared to rural areas has been advocated (Dumbaugh et al., 2019; Shahum, 2018), which is expected to make roads such as Complete Streets safer.

While flexibility in the design of roadways has been encouraged, the design speed approach previously adopted by AASHTO does not give any guidance on specifying an upper limit for speed on a given roadway (Garrick & Wang, 2005), which can be problematic if vulnerable road user safety is a focus. Likewise, a study that examined the relationship between design speed, operating speed, and speed limits reported opposition to the use of design speed as the most important factor in roadway design because of the inconsistency in its use (Stamatiadis et al., 2004).

These issues are important, especially in a Complete Street environment. Driver speed selection greatly impacts the safety of vulnerable road users in the event of a collision, as various studies have shown the crash risk to vulnerable road users changes with vehicular speed.

A study funded by the AAA Foundation for Traffic Safety examined the injury risk among crash-involved pedestrians as a function of vehicle speeds. The results showed that pedestrians struck by a vehicle traveling at 23, 31, and 39 mph see an increased risk of severe injuries by 10%, 50%, and 75%, respectively, when compared with being struck by vehicles traveling with speeds below 15 mph. (Tefft, B.C. 2011). Similarly, a Smart Growth America report on pedestrian fatality risk reported that there is a 45% risk of fatality for pedestrians involved in a crash with a vehicle traveling at 35 mph (Smart Growth America, 2021).

On a related note, a study that examined the law on fatalities involving vulnerable road users in Florida concluded that more than 3500 pedestrian fatalities have been prevented in 29 years with the introduction of Complete Streets (Porter et al., 2018).

While existing literature has provided the safety benefits of Complete Streets and road conversions, very few studies have quantitatively and qualitatively estimated their impact specifically through the lens of vehicle speeds (Grahn et al., 2020; Hui et al., 2018).

2.2.1.1 Access Density

The relationship between speed and access density is inconsistent across research, and there is little consensus on its impact on speed and Complete Streets. Although very limited studies have investigated the relationship between access density and Complete Streets, some researchers have examined urban streets in the context of access density.

A study conducted in 2001 that examined the design factors affecting driver's speed on suburban streets (four-lane streets with 30 to 55 mph speed limits) using regression method on data from the Texas Department of Transportation reported that decreased access density and roadside development caused an increase in operating speed (Fitzpatrick et al., 2001). These results were supported by another 2021 study conducted in Texas using negative binomial models, which also reported a decrease in speed as access density per mile increased (Park et al., 2021). However, these results were not statistically significant, and the number of sites used in the analysis was very few.

A similar study that examined the effects of access control on safety on urban arterial streets in Indiana showed that increased access density causes an increase in speed (Brown & Tarko, 1999). This is counterintuitive as speeds are expected to reduce with the increased friction caused by increased access density.

2.2.1.2 Medians

The effect of the presence of a median or type of median on the driver's speed selection has not been extensively researched. A TWLTL is the most common median type on a complete street, and there is some ambiguity in their operational and safety effectiveness. A paper that explored operating speed on tangent sections in 2005 reported that the presence of a raised or depressed or TWLTL caused drivers to slightly increase their speed compared to the absence of a median (Fitzpatrick et al., 2005). However, the result was not statistically significant, so extensive conclusions could not be drawn. Similarly, in a study examining the design factors such as posted speed limit, lane width, deflection angle, median, and access density that affect driver speed on suburban streets, the result indicated that the presence of a median rather than the type of median caused an increase in speed (Fitzpatrick et al., 2001).

Some studies have also investigated the crash risk potential of the median in different contextual and vehicular environments, and the results are similarly mixed. One such study compared the safety benefits of trucks using a raised median or a TWLTL in Texas and reported that TWLTL with a truck percentage greater than 20% incurs more crash risk compared to the raised median (Qu et al., 2020). A detailed look at the CMFs obtained showed that crashes are reduced by 28% when a TWLTL is replaced with raised median in areas where the truck percentage exceeds 20%. This suggests that with the introduction of TWLTLs may not be appropriate for some contexts with a high percentage of trucks on the roadway. However, another paper that assessed access control on urban streets in Indiana with negative binomial models reported a reduction in crashes with the presence of a median or TWLTL (Brown & Tarko, 1999).

2.2.1.3 On-Street Parking

One common feature of Complete Streets is the presence of on-street parking on one or both sides of the road. However, the effect of on-street parking on the safety and operation of roadways is not consistent across research. While some papers advocate for its safety benefit, others consider that safety and operational issues could arise from its use (Cao et al., 2017; Edquist et al., 2012; Guo et al., 2012). One such examination was a paper by Marshall et al. that assessed on-street parking in

Connecticut. Two hundred and fifty road segments were selected both with and without on-street parking on low-speed streets. The results indicated that streets with on-street parking with a speed limit lower than 35 mph had the lowest rate of fatal and injury crashes (4% of all crashes). Comparing the results with low-speed streets without on-street parking showed a higher rate of fatal and injury crashes (10%) (Marshall et al., 2008).

A study in Australia using a driving simulator found that drivers with higher workloads (due to the presence of on-street parking) will tend to compensate for their crash risk on streets with driving close to the center of the roadway, reacting slower to unexpected pedestrians and thereby causing speed reductions but elevating crash risk (Edquist et al., 2012). However, in a study using path analysis to model the relationship between roadway characteristics and driver's speed selection in Texas, speed reduction resulted from the presence of on-street parking on tangent sections (Park et al., 2021). Similarly, in a study that took advantage of In-Vehicle global Positioning system Data on low-speed urban streets in Atlanta in 2006 using a random effects model, the conclusion reached was that speed reduced with the presence of on-street parking when compared with the absence of on-street parking. (Wang et al., 2006). Additionally, the analysis of vehicle operating speed on urban roads using an ordered probit model in Canada in 2013 showed that the presence of parking, when compared to its absence, also caused a decrease in vehicular speed. (Eluru et al., 2013).

2.2.1.4 Lane Width/Number of Lanes

As lane conversion or narrowing is a key part of Complete Streets, how it affects vehicle speed and safety of vulnerable users is of interest. Design speed has always been the major determinant of the width of the roadway (Stamatiadis et al., 2004). However, results from research have been inconsistent on what impacts lane width has on speed. One example of this is a study conducted in Pennsylvania on 27 urban collection sites with speed limits of either 25 mph or 35 mph. The results showed that increased lane width near the midpoint of horizontal curves is related to speed reduction (Poe & Mason, 2000). Similarly, a study that modeled operating speeds on tangent sections of urban residential streets in Japan using a simultaneous equation approach with a three-stage least square estimator reported a reduction in the mean speed with increasing lane width (Dinh & Kubota, 2013).

However, a study that examined the safety and operational effects of lane width on midblock sections in urban Nebraska using negative binomial and random effects models concluded that there is no linear relationship between increased lane width and vehicular speed. The result showed that 9 – 10 ft wide lanes have a positive relationship with higher operating speeds in central business districts with speed limit of 25 mph compared to 11 ft to 12 ft wide lanes, while lower speeds were reported on roads with a 40-45 mph speed limit with the same lane width of 9 – 10 ft (Sharma et al., 2015). Furthermore, a study in Montreal that examined vehicle operating speed on urban streets in 2013 with the aim of modeling the proportion of vehicles traveling at different speeds with probit models showed that an increase in the number of lanes causes an increase in operating speed (Eluru et al., 2013).

In terms of safety, an analysis of 3031 sites in Michigan and Minnesota showed that total crashes increased when the lane width was increased from 9 to 10 ft as compared to increasing from 9 to 12 ft.

The result also showed that there is no significant difference between a 9 ft or 10 ft lane on safety at midblock sections (Potts et al., 2007). This was consistent with a study of ten years of crash data in Nebraska. Statistical analysis performed did not show any statistical difference in crash frequency between 11 ft and 12 ft lanes. Similar to the study by Potts et al., a study conducted in four cities in Nebraska to estimate the safety effect of lane widths on urban streets using propensity scores potential outcomes modeling technique concluded that crash frequency was highest on the 10 ft wide roadway as compared to 9 ft, 11 ft, and 12 ft (Wood et al., 2015). Similar to speed, there are no linear trends or consensus on the effects of lane width on road safety, and this warrants detailed investigation in a complete street context.

2.2.1.5 Bicyclist Facilities

Many roadway conversions involve adding bicycle lanes. These lanes could be buffered or non-buffered, and bicycle ridership has been shown to increase by 200% with the introduction of a road conversion (Gudz et al., 2016). However, the lack of data for people walking and biking on adjoining streets limited the assessment as inference could not be made on whether people biking from other streets decided to use the newly built bicycle lanes.

In assessing speed and operational impacts, a comparison of the proportion of speed categories on local roads and arterials in Montreal showed that the presence of bicycle routes increased the proportion of high-speeding vehicles on the roadway (Eluru et al., 2013). Further research is needed on the impact of a bicycle lane on speeding vehicles in a Complete Street context.

Regarding bicycle lanes and crashes, a North Carolina study evaluating the effectiveness of on-street bicycle lanes showed that people biking are at least three times more likely to be involved in a crash in the absence of an on-street bicycle lane compared with a bicycle lane. This study also noted that limiting the access density to 63 access points per mile lowered crash risk. Increasing the road lane width to about 15 ft when on-street bicycle lanes cannot be provided also reduced crash exposure (Pulugurtha & Thakur, 2015).

Another study in Central Florida that developed a hierarchical Bayesian model to model crashes and bicycle exposure showed that increased bicycle volume, traffic volume, higher speed limit, access per mile, and the number of parking spaces per segment caused an increase in bicycle crashes. However, the result of using outside shoulder width, median width, and TWLTL length as continuous variables in the model showed that they negatively correlated with the number of bicycle crashes (Ugan et al., 2021).

2.2.1.6 Shoulder Width

Minimal research has investigated the influence of shoulder width or type on the drivers' speed selection or in a Complete Streets environment. Most research usually combines the width of the shoulder change with the lane width for analysis. However, a study investigating speed management strategies for bicycle lanes in Florida with crowd source data and Bayesian joint models concluded that widening the shoulders helped to reduce bicycle crashes (Ugan et al., 2021). Similarly, a study that investigated the effects of access control on urban arterial streets in Indiana using a negative binomial model reported that the presence of a shoulder has been reported to cause a reduction in crashes (Brown & Tarko, 1999).

2.2.1.7 Sidewalks

Little research has been completed on the influence of sidewalks on how drivers select their speeds, and the results have been conflicting. A study that modeled operating speed on low-speed urban tangent streets reported that the presence of sidewalks reduced drivers' traveling speed (Wang et al., 2006), however, a study that investigated how road features influence the proportion of high-speeding vehicles reported that the presence of a sidewalk increases the proportion of high-speeding vehicles in the travel stream (Eluru et al., 2013).

2.2.1.8 Gateways

A key component of this research study is how geometric features affect vehicle speeds as they transition from rural areas to urban communities. One commonly used transition feature for this is called a gateway.

Gateways are traffic-calming measures strategically located as motorists enter a community which helps to inform motorists that they are entering a community and are no longer on an open, high-speed roadway. They mark the entry point to a community (Hallmark et al., n.d.). They can also be described as a landmarks (physical or geometric) that indicate a change from a high-speed environment to a low-speed environment. This may be a combination of medians, street narrowing, signs, roundabouts, or other identifiable features (Burden, 2007).

Different studies have examined the effect of gateways from speed and safety perspectives. However, none of the research has examined these effects in a complete street context. One such study was in New Zealand, where a before and after analysis of gateway effectiveness was measured with five years of crash data on 102 treatment and 62 control sites. The control sites were selected such that the population of the town matched those of the treatment sites. The gateway treatments applied to the sites were in five categories of gateway, including flush median with a colored surface, sign-only gateway, gateway with flush median, gateway with flush median and hatched edges, and gateway with solid island and hatched edges. The segment length covered was 328 ft before and after the gateways, as the impacts of the gateways on speed reductions dissipated about 820 ft downstream of the gateway. A chi-square test was used in the analysis, and the result of the measure of the overall effectiveness of gateways showed an overall CMF of 0.74, which is a 26% crash reduction (Makwasha & Turner, 2013). Another study in Nevada in 2011 examined the safety impacts of seven gateway monuments. Data was collected from five monuments located along road segments, while two were at signalized intersections. The analysis was performed using the Empirical Bayes before and after method, with the result showing that the monument did not have any safety impact on sites when viewed individually. However, there was a crash reduction due to the presence of the monuments when all sites were considered together, with a 32% reduction reported (Ye et al., 2011).

Similarly, a study in Italy involved twelve gateways at the exit and entry point of six small towns where speed transitioned from 55 mph to 35 mph. A common theme of the gateways was the presence of different types of central island and chicane deflections (0^{o}, 3^{o}, 4^{o}). The results indicate a 5.6 mph reduction in speed when the gateway was a raised island with a 4-degree chicane compared to 0.88 mph for a 3-degree chicane and ghost central island. Likewise, a comparison of crash frequencies before and after the construction of the gateway for one of the sites showed a 100% and 61.1% reduction in injuries and fatal crashes, respectively (Lantieri et al., 2015).

Another study in Iowa examined the effectiveness of treatments in reducing speeds in five small rural communities. Speed data and traffic volumes were collected with pneumatic tubes before and after treatments were applied to the sites. Two sites were selected as gateway communities, with the remainder as non-gateways. The speed limit on the two gateway sites ranged from 55 mph to 20 mph, with the entry speed (rural road) into the community between 45 and 55 mph and the speed within the community varying between 20 mph and 35 mph. Five single-measure treatments of speed table, on-pavement "Slow" markings, driver speed feedback sign, tubular markers, and on-pavement entrance were evaluated in the non-gateway site. The results indicate that gateway treatments with converging chevrons and 25 mph on-street pavement marking at the entrance of the communities were effective as speeds consistently decreased during the 1-year after data collection. However, gateway treatments with lane narrowing and on-pavement speed markings within the community did not appear to show any effect on speed reduction. Other gateway treatments applied were transverse pavement markings, median and shoulder widening, and driver feedback signs. The results indicated that there was a moderate decrease in speed without feedback signs, and the 85^{th} percentile speed and average speed were found to decrease by 3 -5 mph when a feedback sign was added. The number of drivers going above the speed limit was also found to decrease by 28% (Hallmark et al., n.d.). A similar study using a simulation evaluated the effectiveness of roadway treatment on speed reduction as vehicles traveled from rural to urban areas in Oregon in 2008. Roadway treatment effectiveness was measured by observing 54 drivers in a driving simulator as they traveled from 55-45-35 mph roadways. Eight scenarios were statistically tested, with four having the greatest speed reduction effect. These four scenarios are identified as the presence of medians in series with crosswalks, the presence of medians in series without crosswalks, the presence of a gateway with a median, and the presence of a gateway with lane narrowing. The three scenarios whose results were statistically significant had an average speed reduction of 14 mph downstream of the 35 mph sign as they transitioned from the 55 mph sign on the rural road to the communities (Dixon et al., 2008); the result for the presence of a gateway with lane narrowing was not statistically significant.

Another study in Pennsylvania in 2010 examined how different features affect the operating speed at transition zones by collecting data from 2,859 vehicles from 20 transition zones. Data was collected with sensors using vehicle magnetic imaging technology. A reduced speed ahead sign was used to indicate the beginning of the transition zone, with the end of the transition zone signified with a sign that specifies the lower posted speed limit. The speed limit in the high-speed zone varies from 55-45 mph, while the low-speed zone varies from 40-25 mph. Ordinary least-square (OLS) linear regression models were used to estimate speed reductions. The results using OLS indicate that a speed reduction of 0.16

mph is expected per 1 mph increase in operating speed 500 ft before the beginning of the transition zone. Also, as the lane width, shoulder width, and lateral clearance reduced by one foot in the transition zone, speed was expected to reduce by 2.4 mph, 1 mph, and 0.4 mph, respectively. Lastly, a unit increase in the number of driveways was expected to cause a 0.4 mph reduction in operating speed. The presence of a curb and gutter is also expected to result in a speed reduction of 1.2 mph when compared with its absence (Cruzado & Donnell, 2010).

A similar study examined drivers' response to dynamic speed feedback signs (DSFS) on five sites, which are two-lane rural speed transition zones in Michigan with high speed, with three of the sites having 65 mph speeds on the rural road while the remaining had 55 mph. The speed of entering the communities ranged from 45-40-35 mph. Multiple linear regression was used in the analysis, with results showing that the greatest speed reductions were achieved at the location of the DSFS (3.2 mph – 7.8 mph). The results also indicated that the greatest speed reduction was achieved where there was a steep drop in speed, i.e., from 65 mph to 35 mph (Mahmud et al., 2022). Dynamic speed feedback signs could be a very efficient method of reducing vehicle operating speeds as vehicles travel from high-speed rural roads into Complete Streets.

2.3 Literature Summary

Generally, roadway conversions have been shown to significantly improve traffic safety. Research suggests crash reductions of between 19 and 47% after the implementation of a road conversion (Knapp et al., 2014). In addition to safety impacts, the research literature includes several examples of studies from researchers and practitioners that have documented success stories related to Complete Streets (Jordan & Ivey, 2021; US EPA, 2021). This includes examples of studies that have examined public buy-in for Complete Streets policies (Grossman et al., 2019), as well as the potential implications on state standards in consideration of non-motorized users (Noyce et al., 2013).

While research has been consistent as to potential safety benefits, there is little consensus as to the impacts on operations and travel speeds, specifically. While some studies report that operation improves with roadway conversions, others report delays and reduced capacity.

Looking at specific roadway features, from a speed selection standpoint, there has been concerted pushback against the use of the 85th percentile speed as the basis for setting speed limits, with effort geared towards designing for a target speed. However, very little guidance is available on designing for target speed, especially in a Complete Streets context. For access density, inconsistency in the results of studies examining its effect on speed indicated that there is a need for a more vigorous examination of its effect regarding medians, the presence and type of median have been found to influence vehicular speed and safety, though the results have also been mixed.

Research looking at the effects of parking on speed selection shows the presence of on-street parking generally results in speed reduction. In looking at the effect of lane width, there is no consensus on how lane width impacts speed or safety. Likewise, little research exists on how shoulder width impacts travel because most investigation combines the width of the shoulder with the lane width for analysis. One of the most effective means for reducing crash risks among people who are biking is the introduction of mode-specific facilities, such as bike lanes or buffered bike lanes. Additionally, sidewalks have safety benefits for pedestrians; however, there is no consensus on how they impact driver speed selection. Lastly, there has been some research on the effect of geometric and traffic-calming features on vehicle operating speed as they transition from high-speed rural roads to urban communities, known as gateways. However, there has been little or no research on how this effect may vary in a complete street context.

Overall, evaluative research has been limited, particularly as it relates to the speed-related impacts of Complete Street projects (Grahn et al., 2020). Consequently, this study will fill an important gap and advance fundamental knowledge related to driver speed selection.

Chapter 3: Site Selection

To better understand the behavior of drivers on Complete Streets, there was a need to collect high-fidelity data, including drivers' operating speed while traversing into, within, and outside Complete Streets. To that end, the research team worked with the technical advisory panel (TAP) to screen and identify sites suitable for field data collection. The TAP was particularly interested in sites where high-speed roads transition to low-speed roads. Therefore, sites were selected across different combinations of contexts (rural town vs urban/suburban), roadway types (multilane divided vs. multilane undivided vs two-lane undivided), posted speed limit, the presence of specific features (bike lanes, raised media, on-street parking) and traffic volume ranges. A list of the cross-sectional features generally considered as a part of site selection are as follows:

- Access density (access points/mile)
- Bicyclist activity (low/medium/high)
- Lane width (ft)
- Speed limit (mph)
- Median type (none, TWLTL, raised)
- Number of lanes (two-way total)
- Number of signals in the segment
- Intersection density
- Presence of bicycle lane
- On-street parking (parallel/angle/none)
- Pedestrian activity (low/medium/high)
- Shoulder width (ft)
- Sidewalk (none/narrow/wide)
- Sidewalk buffer/separation (yes/no)
- Land use (residential/commercial)
- Vehicle volume (veh/day)

Based on the initial screening process and the recommendations from the TAP, 27 corridors were identified by the TAP, with 49 sites selected initially by the research team. Further assessment of each site by the research team with Google Maps resulted in the removal of some sites due to lack of access to the site access for field data collection, the non-suitability of the site for the research objective, and ongoing work zone activities. Overall, 39 sites along 17 locations, as shown in Figure 3, were selected such that they covered the length and breadth of Minnesota and satisfied the above criteria and research objective. Along the line, the TAP was interested in two other corridors, and they were subsequently incorporated into the site selection list, which brings the final number of corridors to 19 and the number of sites to 48.

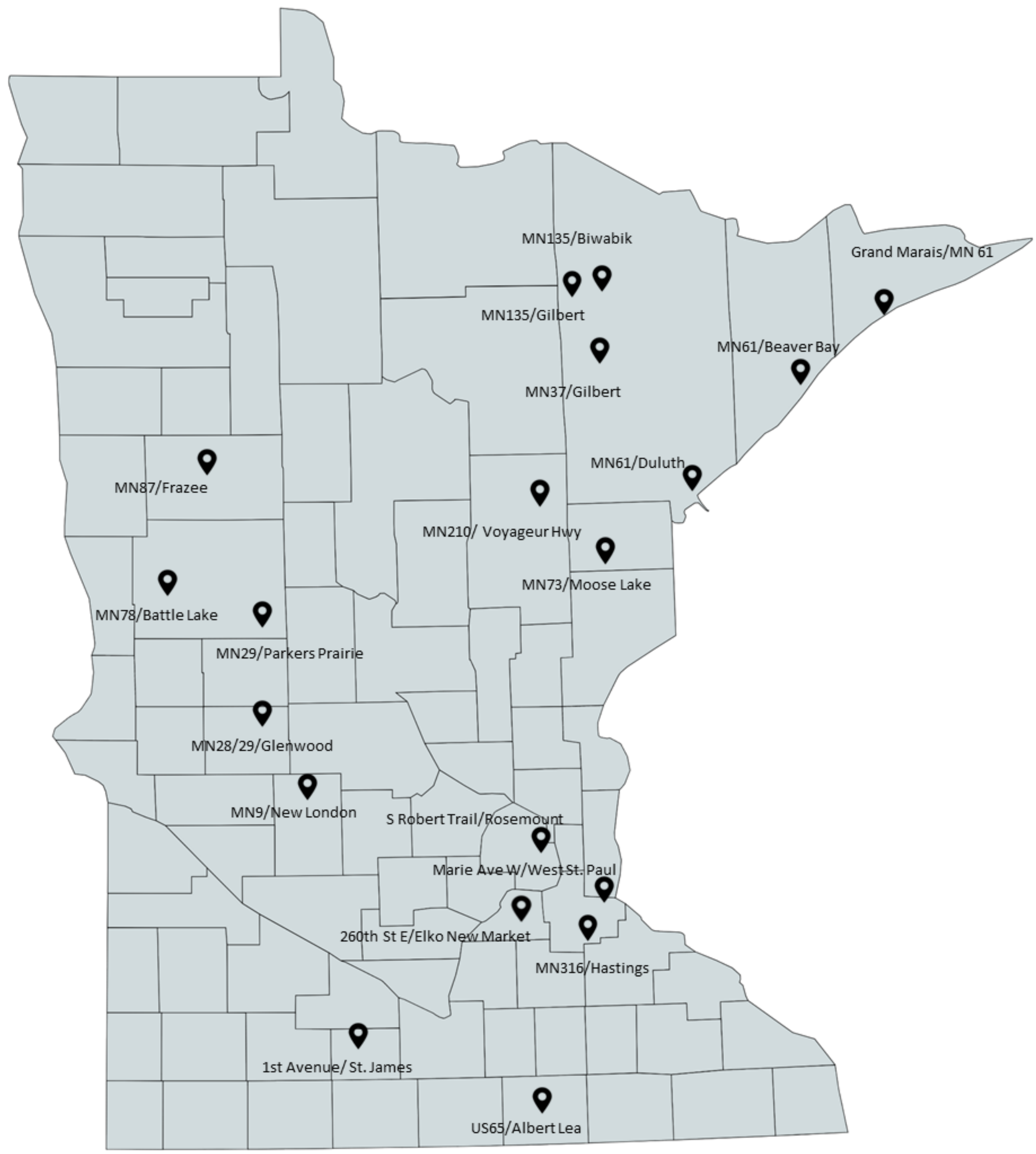

Figure 3 Map showing the 19 locations selected for data collection

Fourteen-speed transition zones entering small communities around Minnesota were identified and selected for this study, while the remaining five were located in the suburban/urban core. Nine of the speed transition zones had a speed limit of 60 mph upstream, two were 55 mph, and two were 45 mph. All speed transitions were on two-lane rural highways except for US65/Albert Lea and MN61/Duluth, which transitioned from a four-lane rural highway to a two-lane rural highway. Five locations had other speed-impacting measures, such as dynamic speed feedback signs (DSFS).

Chapter 4: Field Data Collection

In order to ascertain the relationship between driver speed selection and various roadway elements, there was a need to collect very detailed field data to develop trajectories for individual vehicles. To that end, this chapter details the field data collection activities that were conducted on the 19 identified corridors and 48 sites as a part of this project.

4.1 Data Collection Overview

Initial data collection was conducted over a period of five days during October 2022. These data were subsequently reduced and analyzed. During the process of data reduction and preliminary analysis, the research team identified the need for additional data collection in order to address some gaps. In particular, the preliminary results showed that vehicle speeds were already beginning to decline at many of the upstream locations, which were intended to provide "baseline" speed data of vehicles traveling under normal conditions on high-speed, rural two-lane highways. For example, Figure 4 illustrates the trajectories of vehicles approaching a speed-reduction zone along MN-37 in Gilbert. These data show that speeds were already significantly below the upstream 60 mph limit along this corridor. Similar trends were observed on other corridors, which demonstrated the need for additional data (from further upstream) in order to capture the full magnitude of the speed reductions as vehicles approached these communities. As such, the MSU team identified additional sites in consultation with the TAP.

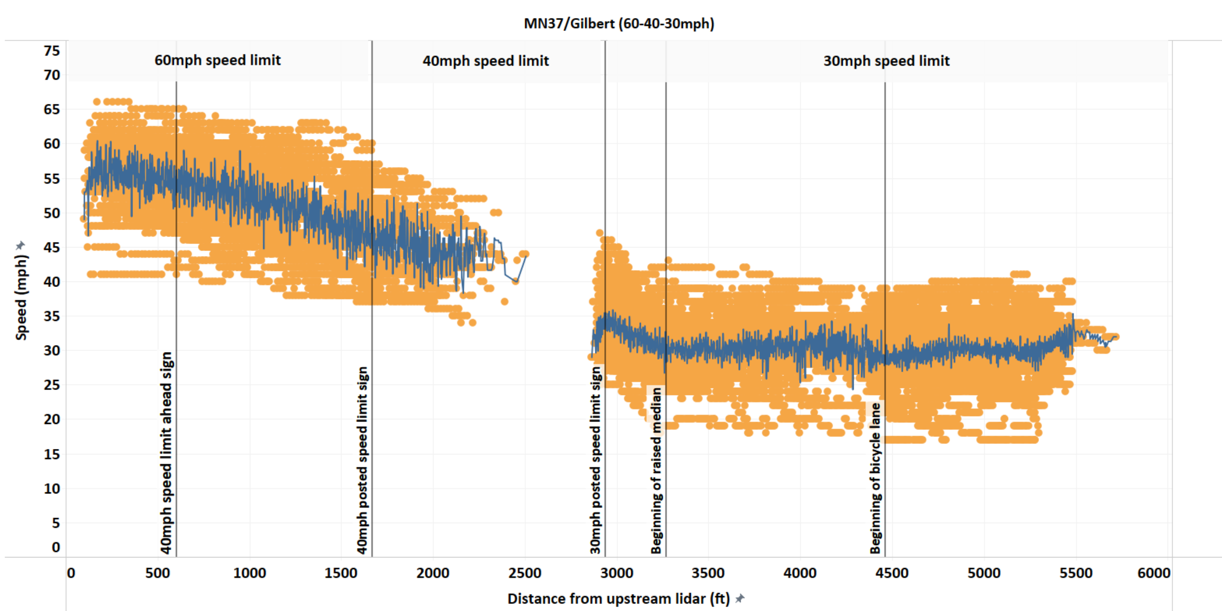

Figure 4 Speed Profile Showing Speed Reduction as Vehicles Approach MN37/Gilbert.

Ultimately, 10 sites were identified for this subsequent round of data collection. This included 8 baseline locations that were drawn from locations further upstream along the 17 initial corridors. Two (2) additional (i.e., “new”) corridors were also identified in consultation with the TAP, bringing the total number of corridors to 19. Speed profiles were developed using data from these sites, which included an average sample size of 100 vehicles per location. This second round of field data collection occurred during August 2023. It should be noted that the baseline speed data collected in August 2023 were all in the same direction of travel as that of October 2022, except for 260th St E/Elko New Market where the shoulder width was not sufficient to allow for parking. Consequently, data were collected in the opposite direction at this location. In total, this project involved field data collection at 48 sites across 19 corridors.

Table 1 presents details of these corridors, the number of data collection sites/locations per corridor, and the range of speed limit changes that occurred across these locations. The field data collection process focused on collecting operating speed data as vehicles transitioned from high-speed rural two-lane highways into rural towns and suburban communities. The remainder of this section provides further details of these data collection activities.

Table 1 Details of Corridors used in Data Collection

S/N	Corridor	Number of Data Collection Locations	Speed Limit Range
1	US 65/Albert Lea	3	60-40-30
2	MN 29/Parkers Prairie	4	60-45-30
3	MN 87/Frazee	2	45-30
4	1st Ave S/St. James	2	30
5	260th St E/Elko New Market	3	55-45-30
6	Marie Ave W/West St. Paul	2	30
7	MN 9/New London	2	45-30
8	MN 78/Battle Lake	2	40-30
9	S Robert Trail/Rosemount	1	30
10	MN 28/MN 29/Glenwood	2	60-30
11	MN 316/Hastings	3	60-45
12	MN 73/Moose Lake	3	55-40-30
13	MN 61/Duluth	3	40-30
14	MN 37/Gilbert	4	60-40-30
15	MN 61/Grand Marais	4	60-40-30
16	MN 210/Voyageur Hwy	3	60-40
17	MN 61/Beaver Bay	2	35
18	MN 135/Gilbert	1	60
19	MN 135/Biwabik	2	60-30

4.2 Data Collection Methods

Detailed speed trajectory data was collected with handheld lidar devices. The lidar guns can measure speed and distance (to the target) at a rate of three times per second with an accuracy ± 1 mph at a range of up to 6,000 ft. From a practical perspective, each lidar gun is typically used to track over a range of up to 1,200 ft. Greater distances are generally difficult to monitor due to changes in road geometry and encroachment from other (i.e., non-subject) vehicles.

Data were collected during the weekday off-peak period from Monday to Friday in October 2022 and Monday to Friday, August 2023, under clear weather conditions. The speeds of vehicles entering the speed transition zones and the small towns were continuously tracked in unmarked vehicles parked on the outside shoulder or in on-street parking spaces. The vehicles were positioned to be as far away as possible from the feature of interest as possible to minimize influencing drivers, as shown in Figure 5

To ensure these data were reflective of operating speeds, only free-flowing vehicles with a headway of at least 3 seconds were observed. During the field data collection, each lidar gun was connected to a laptop using a data transfer cable, which allowed for the recording of all measurements in real time using proprietary software. The data collectors ensured that the lidar recordings included timestamps, distances, and speeds for each tracked vehicle. Cases where vehicles turned at an intersection or a driveway or where their speeds were influenced by changes in signal phases were ultimately removed from the dataset.

After completing the lidar tracking for each vehicle, both data collectors added remarks on the make and color of the vehicle in addition to any other comments that could help in combining the dataset into a continuous speed profile for each subject vehicle.

Figure 5 An Example of Data Collector Vehicle Parking to Avoid Interfering with the Data Collection Process at MN61/Grand Marais

Table 2 provides a matrix that illustrates those road features that were included as a part of the subsequent analysis activities. For each feature, details are also provided as to the corresponding speed limits, providing a general sense of the differences that were observed in terms of cross-sectional characteristics at various limits. These features included two-way left-turn lanes (TWLTL), raised medians, dynamic speed feedback signs (DSFS), depressed medians, bicycle lanes, curb-out/bump-outs, curb and gutter, crosswalks, single-lane roundabouts, on-street parking, and paved shoulders.

Table 2 Road Feature Matrix

Features	Speed limit						
	60 mph	55 mph	45 mph	40 mph	35 mph	30 mph	25 mph
Stop-controlled intersections	✓	✓	✓	✓	✓	✓	✓
Two-way Left-turn Lane (TWLTL)			✓		✓	✓	
Depressed median	✓			✓			
Raised median				✓		✓	
Single-lane roundabout			✓			✓	
Traffic signal				✓		✓	
On-street parking						✓	✓
Curb-outs						✓	✓
Dynamic Speed Feedback Sign (DSFS)			✓			✓	
Crosswalk					✓	✓	✓
Horizontal curve				✓			
Curb and Gutter					✓	✓	✓
Shoulders	✓	✓	✓	✓			
Bike lanes					✓	✓	
Island						✓	
Bump-outs						✓	

In general, the data collection team sought to collect data over as much of each corridor as possible, with particular emphasis on where changes occurred with respect to the posted speed limit or the cross-sectional characteristics of the roadway. In some instances, obstructions resulted in gaps along the corridor that inhibited data collection (e.g., horizontal curves, vertical curves) or where disruptions occurred (e.g., signalized intersections).

4.3 Data Collection Scenarios

In general, four different scenarios were encountered during the field data collection process. These scenarios varied based on factors such as vertical curvature, horizontal curves, and the proportion of turning vehicles. This influenced the number of lidar setups that were required at each location, as well as the distance between consecutive lidars, and the tracking distance. The implication is that the team of 2-3 lidar technicians may or may not be able to track the same vehicle continuously on a stretch of the roadway. Typically, four scenarios were encountered:

- Scenario 1: Two (2) lidar setups where both technicians could track the same vehicle.
- Scenario 2: Three (3) lidar setups where the three technicians could track the same vehicles.
- Scenario 3: Three (3) lidar setups where two (2) of the technicians could track the same vehicle, and the third technician tracked an independent vehicle in the same direction of travel as the other technicians.
- Scenario 4: Various (i.e., one, two, or three) lidar setups occurred in this scenario where one (1) or more lidar technicians could not track vehicle speeds in the same direction.

Table 3 provides details from each of the corridors at which data were collected. This includes details of the specific road features, as well as the corresponding data collection scenarios.

4.4 Data Collection Challenges

Various challenges were encountered during the field data collection process, and details are provided below.

- **MN87/Frazee:** One of the lidar locations could not be used because of ongoing work zone activities at the time of data collection. Therefore, only data from the upstream lidar position is available.
- **MN78/Battle Lake:** The presence of two consecutive vertical curves made it impossible to track vehicles at a downstream lidar position. Although some of the intended features of interest were captured on this site, there is not a continuous speed profile.
- **MN316/Hastings:** At this location, there was no space for a downstream lidar data collector to set up as the road had no on-street parking or shoulders. Consequently, this site does not have a full-speed profile.
- **Lake Rd/Woodbury:** A road conversion was planned at this location. However, at the time the field data collection was completed, this conversion had not occurred. Consequently, data were not collected on this corridor. It should be noted that this corridor was replaced with S Robert Trail/Rosemount.

- **MN9/ New London:** The data collection team encountered very low traffic volumes at this site and could only collect data for about 45 vehicles within 3 hours.
- **Marie Ave W/West St Paul:** In the eastbound direction, tree-cutting activities were occurring. The associated equipment caused vehicles to slow down, resulting in a downward bias in the speed data from this location.

Table 3 Details of Data Collection Scenarios and Road Features

Scenarios	Location	Number of sites	Comments	Road features
1	US 65/Albert Lea	3	Each site required two lidar setups. Data were collected at the 60-40 mph road corridor first before the 40-30 mph, and a single vehicle was tracked through each individual site. It should be noted that the third site was for baseline data.	Dynamic speed feedback sign (DSFS), Bicycle lanes, On-street parking, TWLTL, Depressed median, Raised median.
	260th St E/Elko New Market	3	The two sites required two lidar setups, and a single vehicle was tracked through the corridor. The third site was for baseline data collection	Dynamic speed feedback sign, Sidewalk
	MN 28/MN 29/Glenwood	2	The two sites required two lidar setups, and a single vehicle was tracked through the corridor.	Bumps-out, Bike lane
	MN 210/Voyageur Hwy	2	The two sites required two lidar setups, and a single vehicle was tracked through the corridor.	Reduced speed limit ahead signs, Speed warning sign
	MN 61/Beaver Bay	2	The two sites required two lidar setups, and a single vehicle was tracked through the corridor.	TWLTL, Crosswalk
	MN135/Biwabik	2	The two sites required two lidar setups, and a single vehicle was tracked continuously through the corridor.	Islands, On-street parking, bumps-out, Crosswalk
2	MN 29/Parkers Prairie	4	The 45-30 mph required a three-lidar setup. The same vehicle was tracked through this corridor. Speed data were collected on the 60 mph corridor by a single lidar technician after completing the three-man lidar setup. The fourth site was for baseline data collection.	Bumps-out, Crosswalk, TWLTL
3	1st Ave S/St. James	2	Three lidar setups were needed on the two sites identified because of road geometry and the presence of single-lane roundabouts.	Single-lane roundabouts, Bumps-out, On-street parking
	MN 9/New London	2	A 3-lidar setup was needed for the two sites.	Crosswalks, On-Street Parking, Bumps-out

Scenarios	Location	Number of sites	Comments	Road features
	MN 73/Moose Lake	3	The three sites needed a three-lidar setup. Speed data were collected on 55-40 mph independently, while the 45-30 mph lidar technicians tracked the same vehicle.	Dynamic speed feedback sign, TWLTL
	MN 61/Duluth	3	The three sites needed three lidars set up. The upstream and midstream technician tracked the same vehicle, while the downstream technician tracked a different vehicle.	Bicycle lane, Depressed median
	MN 37/Gilbert	4	The three sites needed three lidars set up. The upstream and midstream technician tracked the same vehicle, while the downstream technician tracked a different vehicle. The fourth site was for baseline data collection.	Crosswalk, On-street parking, Bike lane
	MN 61/Grand Marais	4	The three sites needed three lidars set up. Two lidars were set up at first to capture speeds from 55 mph to 30 mph. After completing this, a lidar technician stayed back to collect data within the 30 mph corridor.	Bumps-out, On-street parking
4	MN 316/Hastings	3	Three lidar setups were needed in the same direction on the two sites. However, one lidar setup had to move in the opposite direction.	Dynamic speed feedback sign, Single-lane roundabouts
	Marie Ave W/West St. Paul	2	Two lidar setups were needed on the two sites as they were in opposite directions.	On-street parking, Crosswalk, Dynamic speed feedback sign
	MN 78/Battle Lake	2	The two sites required two lidar setups in the same direction. However, only a single lidar setup could be done in the opposite direction.	Bumps-out
	MN 87/Frazee	2	The two sites required two lidar setups. However, only a single lidar setup was possible.	On-Street parking
	S Robert Trail/Rosemount	1	A single lidar setup because speed limit was uniform throughout the corridor	TWLTL
	MN135/Gilbert	1	A single lidar setup, which was mainly for baseline data collection	

Chapter 5: Data Analysis

The data analysis task involves detailed statistical analysis to discern the relationship between operating speeds and site characteristics. The focus of much of the empirical research in this area to date has focused on how operating speed varies with respect to the posted speed limit. While speed limits serve as a reasonable proxy for operating speeds, driving speeds are also influenced by the physical characteristics of the road, weather, and the behavior of other drivers. This task aims to determine how various speed metrics are impacted by speed limits while controlling for the effects of other variables. Consequently, multiple linear regression models were estimated to quantify impacts of speed limits and various roadway features on drivers' operating speeds. Additional supplementary analyses were conducted to investigate the prevalence of drivers exceeding the speed limit as well as the degree to which these same roadway features affected the variability in travel speeds along the study corridors. Ultimately, this chapter details the data extraction process, the statistical methods that were applied, and the results of these analyses.

5.1 Data Extraction

During field data collection, each lidar gun was connected to a laptop using a data transfer cable, which allowed for the recording of all measurements in real-time using proprietary software. The data collectors ensured that the lidar recordings included timestamps, distances, and speeds for each tracked vehicle. Cases where vehicles turned at an intersection or a driveway or where their speeds were influenced by changes in signal phases were ultimately removed from the dataset. After completing the tracking of each subject vehicle, all lidar technicians added remarks on the type and color of the vehicle in addition to any comments that will be useful during data extraction (e.g., the subject slowed down and the vehicle turned left). This information was then used to combine the data for each vehicle into a continuous speed profile. Since the relative distance between the lidar guns is known, all the distances of the subject vehicles were calculated relative to a baseline position. An example of the output from the raw lidar data is shown in Figure 6.

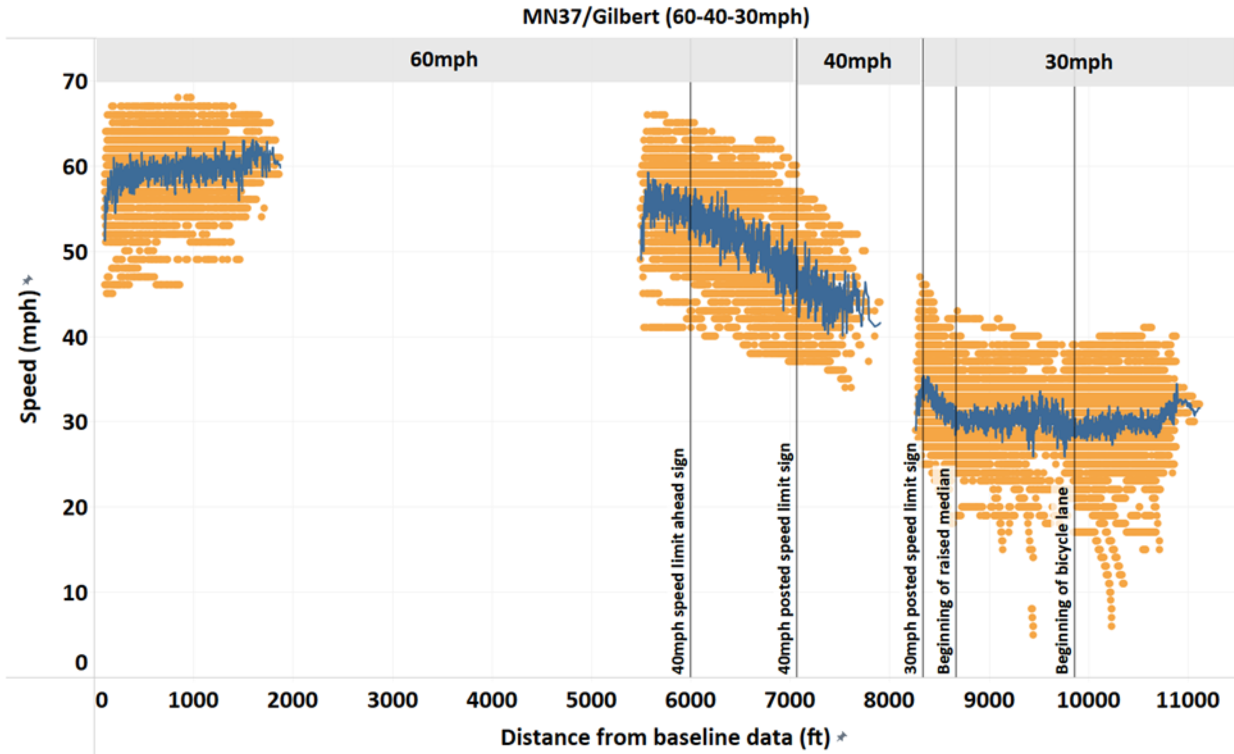

Figure 6 Raw Speed Profile showing Speed Reduction as Vehicles Approach the Town at MN37/Gilbert.

Using the trajectory data, a series of spot speeds were determined at specific points of interest, such as crosswalks, speed limit signs, the introduction of medians, etc. Ultimately, average speeds were calculated every 50 ft at these other key points of interest, as shown in Figure 7. Vehicles that had large distance gaps (i.e., missing data) during the tracking process were removed from the dataset. The plot of the average speed profile on each of the study corridors is overlaid with map/aerial photography in the appendix.

Next, a spreadsheet was prepared in Microsoft Excel to include all site characteristics measured from the field and Google Maps. A series of binary indicator variables were created in the associated dataset to indicate whether a particular roadway feature was present or absent at a specific location along each corridor. Various site characteristics that were anticipated to potentially relate to speed selection were identified, including intersections, crosswalks, curb-outs, and midblock crossings. The locations of these features were flagged in the analysis dataset (again, using binary indicator variables). Other longitudinal features (e.g., TWLTLs, on-street parking, bike lanes, curb and gutter) were identified over the entire distance over which they were present.

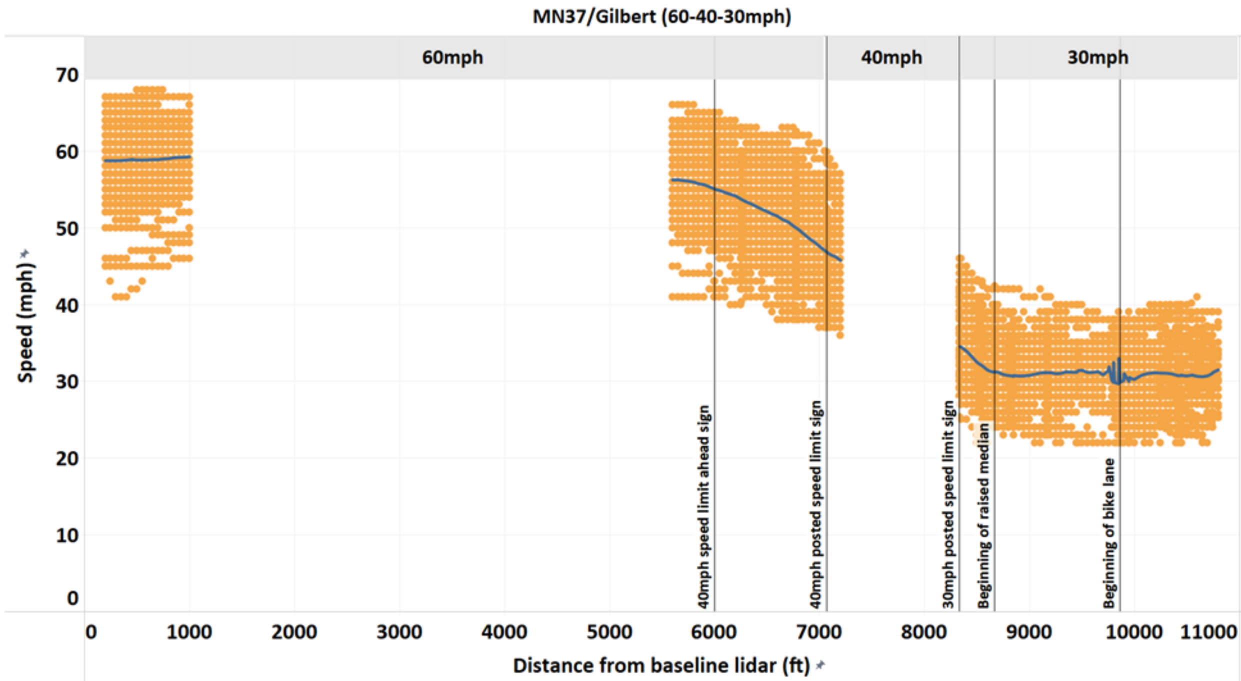

Figure 7 Interpolated Speed Profile at every 50 ft as Vehicles Approach the Town at MN37/Gilbert.

In general, data were collected using lidar guns from locations that were upstream and downstream of where speed limit changes occurred. The position of the upstream/baseline lidar is known, and the position of the speed signs and subject vehicles was measured relative to this location. The distance between each vehicle and the speed limit signs could also be determined. This allowed for a determination of general trends in travel speeds as vehicles approached and then passed the speed limit signs.

5.2 Data Summary

In quantifying the effects of site characteristics, the research team collected and extracted speed data on 19 corridors throughout Minnesota. This analysis focused on cases where the speed limits remained constant (e.g., 30 mph) or were reduced (e.g., from 40 mph to 30 mph). In total, the final dataset contained data for 3,372 vehicles.

The speed limits on the study corridors ranged from 25 mph to 60 mph, with 30 mph zones being the most common, as many of the corridors terminated with 30 mph as the lowest limit. There was also one corridor that terminated at 25 mph. Most of the vehicles tracked were passenger cars (88%), with the remainder being comprised of heavy vehicles (13%). The average width of the median was 4.95 ft, with a maximum width of 36 ft, which was mainly observed in corridors with depressed medians. Corridors with depressed and raised medians constituted about 6% and 5% of the dataset, respectively. The average width of the shoulder was approximately 6.4 ft, and in areas where curb and gutter were observed, the shoulder width was noted as 0 ft. Lane widths typically ranged from 11 ft to 12 ft, with an average width of 11.22 ft observed across all corridors. Table 4 shows the descriptive statistics for speed and site characteristics.

Table 4. Descriptive Statistics for Analysis Datasets

Variable	Min	Max	Mean	SD
Operating speed (mph)	5	81	41.94	12.71
Heavy vehicles (1 if yes)	0	1	0.12	0.33
Passenger car	0	1	0.88	0.33
Speed limit (mph)				
60 (far upstream) (1 if yes)	0	1	0.15	0.36
60 w/in 0.5mi. of town (1 if yes)	0	1	0.18	0.38
55 (1 if yes)	0	1	0.03	0.17
45 (1 if yes)	0	1	0.09	0.28
40 (1 if yes)	0	1	0.14	0.34
35 (1 if yes)	0	1	0.03	0.18
30 (1 if yes)	0	1	0.38	0.49
25 (1 if yes)	0	1	0.01	0.09
Geometric features				
Three-leg intersection (1 if yes)	0	1	0.02	0.14
Four-leg intersection (1 if yes)	0	1	0.04	0.19
Depressed median (1 if yes)	0	1	0.06	0.23
Raised median (1 if yes)	0	1	0.05	0.22
TWLTL (1 if yes)	0	1	0.15	0.36
On-street parking (1 if yes)	0	1	0.15	0.35
Crosswalk (1 if yes)	0	1	0.02	0.13
Curb-out/Bump-out (1 if yes)	0	1	0.01	0.08
Midblock crossings (1 if yes)	0	1	<0.001	0.03
Single-lane roundabout w/in 500 ft downstream and upstream (1 if yes)	0	1	0.03	0.16
Island (1 if yes)	0	1	0.01	0.11
Bicycle lane (1 if yes)	0	1	0.04	0.18
Horizontal curve w/in 500 ft downstream (1 if yes)	0	1	0.02	0.15
Curb and gutter (1 if yes)	0	1	0.24	0.43
Context				
Rural (1 if yes)	0	1	0.33	0.47
Suburban (1 if yes)	0	1	0.57	0.50
Urban (1 if yes)	0	1	0.11	0.31
Dimension of road corridors (ft)				
Lane width	11	12	11.22	0.41
Median width	0	36	4.95	8.77
Shoulder width	0	14	6.40	4.11

Two-way left-turn lane (TWLTL) and on-street parking were observed to be present at 15% of the total corridor lengths, while curb and gutter were observed at 24% of the corridor lengths, which implies that road shoulders were present at over 75% of the dataset. Curb-outs, bump-outs, midblock crossings, and crosswalks were observed at less than 2% of the corridor length. This is due to the fact that these features typically occur at some points on the road corridor instead of a stretch like TWLTL or curb and gutter. In terms of contexts, over 50% of the corridor length could be classified as being suburban, with about 11% urban and the rest rural. The low number of urban contexts is because the research focuses on the speed transition into rural towns.

5.3 Analysis of Operating Speeds

The aim of this analysis was to investigate changes in driver speed selection when encountering speed limit reductions and various geometric features of interest while accounting for the effects of other variables that have also been found to impact operating speeds.

5.3.1 Statistical Analysis

To understand how operating speeds varied with respect to various site characteristics, a series of random effects multiple linear regression models were estimated to discern those factors associated with driver speed selection. The general form of the regression model is shown below:

$$Y_{i,j,k} = \beta X_{i,j,k} + u_{0j} + u_{1i(j)} + \varepsilon_{i,j,k}$$

where:

- $Y_{i,j,k}$ = Operating speed of vehicle *i* at site *j* at a distance *k* from the upstream lidar
- $X_{i,j,k}$ = Vector of parameters that influence driver's speed selection behavior such as speed zone, median, TWLTL, etc.
- β = Vector of estimable parameters that quantify the effects of these parameters,
- u_{0j} = Random effect that captures unobserved site-specific effects
- $u_{1i(j)}$ = Nested random effect for vehicle level within site (*i* within *j*),
- $\varepsilon_{i,j,k}$ = random error term of vehicle *i* at site *j* at a distance *k* from the upstream lidar

A total of 111,503 speed measurements were included in this analysis. Analysis results are presented in Table 5. These results include estimated coefficients, along with the associated standard errors, t-statistics, and p-values estimated through linear regression model. When interpreting the results, each parameter estimate reflects the average change in speed that was associated with the select characteristics of interest. For example, the results show that heavy vehicles traveled about 1.6 mph slower than passenger cars on average.

The models were estimated such that the highest upstream speed limit serves as the default condition. In this case, that corresponds to a rural two-lane highway with a 60 mph speed limit. The average speed on such segments under baseline conditions (i.e., in the absence of any of the geometric features) is approximately 64.5 mph. Interestingly, speeds were approximately 8.0 mph lower within 0.5 mi of a downstream speed limit reduction, which suggests drivers begin adjusting their speeds significantly in advance of the speed limit sign. When interpreting the subsequent speed limits, these parameter estimates are reflective of the difference in mean speeds as compared to this 60 mph baseline. In general, a 5 mph speed limit reduction corresponded with a reduction in mean speeds of 3 to 5 mph.

Table 5 Random Effects Linear Regression Results for Speeds of Vehicles

Parameters	Estimate	Std. Error	t-Statistic	p-Value
Intercept	64.470	0.759	84.900	<0.001
Vehicle type				
Passenger car	Baseline			
Heavy vehicle	-1.526	0.217	-7.039	<0.001
Speed limit (mph)				
Speed 60 (far upstream)	Baseline			
Speed 60 w/in 0.5 mi. of town	-8.310	0.217	-38.289	<0.001
Speed 55	-9.203	0.245	-37.593	<0.001
Speed 45	-16.910	0.222	-76.136	<0.001
Speed 40	-18.330	0.218	-83.933	<0.001
Speed 35	-23.760	3.295	-7.211	<0.001
Speed 30	-28.120	0.222	-126.536	<0.001
Speed 25	-35.420	0.332	-106.768	<0.001
Geometric features (i.e. speed reduction factors)				
Single-lane roundabout w/in 500 ft	-6.955	0.099	-70.396	<0.001
Raised median	-3.099	0.078	-39.896	<0.001
Depressed median	-1.330	0.111	-11.961	<0.001
Two-way left-turn lane	-0.706	0.047	-15.106	<0.001
On-street parking	-1.709	0.052	-32.843	<0.001
Bike lane	0.390	0.106	3.694	<0.001
Crosswalk	-1.265	0.063	-20.119	<0.001
Curb and gutter	-0.978	0.060	-16.238	<0.001
Intersection w/stop control on minor road	-0.176	0.041	-4.274	<0.001
Distance of vehicle upstream to speed sign (ft)				
>1100	Baseline			
> 1000 and ≤ 1100	0.194	0.053	3.626	<0.001
> 900 and ≤ 1000	-0.055	0.054	-1.018	0.309
> 800 and ≤ 900	-0.224	0.051	-4.368	<0.001
> 700 and ≤ 800	-0.572	0.054	-10.594	<0.001
> 600 and ≤ 700	-0.977	0.055	-17.857	<0.001
> 500 and ≤ 600	-1.588	0.054	-29.514	<0.001
> 400 and ≤ 500	-2.186	0.054	-40.364	<0.001

> 300 and ≤ 400	-2.851	0.055	-52.119	<0.001
> 200 and ≤ 300	-3.711	0.054	-68.999	<0.001
> 100 and ≤ 200	-4.674	0.054	-85.950	<0.001
≤ 100	-5.709	0.054	-105.925	<0.001
Distance of vehicle downstream to speed sign (ft)				
≤ 100	Baseline			
>100 and ≤ 200	-1.010	0.052	-19.307	<0.001
>200 and ≤ 300	-1.765	0.052	-33.646	<0.001
>300 and ≤ 400	-2.097	0.058	-36.098	<0.001
>400 and ≤ 500	-2.509	0.059	-42.791	<0.001
>500 and ≤ 600	-2.635	0.061	-43.130	<0.001
>600 and ≤ 700	-2.777	0.066	-41.796	<0.001
>700 and ≤ 800	-2.747	0.073	-37.607	<0.001
>800 and ≤ 900	-2.746	0.071	-38.406	<0.001
>900 and ≤ 1000	-3.296	0.072	-45.853	<0.001
>1000	-3.619	0.052	-69.897	<0.001

Turning to the geometric characteristics, the parameter estimates for these variables can be thought of as “speed reduction factors”. That is, these estimates reflect the degree to which speeds were reduced in the presence of a specific feature.

The strongest influence on speeds was shown by the presence of a single-lane roundabout within 500 ft upstream or downstream, which was associated with an average speed reduction of 7 mph, reflecting the utility of single-lane roundabouts as a speed control measure.

The presence and type of median also showed a substantive impact on travel speeds. Raised and depressed medians showed speeds that were 3.1 mph and 1.3 mph lower, respectively (as compared to an undivided facility). The presence of TWLTL showed a speed reduction of less than 1 mph. It should be noted that raised medians in this study were continuous medians (not pedestrian refuge islands). Therefore, the length of the raised median was not considered as a part of the analysis.

Turning to other features of interest, speeds were 1.7 mph lower where on-street parking was present. Similar reductions were observed in the case of marked crosswalks (1.3 mph) or where curb and gutter were present (1.0 mph) as compared to paved shoulders.

The presence of stop control on the minor approach did not have a substantive impact on speeds (less than 0.2 mph). Similarly, speeds were only marginally higher (0.5 mph) where bicycle lanes were present. However, it should be noted that there was generally little to no bicycle activity during the times when the data were collected. Different trends may be observed in more urbanized areas.

Interestingly, site characteristics that related to the dimensions of the road corridors (i.e., lane width and shoulder width) generally did not show any substantive impact on vehicle speeds. The study evaluated lane width and shoulder width, both separately and in combination with one another. Ultimately, all lane widths were either 11 ft or 12 ft, with nearly 75 percent of the segments being 11 ft wide. Overall, speeds were slightly lower on the segments with 12 ft lanes, but this was largely due to other factors. For instance, the corridors with 11-ft wide lanes typically had higher speed limits (mean posted speed limit = 45.2 mph) compared to those with 12-ft lanes (mean posted speed limit = 35.8 mph). There was also significant variability in these speeds across locations. When these other factors are controlled for, there is no significant difference in speeds between 11 and 12-ft lanes as shown in Figure 8.

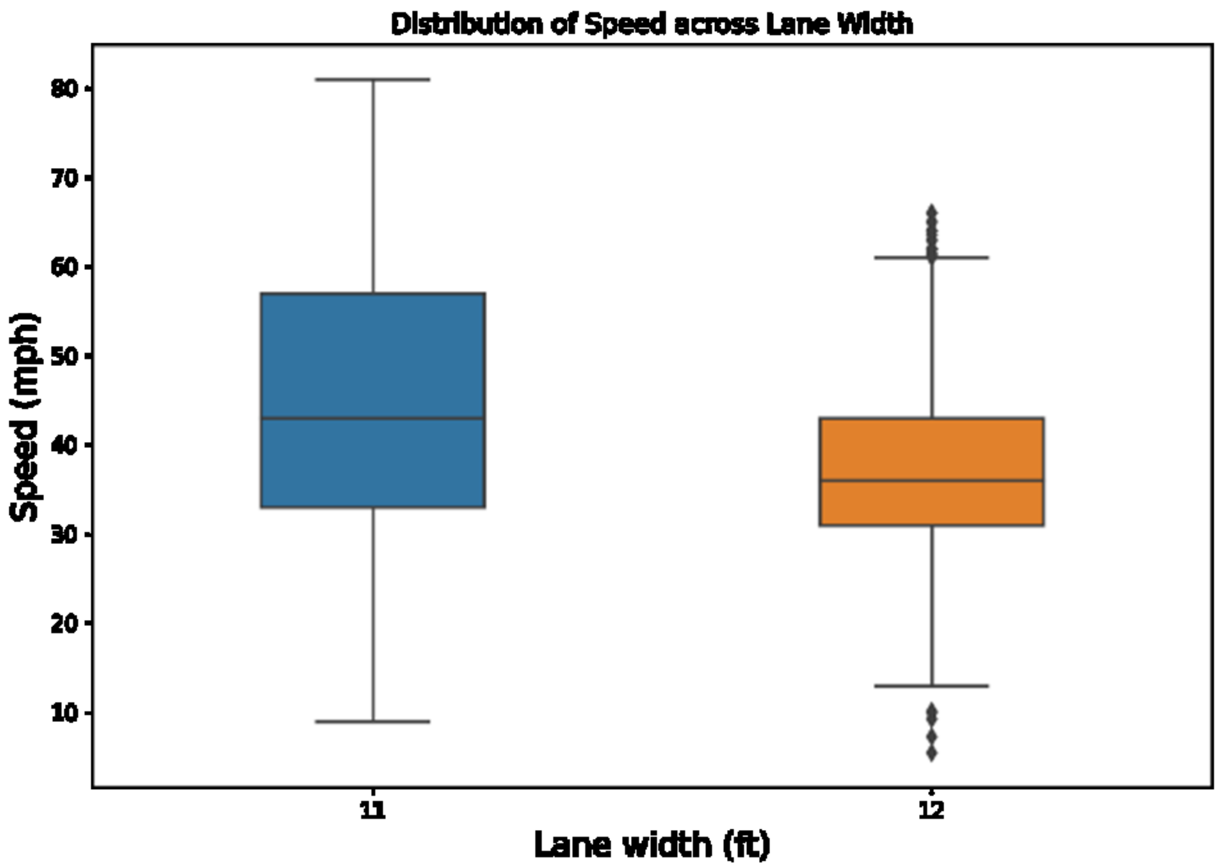

Figure 8 Speed Distribution across Lane Width

Similarly, Figure 9 shows a plot of the speed distribution by shoulder width. In this case, there was quite a bit of variability in shoulder widths across sites. This plot of the raw data does not consider the effects of other factors (e.g., speed limit, median type/presence). As such, no clear trends emerged, except for the curb and gutter sections, which consistently showed lower speeds as compared to those sites with paved shoulders. When considering only shoulder width and speed limit, a weak relationship is found, with speeds increasing by only about 0.1 mph for every 1-ft increase in shoulder width.

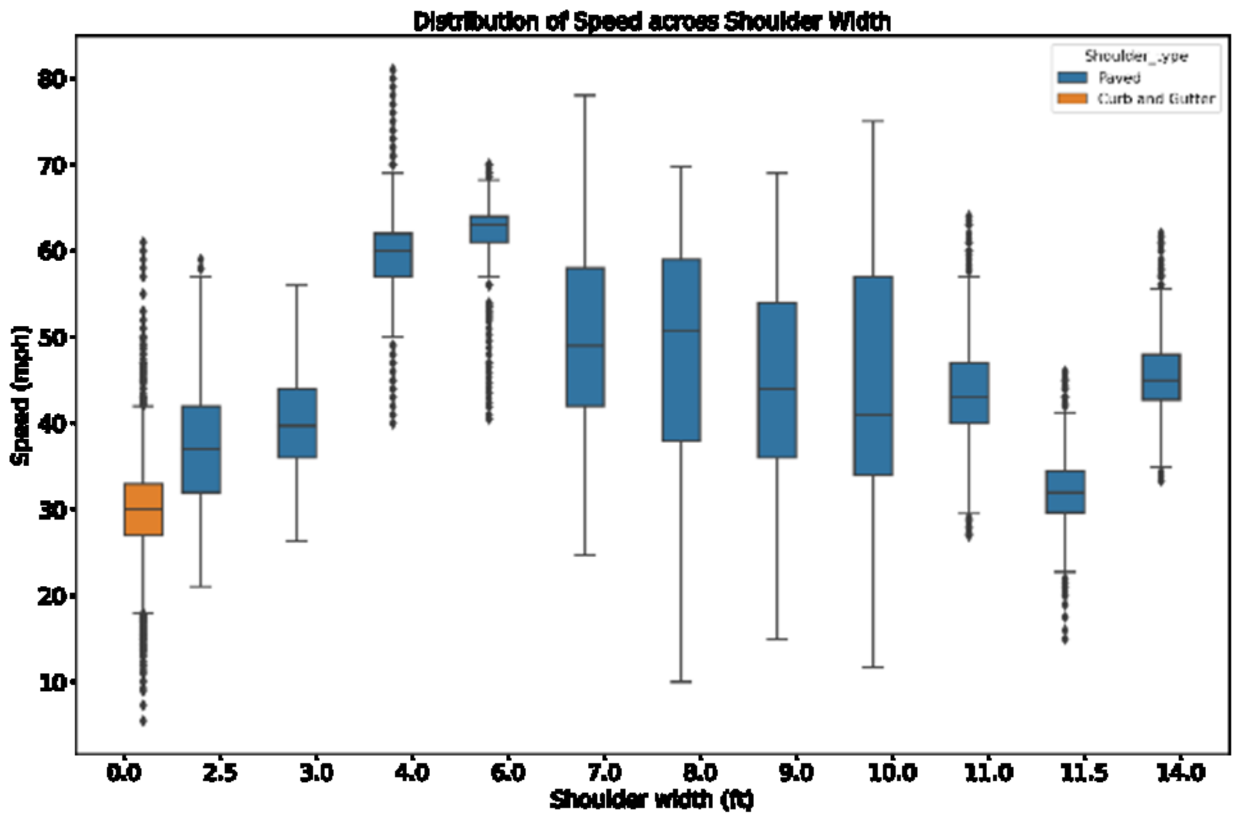

Figure 9 Speed Distribution across Shoulder Width

It should also be noted that there are some inherent limitations here. For example, the sample of sites did not include any 10-ft lanes. The research literature has generally shown limited differences in both the speed and safety performance of 11-ft vs. 12-ft lanes. In terms of future research, it would be of value to broaden investigations into more urbanized settings to better understand the relationship between speeds and lane/shoulder width on narrower cross-sections.

Several other features were examined as part of this study, including the presence of upstream horizontal curves, as well as isolated median islands. However, no significant differences were observed in these cases. It should be noted that this does not necessarily imply the absence of an effect as these scenarios comprise a very small subset of the overall sample.

Analysis of spatial trends showed that drivers started to reduce their speeds at distances of up to 1,000 ft upstream of the speed limit reduction. The rate of reduction increased more rapidly the nearer a vehicle was to the upcoming speed limit sign. Once a vehicle was within 400 ft of the speed signs, speeds were reduced by about one mph for every 100 ft a vehicle got nearer to the sign. The overall reduction from 1,000 ft to 100 ft upstream of the sign was approximately 5.7 mph on average. Vehicles continued to reduce their speeds once they passed the speed limit sign, up to a distance of approximately 400 ft downstream. Beyond this distance, speeds remained relatively constant, as shown in Figure 10. It should be noted that Figure 10 provides a 40-mph speed limit as an example, but this speed profile is reflective of the average profiles across all speed limit reduction zones (irrespective of the actual limit). The plot is less smooth downstream of the speed limit sign as there was considerable variability across sites in terms of the distance to the next speed limit reduction or other feature that impacted travel speeds. In other words, different features would tend to be introduced in combination with the speed limit reduction.

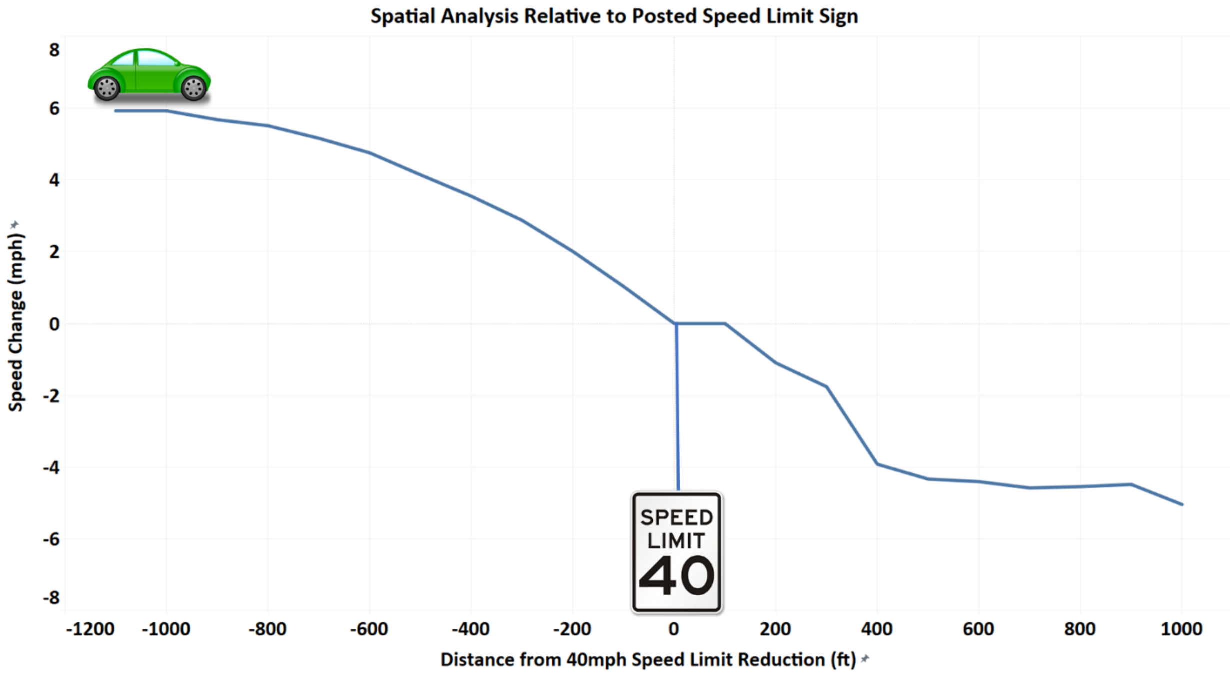

Figure 10 Spatial Trends Relative to Posted Speed Limit Sign

A summary of the preceding analysis results is illustrated in Figure 11 , which shows the mean speed reduction associated with various factors of interest, along with 95-percent confidence intervals for these effects. Any of the intervals which include zero are reflective of results that are not statistically significant (at 95 percent confidence). Those intervals located to the left of zero are associated with factors for which speeds were lower while bars located to the right of zero are reflective of scenarios where speeds were higher.

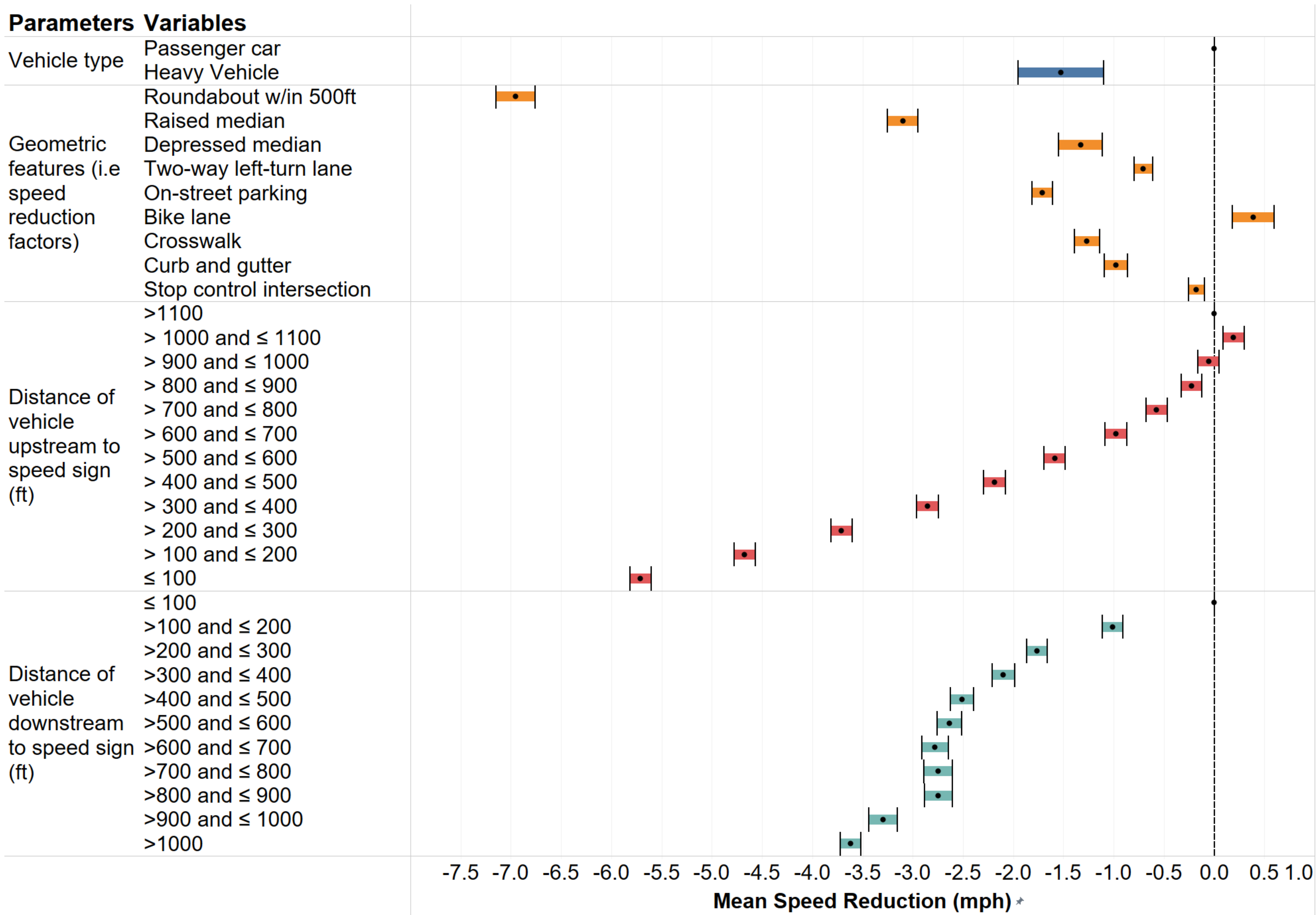

Figure 11 Linear Regression Parameter Estimates for Mean Speed Reduction (with 95% Confidence Intervals)

5.4 Speed Limit Violations

In addition to understanding impacts on average travel speeds, a related question of interest is the degree to which drivers exceed the posted speed limit under various contextual environments. To that end, additional analyses were conducted to discern when and where drivers were most likely to exceed the posted speed limit.

Figure 12 shows the percentage of drivers who were found to be exceeding the speed limit along the study corridors, both by any amount and by more than 5 mph. At an aggregate level, more than 60% of drivers were exceeding the speed limit at the 60-mph locations far upstream of the speed-reduction zones. Violation rates also tended to be higher in the intermediate speed limit ranges (e.g., 30-40 mph) as compared to the other road segments. These segments with moderate speed limits also tended to show the highest percentage of drivers who were traveling 5 mph or more above the posted limit. With that being said, these aggregate-level summarie do not account for some of the other differences across these locations that also have an influence on speed selection and speed limit compliance. This motivatesadditional analyses to better understand the underlying factors that influence when and where drivers tend to exceed the posted speed limit.

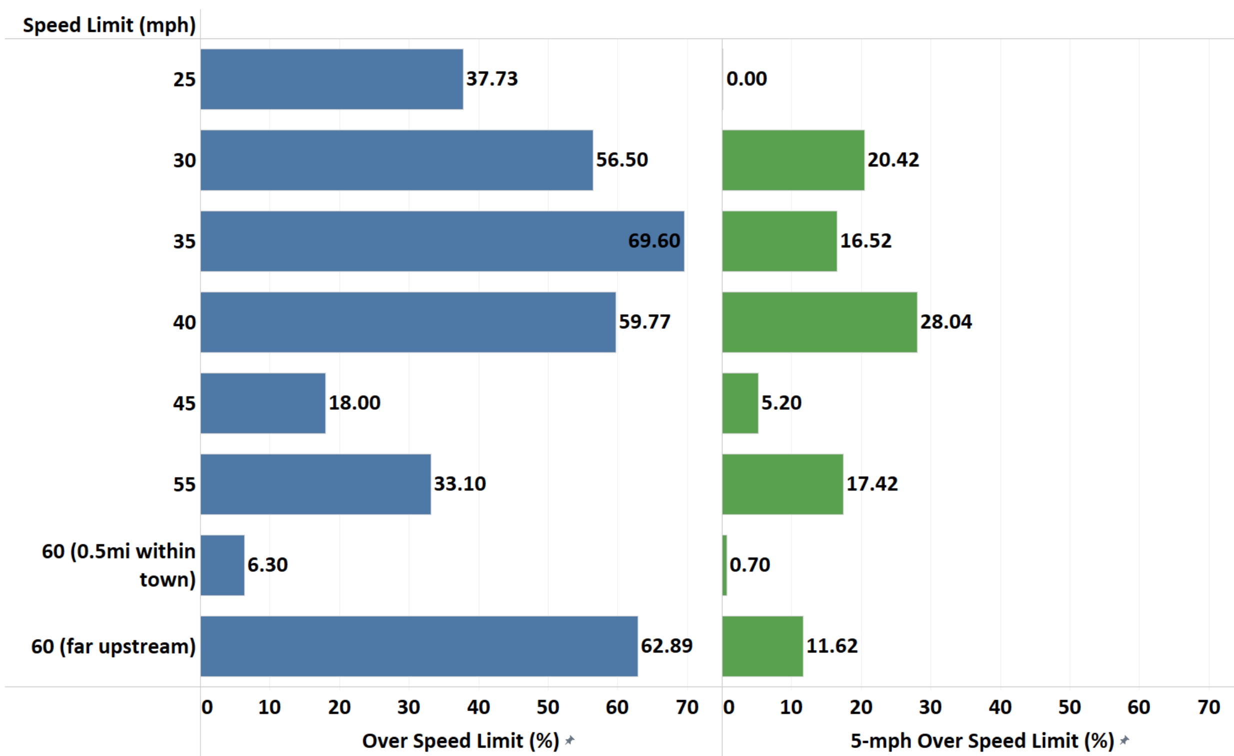

Figure 12 Percentage of Vehicles exceeding the speed limit and 5-mph over the speed limit

5.4.1 Statistical Analysis

To examine the how speeding varies in the presence of various site characteristics, a logistic regression model was esimated. Logistic regression is well suited for this scenario as the dependent variable (i.e., whether the driver exceeded the posted limit or not) is dichotomous in nature. The general form of the the logistic regression model is shown below:

$$Y_{i,j,k} = logit(P_{i,j,k}) = ln\left(\frac{P_{i,j,k}}{1-P_{i,j,k}}\right) = \beta X_{i,j,k} + u_{0j} + u_{1i(j)} + \varepsilon_{i,j,k}$$

where:

- $P_{i,j,k}$ = Probability of operating speed of driver/vehicle *i* exceeding the posted speed limit at site *j* at a distance *k* from the upstream lidar
- $X_{i,j,k}$ = Vector of parameters that influence speeding behavior, such as the posted speed limit, the presence of a raised median, TWLTL, etc.
- β = Vector of estimable parameters that quantify the effects of these parameters,
- u_{0j} = Random effect that captures unobserved site-specific effects
- $u_{1i(j)}$ = Nested random effect for vehicle level within site (*i* within *j*),
- $\varepsilon_{i,j,k}$ = random error term of vehicle *i* at site *j* at a distance *k* from the upstream lidar

Similar to the driver operating speed analysis, a total of 111,503 speed measurements were used in this analysis. The analysis results are presented in Table 6. These results include the parameter estimates obtained from the logistic regression model, along with the associated standard errors, t-statistics, and p-values. When interpreting the results, a positive parameter indicates that drivers were more likely to speed as that variable increases or, in the case of binary (0/1) indicator variables, that the drivers were more likely to speed when this condition was true (e.g., when a bike lane was present) versus not. Thee opposite is true for negative parameter estimates. To aid in the interpretation of the results, odds ratio (OR) have also been estimated, which represent the change in the odds of a driver/vehicle speeding when a specific parameter is increased by one unit.

Table 6 Logistic Regression Analysis for Speeding

Parameters	Estimate	Std. Error	p-Value	Odds Ratio (OR)
Intercept	6.365	0.672	<0.001	na
Vehicle type				
Passenger car	Baseline			
Heavy vehicle	-1.452	0.271	<0.001	0.234
Speed limit (mph)				
Speed 60 (far upstream)	Baseline			
Speed 60 w/in 0.5 mi. of town	-8.578	0.289	<0.001	<0.001

Speed 55	-4.533	0.459	<0.001	0.011
Speed 45	-4.561	0.286	<0.001	0.010
Speed 40	-3.096	0.276	<0.001	0.045
Speed 35	-1.001	4.416	0.821	0.368
Speed 30	-2.308	0.279	<0.001	0.099
Speed 25	-5.633	0.429	<0.001	0.004
Geometric features				
Single-lane roundabout w/in 500 ft	-7.991	0.330	<0.001	<0.001
Raised median	-0.616	0.126	<0.001	0.540
Depressed median	0.001	0.214	0.997	1.001
Two-way left-turn lane	-0.853	0.067	<0.001	0.426
On-street parking	-0.477	0.077	<0.001	0.621
Bike lane	2.622	0.170	<0.001	13.763
Crosswalk	-0.888	0.087	<0.001	0.412
Curb and gutter	-0.661	0.094	<0.001	0.516
Intersection w/stop control on minor road	-0.079	0.060	0.186	0.924
Distance of vehicle upstream to speed sign (ft)				
>1100	Baseline			
> 1000 and ≤ 1100	0.308	0.082	<0.001	1.361
> 900 and ≤ 1000	0.391	0.080	<0.001	1.478
> 800 and ≤ 900	0.244	0.078	0.002	1.277
> 700 and ≤ 800	0.267	0.080	0.001	1.307
> 600 and ≤ 700	0.059	0.084	0.477	1.061
> 500 and ≤ 600	-0.368	0.083	<0.001	0.692
> 400 and ≤ 500	-0.445	0.087	<0.001	0.641
> 300 and ≤ 400	-0.821	0.095	<0.001	0.440
> 200 and ≤ 300	-1.399	0.103	<0.001	0.247
> 100 and ≤ 200	-2.018	0.112	<0.001	0.133
≤ 100	-3.434	0.140	<0.001	0.032
Distance of vehicle downstream to speed sign (ft)				
≤ 100	Baseline			
>100 and ≤ 200	-0.562	0.078	<0.001	0.570
>200 and ≤ 300	-1.351	0.078	<0.001	0.259
>300 and ≤ 400	-1.793	0.086	<0.001	0.167
>400 and ≤ 500	-2.252	0.088	<0.001	0.105
>500 and ≤ 600	-2.394	0.092	<0.001	0.091
>600 and ≤ 700	-2.530	0.097	<0.001	0.080
>700 and ≤ 800	-2.816	0.108	<0.001	0.060
>800 and ≤ 900	-2.921	0.107	<0.001	0.054

>900 and ≤ 1000	-3.368	0.108	<0.001	0.034
>1000	-3.988	0.088	<0.001	0.019

Starting with the speed limit zones, the results show that drivers were more likely to comply with the posted speed limit at very high (60 mph when within 0.5 miles of a town) and very low (25 mph) speed limits. This suggests that additional speed countermeasures may be most important over the range of intermediate speed limits.

Regarding the geometric features, the results generally align with those observed previously for the average speed model in Table 5. The likelihood of speeding was the minimum when encountering a roundabout and the maximum where bike lanes were present. The latter result may be due to the greater lateral space that is available to drivers, as well as the fact that very few bicyclists were observed over the course of data collection. Speeding also occurred much less frequently along roadway sections with raised medians, two-way left turn lanes, on-street parking, crosswalks, and curb and gutter.

A summary of the analysis results is illustrated in Figure 13, which shows the odds ratio associated with various factors of interest, along with associated 95-percent confidence intervals for each effect. Any of these confidence intervals that include 1.0 are reflective of differences that are not statistically significant at a 95-percent confidence level. Those intervals located to the left of 1.0 are reflective of factors that are associated with less frequent speeding, while bars located to the right of 1.0 are reflective of scenarios where the likelihood of speeding was higher.

In terms of spatial trends, the likelihood of speeding was relatively consistent at distances between 1100 ft and 600 ft upstream of the speed limit signs, as shown in Figure 13. However, there is a notable decrease in the likelihood of speeding as vehicles approach within 600 ft upstream of the posted speed limit sign. Specifically, the likelihood of speeding decreases by approximately 10% for every 100 ft nearer to the posted speed limit signs where the reductions were introduced. Furthermore, the likelihood of speeding continues to decrease as the vehicles travel downstream of the speed limit sign.

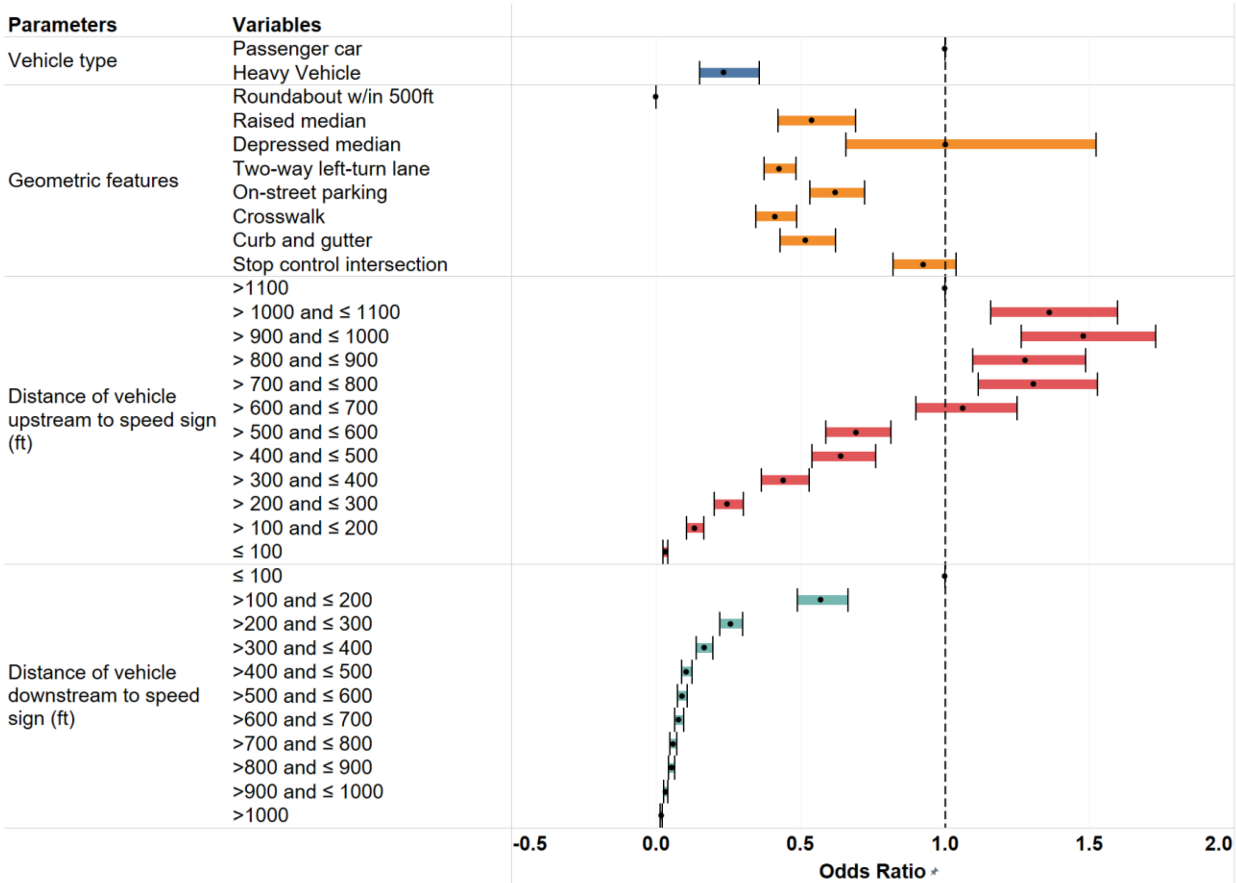

Figure 13 Odds Ratio Estimates for Logistic Regression (with 95% Confidence Intervals)

5.5 Standard Deviation of Travel Speeds

In addition to speeding, another important speed-related metric that has been linked to crash frequency and severity is the variability in travel speeds (Gupta et al., 2022; Hu, 2017; Lave, 1985). Therefore, it is imperative to understand how speed variability is affected by different site features. To investigate this measure, multiple linear regression models were estimated to examine the relationship between the standard deviation of travel speeds at specific locations along each study corridor.

5.5.1 Statistical Analysis

A random effects multiple linear regression model was estimated to ascertain the various site characteristics that may influence speed variability among drivers. The general form of the regression model is presented below:

$$Y_{i,j} = \beta X_{i,j} + u_i + \varepsilon_i$$

where:

- $Y_{i,j}$ = Standard deviation in speed at site *i* at a distance *j* from the upstream lidar
- $X_{i,j}$ = Vector of parameters that influence speed deviation, such as speed zone, median, TWLTL, etc.
- β = Vector of estimable parameters that quantify the effects of these parameters,
- u_i = Random effect that captures unobserved site-specific effects
- ε_i = random error term

The dependent variable was calculated as the standard deviation of the travel speed of all vehicles at each 50-ft interval along a corridor, as well as at specific locations where geometric features were introduced. The model can be interpreted similarly to that of operating speeds, and the results generally follow the same trends as were found as a part of that analysis.

A total of 1,256 standard deviation measurements were included in this analysis (i.e., one at each cross-sectional location). The analysis results are presented in Table 7. These results again include parameter estimates, along with the associated standard errors, t-statistics, and p-values. When interpreting the results, each parameter indicates the degree to which the standard deviation was higher (positive coefficients) or lower (negative coefficients) when a specific parameter was increased by one-unit (or when a condition was true or not in the case of binary indicator varaibles). For example, the results show that the standard deviation in the speeds of heavy vehicles was 0.2 mph higher on average as compared to passenger cars.

Table 7 Random Effects Linear Regression Results for Standard Deviation in Speed

Parameters	Estimate	Std. Error	t-Statistic	p-Value
Intercept	4.107	0.160	25.742	<0.001
Vehicle type				
Passenger car	Baseline			
Heavy vehicle	0.212	0.055	3.831	<0.001
Speed limit (mph)				
Speed 60 (far upstream)	Baseline			
Speed 60 w/in 0.5 mi. of town	1.684	0.081	20.723	<0.001
Speed 55	1.456	0.199	7.334	<0.001
Speed 45	1.146	0.111	10.292	<0.001
Speed 40	1.035	0.088	11.786	<0.001
Speed 35	0.672	0.521	1.289	0.214
Speed 30	0.511	0.102	5.033	<0.001
Speed 25	0.013	0.240	0.053	0.958
Geometric features				
Single-lane roundabout w/in 500 ft	-0.582	0.130	-4.476	<0.001
Raised median	-0.507	0.100	-5.057	<0.001
Depressed median	-0.412	0.092	-4.476	<0.001
Two-way left-turn lane	0.007	0.070	0.098	<0.001

On-street parking	-0.379	0.084	-4.532	<0.001
Bike lane	-0.046	0.112	-0.415	0.678
Crosswalk	-0.044	0.110	-0.402	0.688
Curb and gutter	-0.531	0.080	-6.631	<0.001
Intersection w/stop control on minor road	0.174	0.067	2.585	<0.001
Distance of vehicle upstream to speed sign (ft)				
>1100	Baseline			
> 1000 and ≤ 1100	0.137	0.101	1.354	0.176
> 900 and ≤ 1000	0.176	0.097	1.807	0.071
> 800 and ≤ 900	0.196	0.093	2.102	0.036
> 700 and ≤ 800	0.258	0.099	2.623	0.009
> 600 and ≤ 700	0.208	0.099	2.097	0.036
> 500 and ≤ 600	0.279	0.096	2.895	0.004
> 400 and ≤ 500	0.305	0.095	3.199	0.001
> 300 and ≤ 400	0.400	0.097	4.115	<0.001
> 200 and ≤ 300	0.396	0.096	4.117	<0.001
> 100 and ≤ 200	0.332	0.096	3.453	0.001
≤ 100	0.150	0.096	1.562	0.119
Distance of vehicle downstream to speed sign (ft)				
≤ 100	Baseline			
>100 and ≤ 200	-0.129	0.095	-1.357	0.175
>200 and ≤ 300	-0.224	0.095	-2.356	0.019
>300 and ≤ 400	-0.381	0.103	-3.701	<0.001
>400 and ≤ 500	-0.525	0.106	-4.956	<0.001
>500 and ≤ 600	-0.614	0.110	-5.573	<0.001
>600 and ≤ 700	-0.679	0.118	-5.767	<0.001
>700 and ≤ 800	-0.475	0.125	-3.810	<0.001
>800 and ≤ 900	-0.498	0.121	-4.106	<0.001
>900 and ≤ 1000	-0.788	0.125	-6.295	<0.001
>1000	-0.681	0.089	-7.622	<0.001

In terms of the different speed limits, there is typically a reduction in speed variability as the posted speed limit decreases. In general, the standard deviation in speeds remains below 1 mph at posted speed limits below 40 mph. Regarding the various geometric features, standard deviation in speeds tends to reduce in the presence of various geometric features except at intersections. This could be due to the varied approach of drivers at intersections, as some drivers may adjust their speed when a vehicle approaches from the minor road to the major road while others may not.

Interesting trends are observed when considering the distance of the driver upstream or downstream of the posted speed limit signs. The standard deviation in speeds is found to be marginally higher upstream of the speed limit sign and significantly lower downstream of the sign. This indicates that different groups of drivers exhibit different approach speeds when approaching a speed limit sign and transition to more uniform speeds as they pass the posted speed limit sign. Figure 14 presents a summary of the results which shows the trends in speed variability with respect to distance from the speed limit sign at every 100-ft increment. Overlapping confidence intervals of estimates indicate that the estimates are not statistically different from each other.

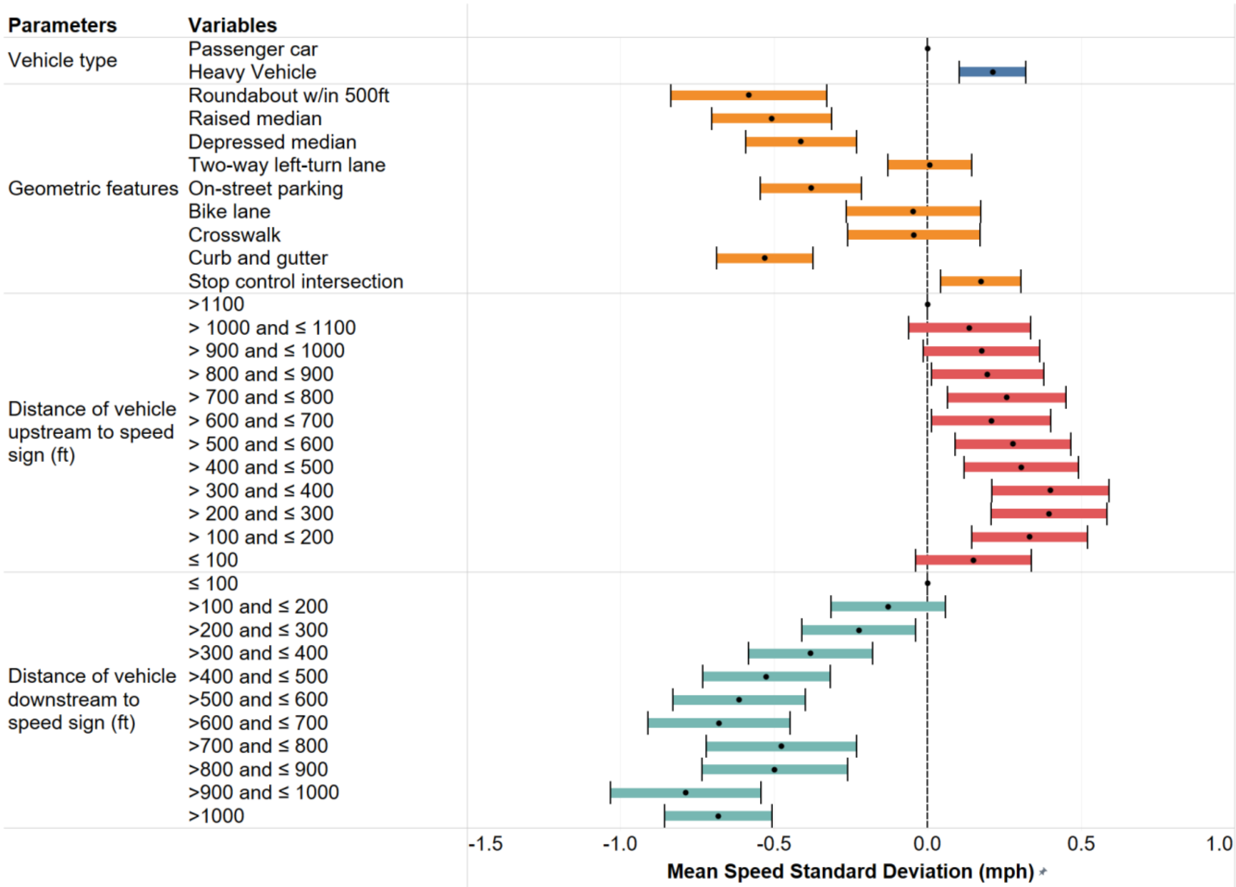

Figure 14 Linear Regression Parameter Estimates for Mean Standard Deviation in Speed (with 95% Confidence Intervals)

Chapter 6: Conclusions, Recommendations, and Implementation

This study involved a series of on-site field studies in which high-fidelity light detection and ranging (lidar) data were collected to obtain speed trajectories of individual vehicles along a diverse set of roadway corridors throughout Minnesota. The project focused on speed-reduction zones, such as those along high-speed roadways that enter rural and suburban communities. The research also considered locations where various design features were introduced, such as bicycle lanes, raised medians, crosswalks, and on-street parking.

These data were analyzed and ultimately provided insights as to how drivers adapt their speeds based on speed limit reductions and other changes in the contextual environment. The project has resulted in quantitative estimates of the impacts of various design elements on vehicle operating speeds (i.e., "speed-reduction factors," or "SRFs"). These SRFs can be thought of as the average reductions that could be expected in the presence or absence of various features of interest. Similarly, supplementary analysis on speeding behavior and speed variability in terms of standard deviation of speed shows a consistent trend with the results for SRFs.

These reductions in travel speeds are anticipated to improve the safety of Minnesota roadways, particularly in areas with high traffic of people walking and biking. This would be realized through the implementation of design decisions that are able to explicitly incorporate the impacts of speed reductions on crash risk, as well as the expected crash severity and injury outcomes, conditional on a crash having occurred. The crash cost savings are expected to be most pronounced at locations that experience high volumes of non-motorized traffic (i.e., people walking and biking). This would allow for performance-based and context-sensitive design decisions in these settings. The remainder of this chapter summarizes the results of this study and presents conclusions and recommendations, including implementation steps, followed by research limitations and directions for future work.

6.1 Conclusions and Recommendations

One of the primary outputs of this research was the development of speed-reduction factors (SRF) that quantify the magnitude of speed reduction due to various roadway geometric features. These SRFs are summarized in Table 8. These SRFs can be used by MnDOT and other local road agencies in the state to forecast the anticipated impacts of design decisions on mean speeds. These factors will also help MnDOT design staff compare various design alternatives on candidate corridors expected to experience substantive volumes of vulnerable road users.

Table 8 Geometric Feature with Speed Reduction Factors

Feature	Speed Reduction Factor (mph)
Single-lane roundabout w/in 500ft	7.0
Raised median	3.1
Depressed median	1.3
Two-way left-turn lane (TWLTL)	0.7
On-street parking	1.7
Crosswalk	1.3
Curb and gutter	1.0

The study showed that the presence and type of median (i.e., raised median, depressed median, or two-way, left-turn lane) were all associated with lower travel speeds as compared to similar undivided roadways. These reductions were most pronounced in the presence of a raised median (3.1 mph), followed by a depressed median (1.3 mph), and a TWLTL (0.7 mph). As noted above, Table 8 Table 8 shows the speed reductions that could be expected when the different types of medians are installed on these roads, as well. Raised medians generally do not require as much space, although additional construction costs are introduced, and they have the added benefit of serving as a refuge for people biking and walking when crossing the road, simplifying the complexity of the crossing maneuver. Therefore, MnDOT should consider including guidelines for installing raised medians in the *Complete Street Handbook* (MnDOT, 2022) to guide local agencies interested in using them as a traffic-calming measure during Complete Streets conversion. While those sites with raised medians in this study occurred on some of the lowest-speed roads (30 mph), FHWA guidance suggests that a raised median may also be appropriate for roads with posted speed limits greater than 35mph in urban and suburban contexts (FHWA, 2021). This MnDOT research study has not shown any substantive difference based on the width of the median.

In addition to medians, the presence of features on the shoulder also showed impacts on speed selection. For example, vehicular speeds were 1.7 mph slower, on average, on road sections where on-street parking was present. MnDOT could consider adding on-street parking when introducing road conversions (i.e., reductions from 4 to 3 travel lanes). On-street parking may reduce speed by restricting lateral space for drivers, therefore forcing them to reduce their speed. Guidance could be provided in the *Complete Street Handbook* (MnDOT, 2022). MnDOT could also consult the on-street motor vehicle parking and the bikeway selection process document produced by the FHWA (Schultheiss et al., 2021) and the traffic calming ePrimer (Traffic Calming ePrimer, FHWA, n.d.). It should be noted that this study only focused on parallel parking, and this result may not be applicable to other types of parking. Therefore, further research may be warranted to measure the impact of alternate on-street parking configurations on travel speeds.

Roadways with curb and gutter were associated with vehicle speeds that were 1.0 mph lower compared to when paved shoulders were present. As in the case of medians, these features generally constrain the lateral space available to drivers and, as such, may explain the reason for these speed reductions. Consequently, MnDOT should also consider including guidance in the *Complete Streets Handbook* regarding the benefit of a curb and gutter design, though this would be associated with other related costs (e.g., drainage).

It should be noted that SRFs are additive when different features are combined. For example, a combination of the presence of on-street parking and a raised median is expected to result in an SRF of about 4.8 mph. However, further research may be warranted to precisely determine the exact SRFs for different combination of features. In addition, research could also explore whether the combination of different features results in a diminishing return in terms of speed reduction.

This study did not show any reduction in vehicle speeds in the presence of bike lanes. However, it is important to note that bike lanes comprised a small portion of the overall sample. Furthermore, no people biking were observed during field data collection, and it is likely that results may vary when bike lanes are both present and being used.

Single-lane roundabouts were demonstrated to be effective speed countermeasures, making them a potential solution for assisting drivers transition from high-speed roadways into Complete Streets, especially at locations where high travel speed is a concern. A recent study funded by the Michigan Department of Transportation (MDOT) highlighted the impact of roundabouts on vehicle speed in the presence and absence of pedestrians (Savolainen et al., 2023). Although this study did not have pedestrians present at the roundabouts, the result was similar in the absence of pedestrians. Consequently, MnDOT should incorporate guidelines in the *Complete Streets Handbook* (MnDOT, 2022) that recommend the installation of single-lane roundabouts at the entrance of the town as vehicles transit into Complete Streets corridor. However, further research may be warranted to explore the speed-reduction impacts of multilane roundabouts. This would involve examining the relationship between lane position and travel speed, thereby providing insights into how different roundabout configurations can influence a driver's speed.

Finally, travel speeds were 1.3 mph lower in the vicinity of marked crosswalks. This is interesting as there was limited pedestrian activity, and, as such, drivers may be somewhat cognizant of potential non-motorized traffic, which could explain this reduction. Since the presence of crosswalks was associated with reduced speeds, agencies can potentially consider crosswalks as traffic-calming measures, with the additional advantage of promoting pedestrian safety.

Turning to general impacts on driver behavior, drivers do not typically reduce their speed until they are 1,000 ft upstream of a speed limit reduction. Agencies interested in reducing drivers' speed before they reach posted speed limit signs could use dynamic speed feed signs (DSFS) or reduced speed limit ahead signs, to alert drivers of impending reductions. The use of DSFS has been found to be very effective on freeways and in other contexts (Fisher et al., 2021; Hallmark et al., 2012; Karimpour et al., 2021; Mahmud et al., 2022). Their effectiveness is due to the fact that they are able to enhance drivers' awareness of their travel speed, thereby helping them reduce their speed at the speed limit reductions.

6.2 Limitations and Future Work

Ultimately, certain geometric features showed minimal impact on travel speeds. These included the presence of stop control on the minor approach, lane width, and shoulder width. Also, travel speeds on sections with bike lanes were marginally higher compared to where they were absent. It should be noted that the research team finding minimal impacts of these geometrics features did not imply that they do not influence travel speed. Instead, it presents an opportunity for further research to measure their impact.

Several other features were examined as part of this study, including the presence of upstream horizontal curves and isolated median islands. However, no significant differences were observed when they were present because of the small sample size. This also presents an opportunity for further research.

The research team also encountered some limitations during the course of this study. These limitations and directions for future work are presented below.

Geometric Features: The field data collection and subsequent data analysis focused on examining various cross-sectional characteristics of roadways. However, certain features commonly associated with Complete Streets, such as bus lanes and bus stops, were not within the scope of this study due to their absence within the study corridor. Similarly, the presence of island median was limited to one corridor; therefore, examining their impact within this study became impractical. Future research endeavors could seek to investigate these features more exhaustively to understand their impact on travel speed. In addition, the influence of horizontal and vertical curves on travel speeds needs to be further examined. Research could focus on speeding behavior when drivers enter and exit the curves and how long they sustain the travel speed. Likewise, different types of geometric features (i.e., parallel parking vs angle parking, curb and gutter vs parking lanes) could be a feature of future research.

Further research may also be warranted on how geometric features impact mode choice for road users. For example, are people biking more or less comfortably when bike lanes are placed side-by-side with on-street parking? In addition, future research could seek to examine how speed-reduction factors vary when different geometric features are combined.

Context: The scope of the current study is primarily focused on rural and suburban environments. This has limited the variability of important parameters such as lane width, which is instrumental in traffic calming. This minimal variation observed between 11-ft and 12-ft lanes did not allow for the measurement of the impact of lane width reduction on travel speed. As a result, this study did not result in any conclusive impact of the effects of narrower lane width on travel speed. To address this limitation, future research could focus on field data collection in urban areas where lane reductions are more common. Results are expected to be different in urban areas because of the different transportation dynamics as compared to rural and suburban areas. In addition, future research could assess travel speed at nighttime compared to daytime as driver behavior is expected to vary in the two conditions. In addition, future research could assess how travel speed varies due to parking use (i.e., comparing full parking spaces with empty parking spaces or half-full parking spaces).

Absence of vulnerable road users (VRU): During the field data collection process, the focus was on observing free-flowing vehicles. As a result, the research did not observe drivers' speed selection behavior in the presence of people biking and walking at the geometric features of interest. Consequently, further research may be warranted to compare driver behavior in scenarios where vulnerable road users are present or absent. Also, further studies could investigate vehicle yielding behavior toward VRUs. Understanding how drivers interact with VRUs could help reduce the constantly increasing pedestrian fatalities nationwide, therefore helping to promote a transportation system that is inclusive and accommodating to all road users.

Safety: While this study focused on analyzing drivers' speed behavior, safety analysis was not conducted. Further research would thus be warranted to assess the safety implications before and after conversion to Complete Streets. This could help measure the effectiveness of Complete Streets in reducing crash frequency and severity. Crash modification factors could be developed based on the geometric features added post-conversion. This would help quantify the safety improvements gained from adopting Complete Streets and help agencies prioritize potential safety treatments in consideration of anticipated speed impacts.

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Appendix A
Mean Speed Profiles for Individual Corridors

This appendix provides the average driver speed selection profile for each corridor where lidar speed data were collected as a part of field evaluations. The profiles are shown based on speeds interpolated at every 50-foot interval, which are averaged across all drivers. Each corridor where speed data were collected far upstream of the town had the speed profile for the baseline speed presented first before other related speed profiles. It should be noted that the baseline speed (collected in 2023) data were collected in the same direction of travel as the speed data close to town (collected in 2022) except at 260 St E/ Elko Market because of the lack of enough shoulder width for parking of the vehicle for covert data collection. The location of different features encountered during the field evaluations was noted with signs.

(15a)

(15b)

Figure 15 Average Speed Profile as Vehicles Transit from 55-45-30 mph on 260 St/Eko New Market Corridor

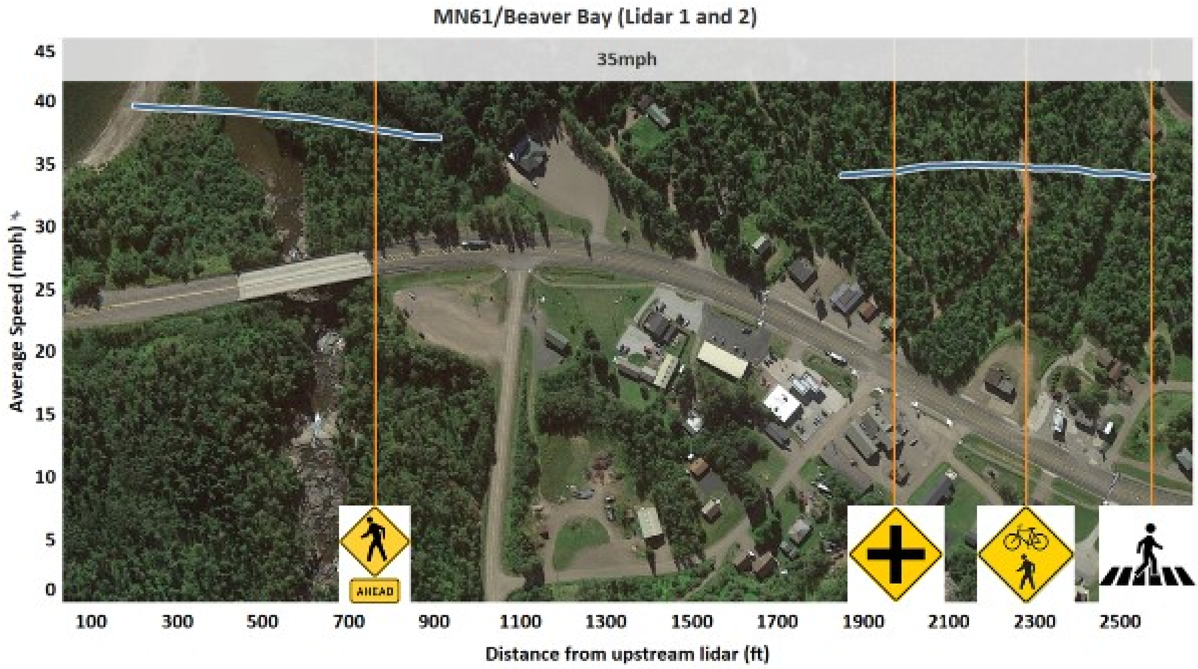


Figure 16 Average Speed Profile as Vehicles Transit through the MN61/Beaver Bay Corridor

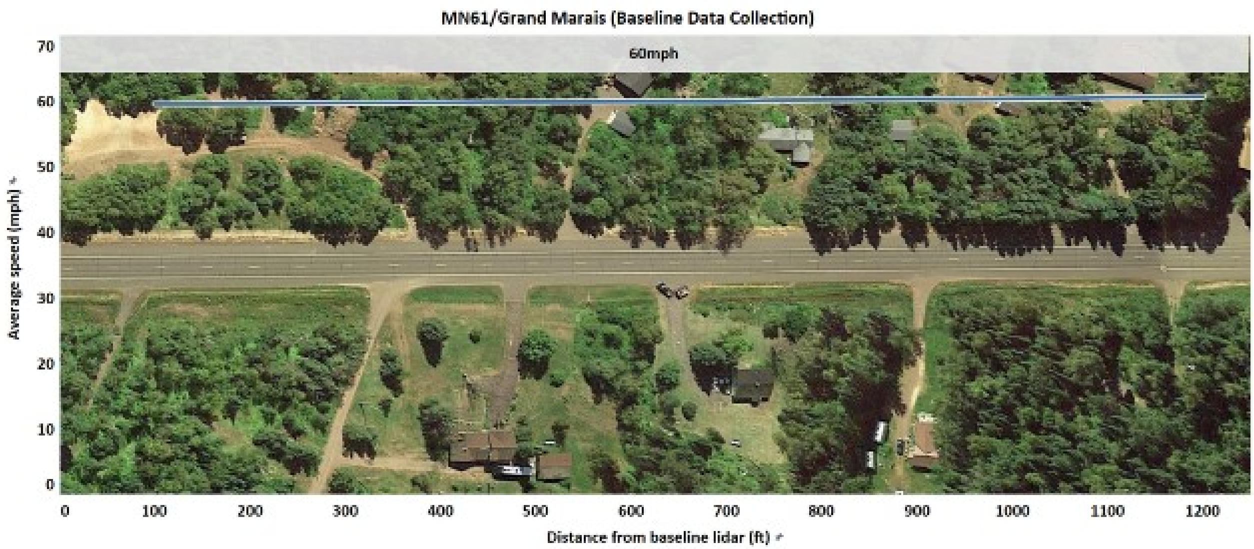
(17)

Figure 17 Average Speed Profile as Vehicles Transit through 60 mph Speed Zone on MN135/Gilbert Corridor

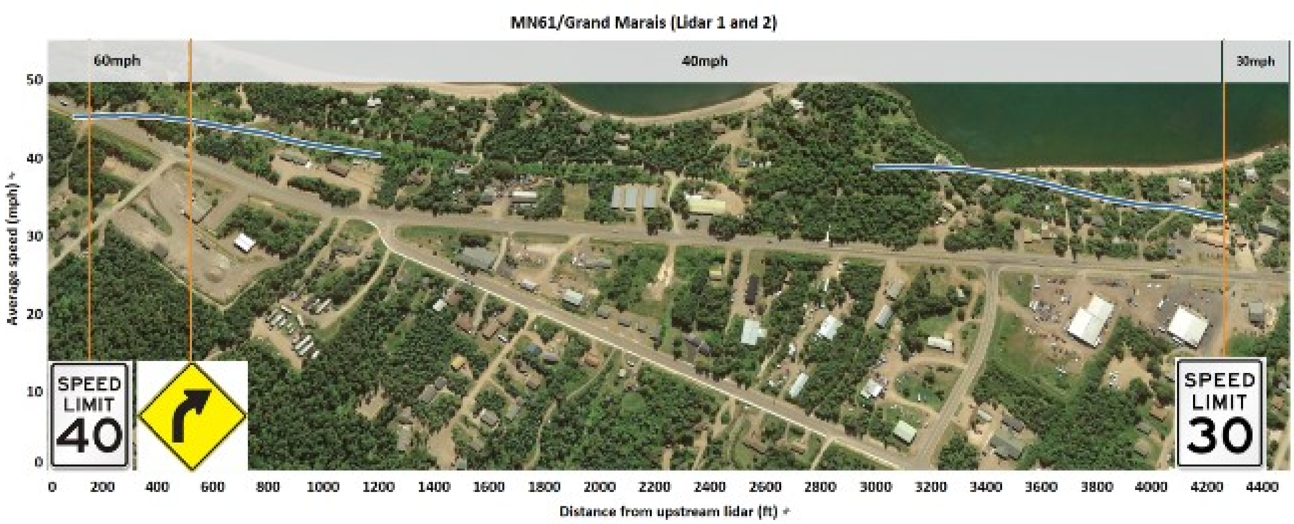
(18a)

(18b)

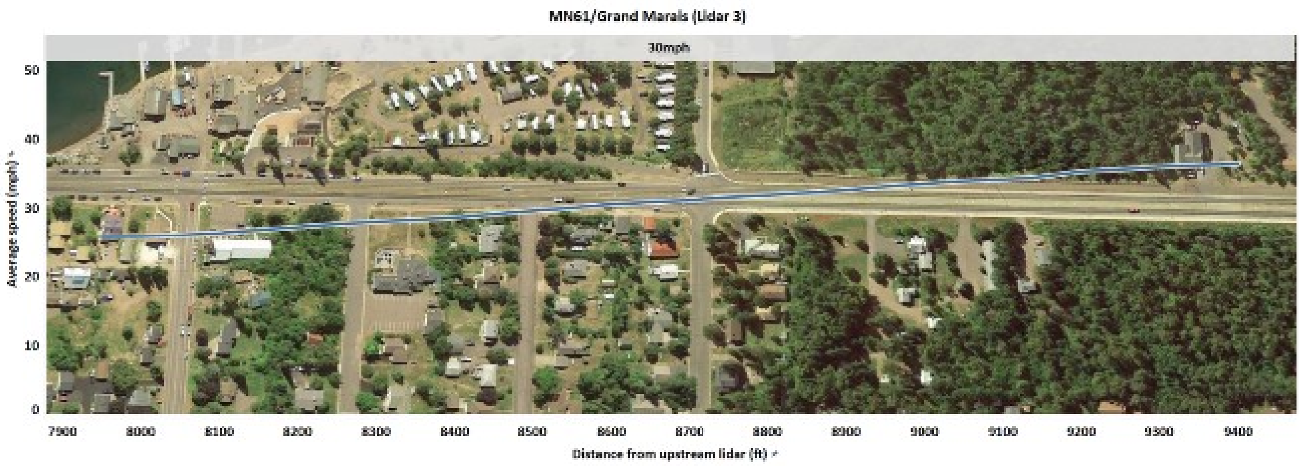
Figure 18 Average Speed Profile as Vehicles Transit from 60-40-30 mph on MN37/Gilbert Corridor


MN61/Grand Marais (Baseline Data Collection)
60mph
Average speed (mph)
Distance from baseline lidar (ft)

(19a)

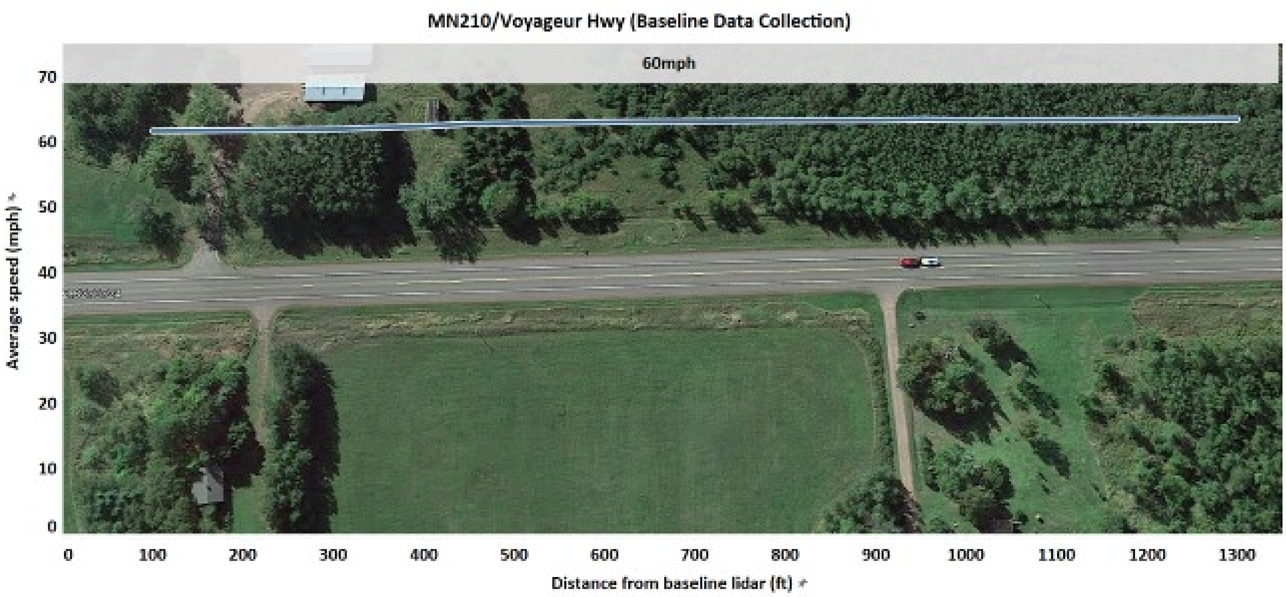

MN61/Grand Marais (Lidar 1 and 2)
60mph
40mph
30mph
SPEED LIMIT 40
SPEED LIMIT 30
Average speed (mph)
Distance from upstream lidar (ft)

(19b)

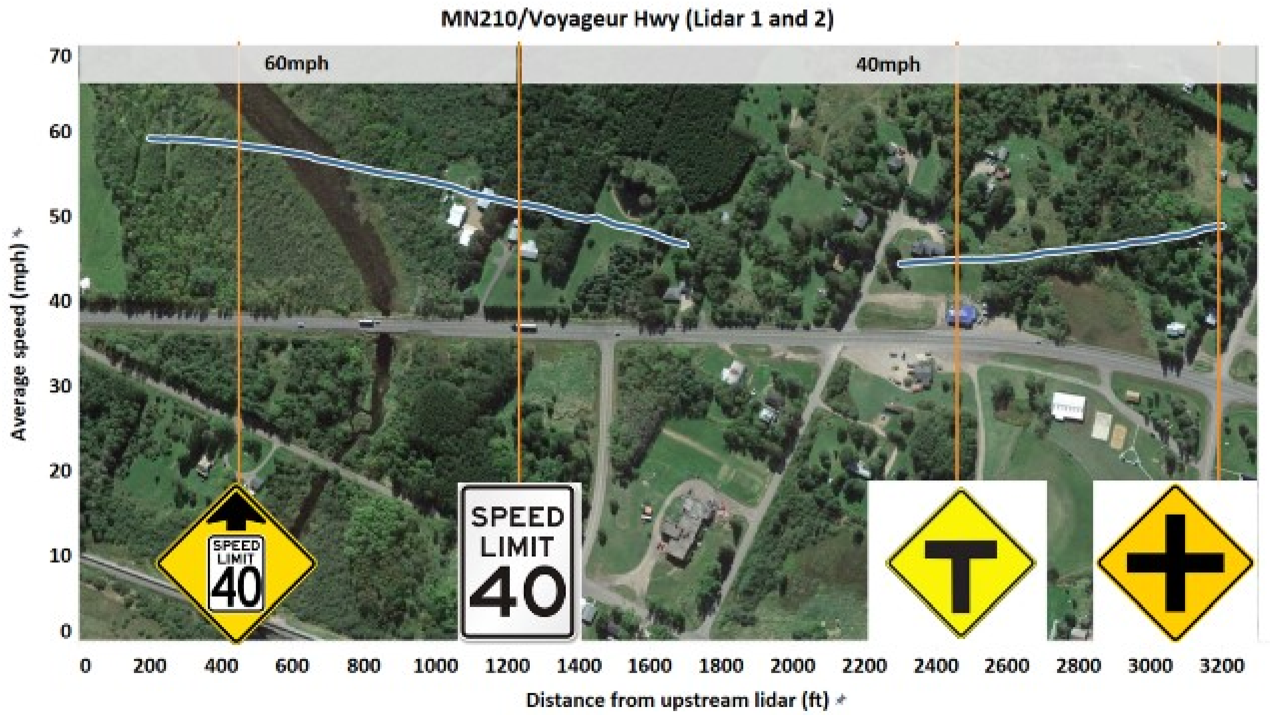


(19c)

Figure 19 Average Speed Profile as Vehicles Transit from 60-40-30 mph on MN61/Grand Marais Corridor



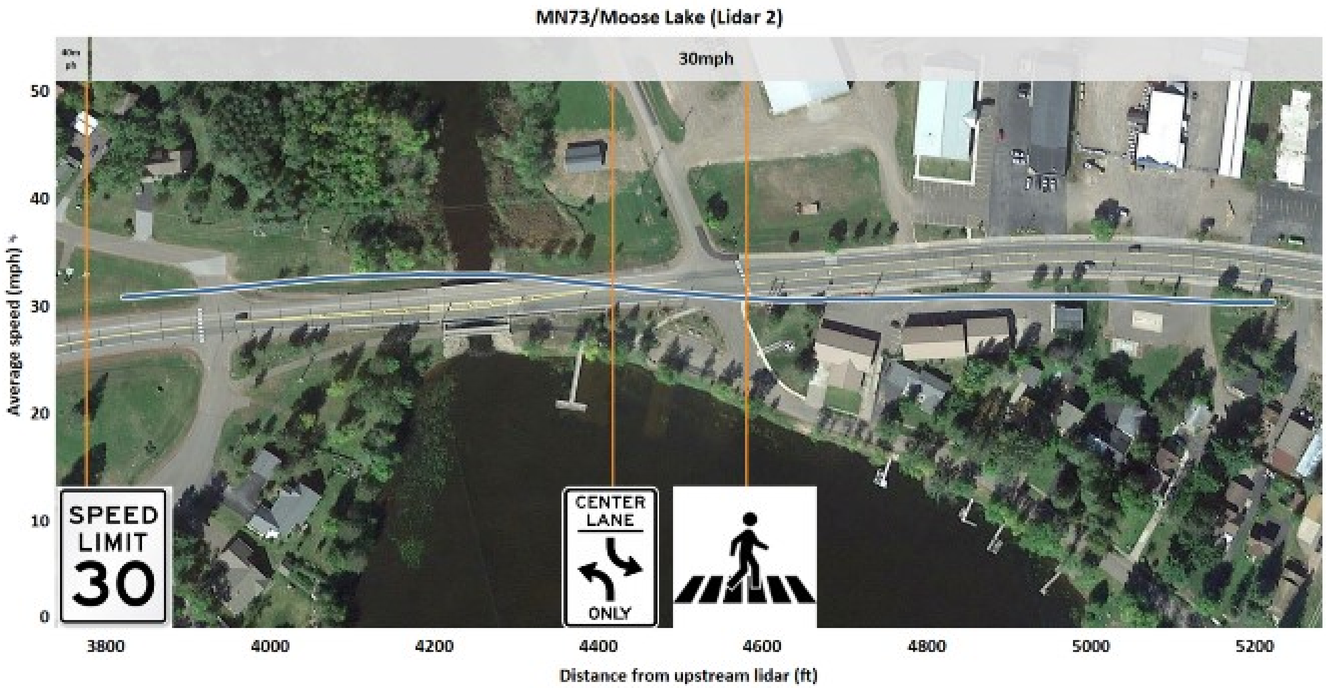
(20a)



(20b)

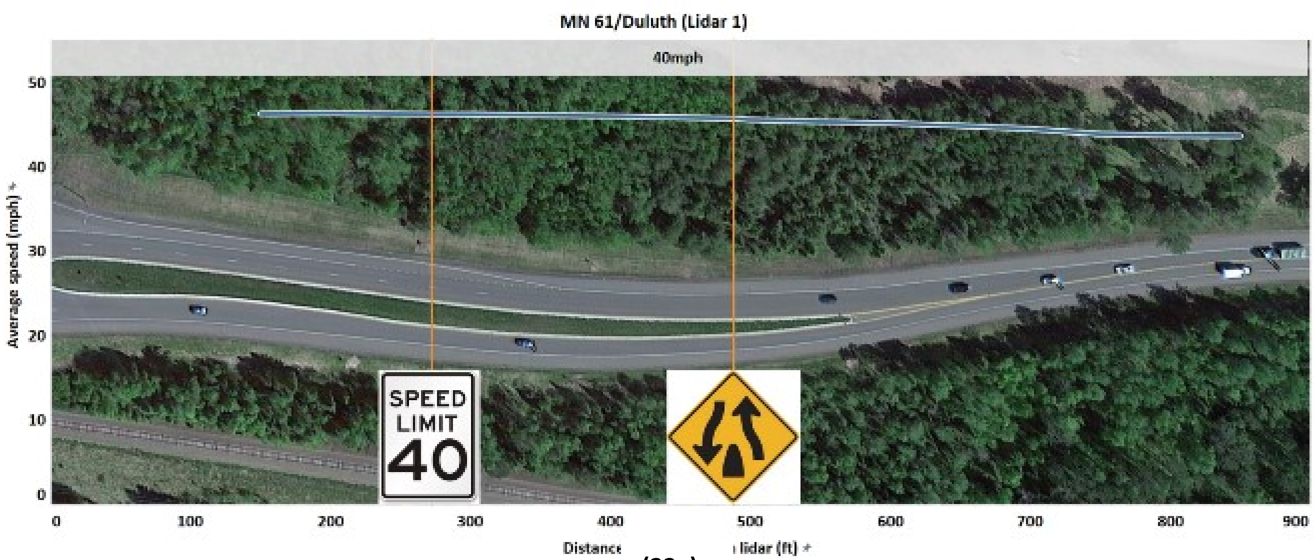
Figure 20 Average Speed Profile as Vehicles Transit from 60-40 mph on MN210/Voyageur Hwy Corridor

(21a)



(21b)

Figure 21 Average Speed Profile as Vehicles Transit from 55-40-30 mph on MN73/Moose Lake Corridor



(22a)

(22b)

Figure 22 Average Speed Profile as Vehicles Transit from 40-30 mph on MN61/Duluth Corridor

(23a)

(23b)

Figure 23 Average Speed Profile as Vehicles Transit from 45-30-25 mph on MN9/New London Corridor

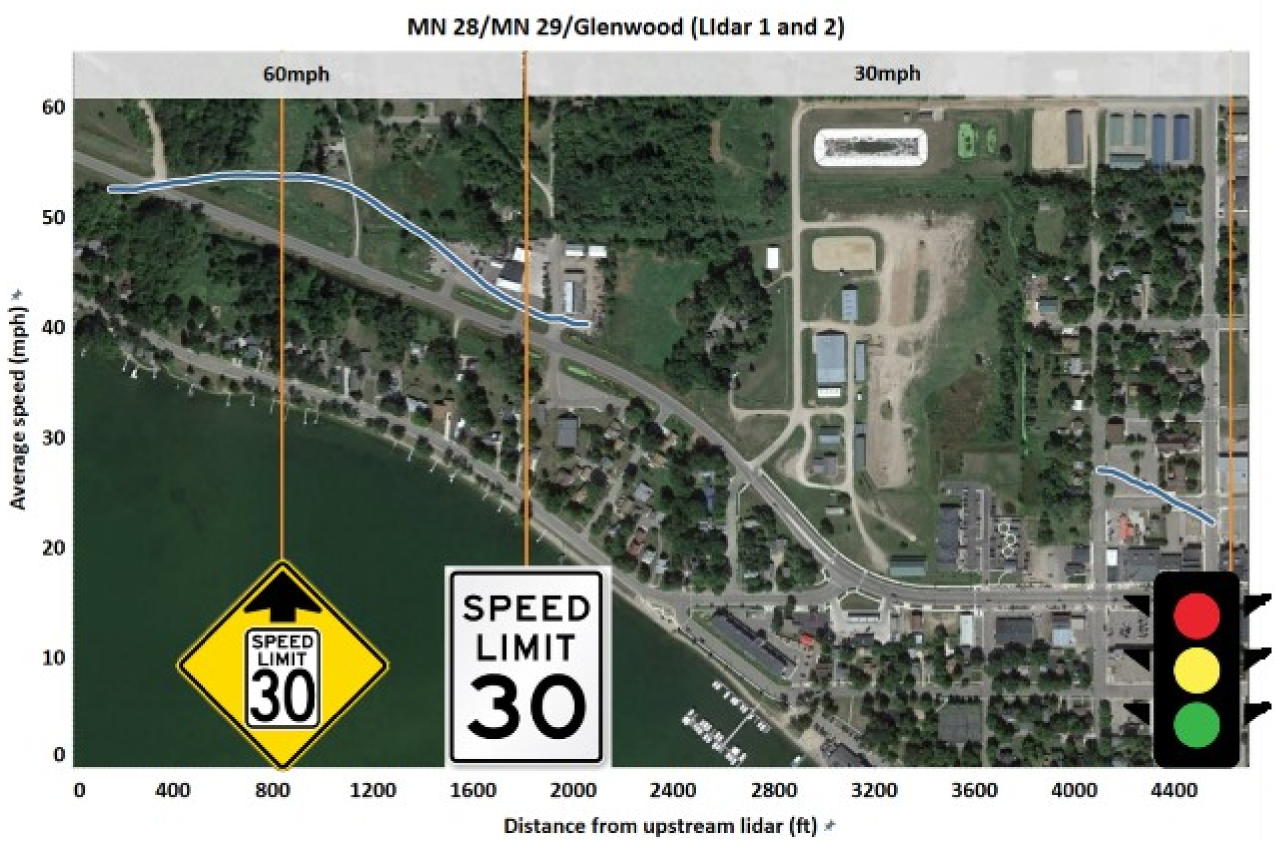
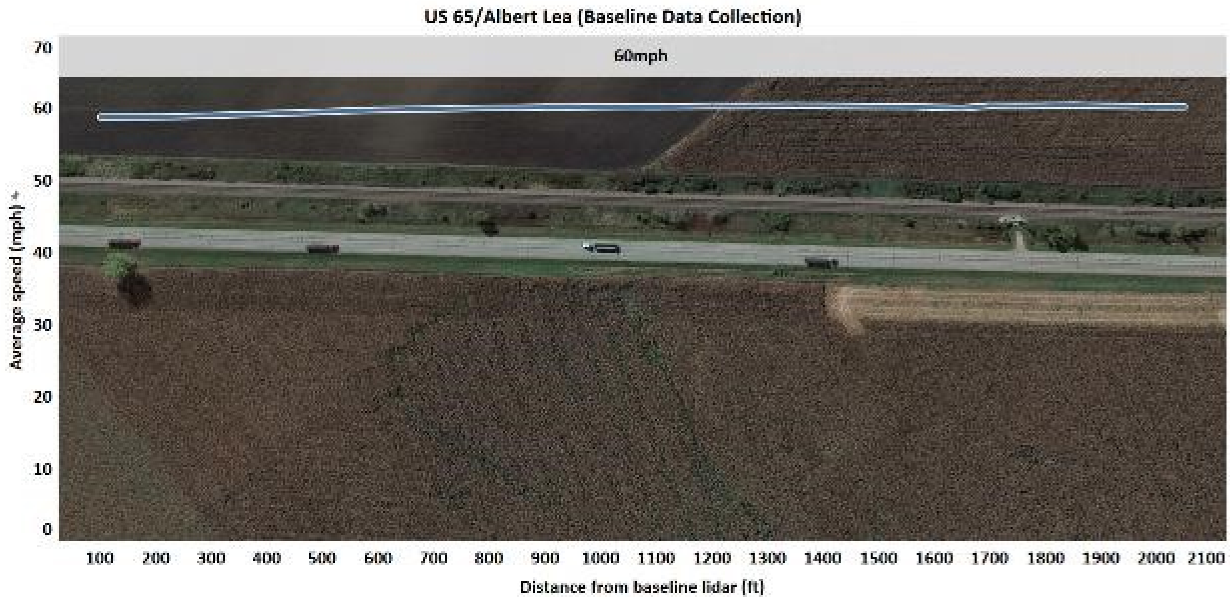
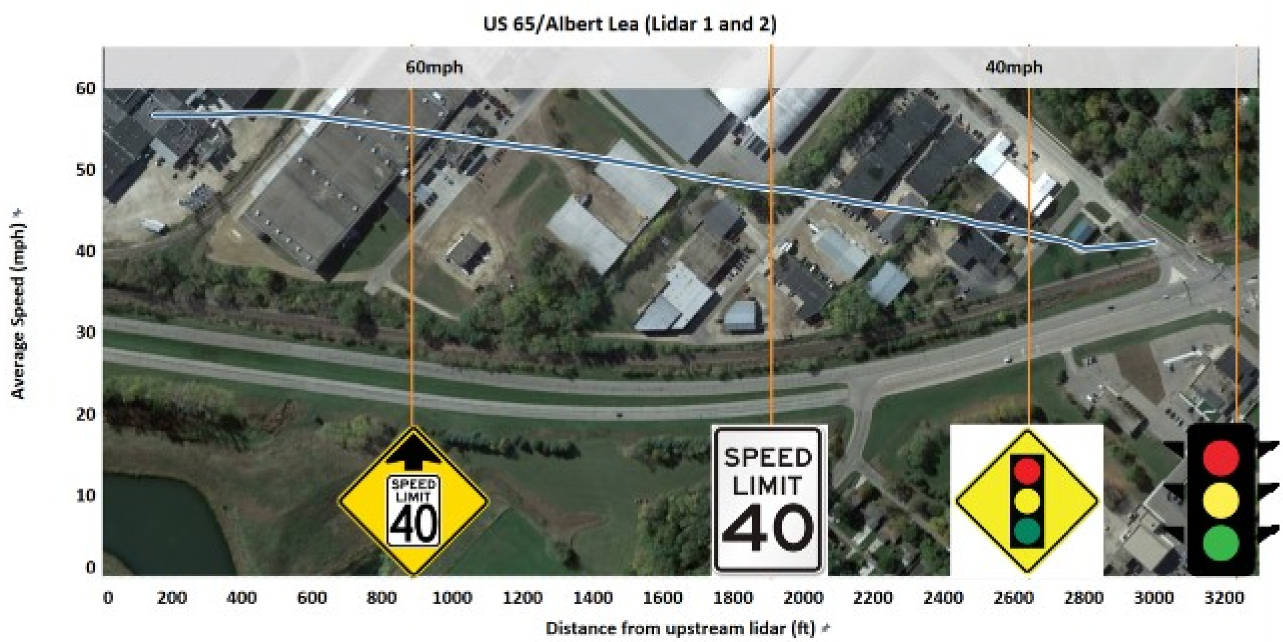


Figure 24 Average Speed Profile as Vehicles Transit from 60-30 mph on MN28/MN29/Glenwood Corridor


US 65/Albert Lea (Baseline Data Collection)
60mph
70
60
50
40
30
20
10
0
Average speed (mph)
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Distance from baseline lidar (ft)

(25a)

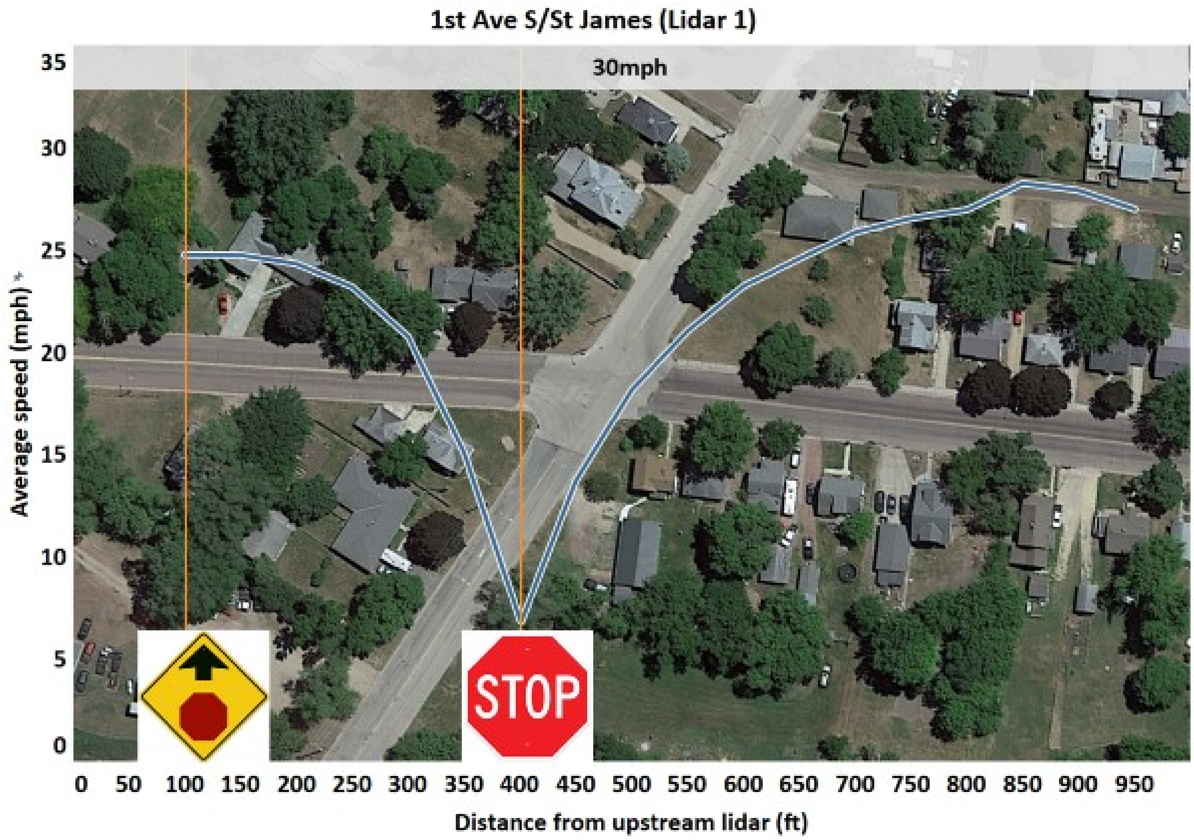

US 65/Albert Lea (Lidar 1 and 2)
60mph
40mph
60
50
40
30
20
10
0
Average Speed (mph)
SPEED LIMIT 40
SPEED LIMIT 40
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200
Distance from upstream lidar (ft)

(25b)

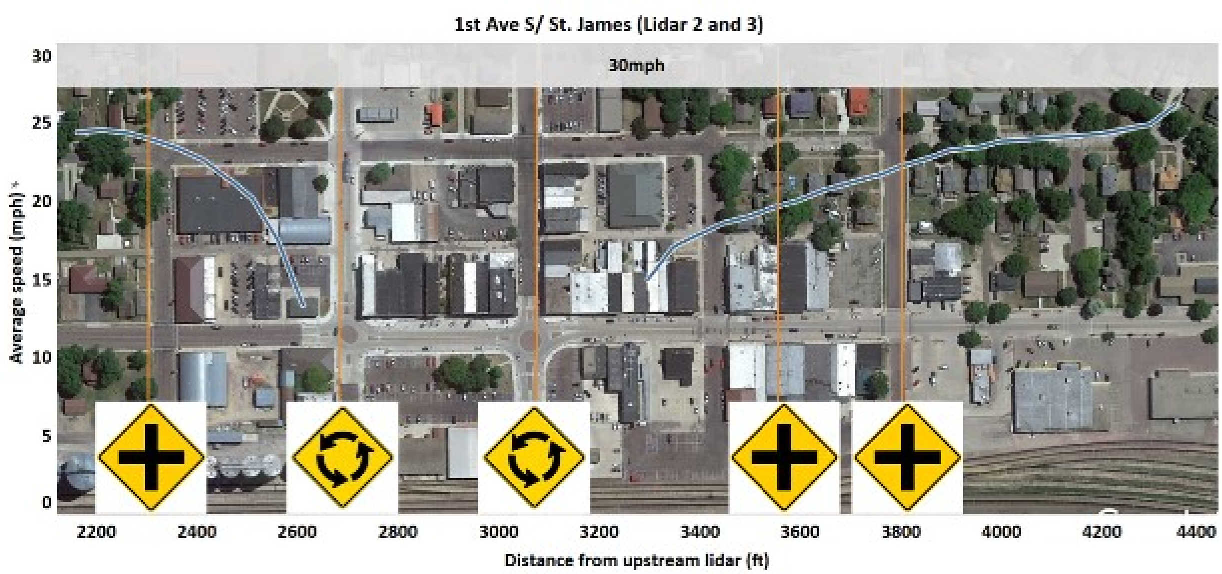
(25c)

(25d)

Figure 25 Average Speed Profile as Vehicles Transit from 60-40-30 mph on US65/Albert Lea Corridor



(26a)



(26b)

Figure 26 Average Speed Profile as Vehicles Transit through the 1st Ave S/St James Corridor

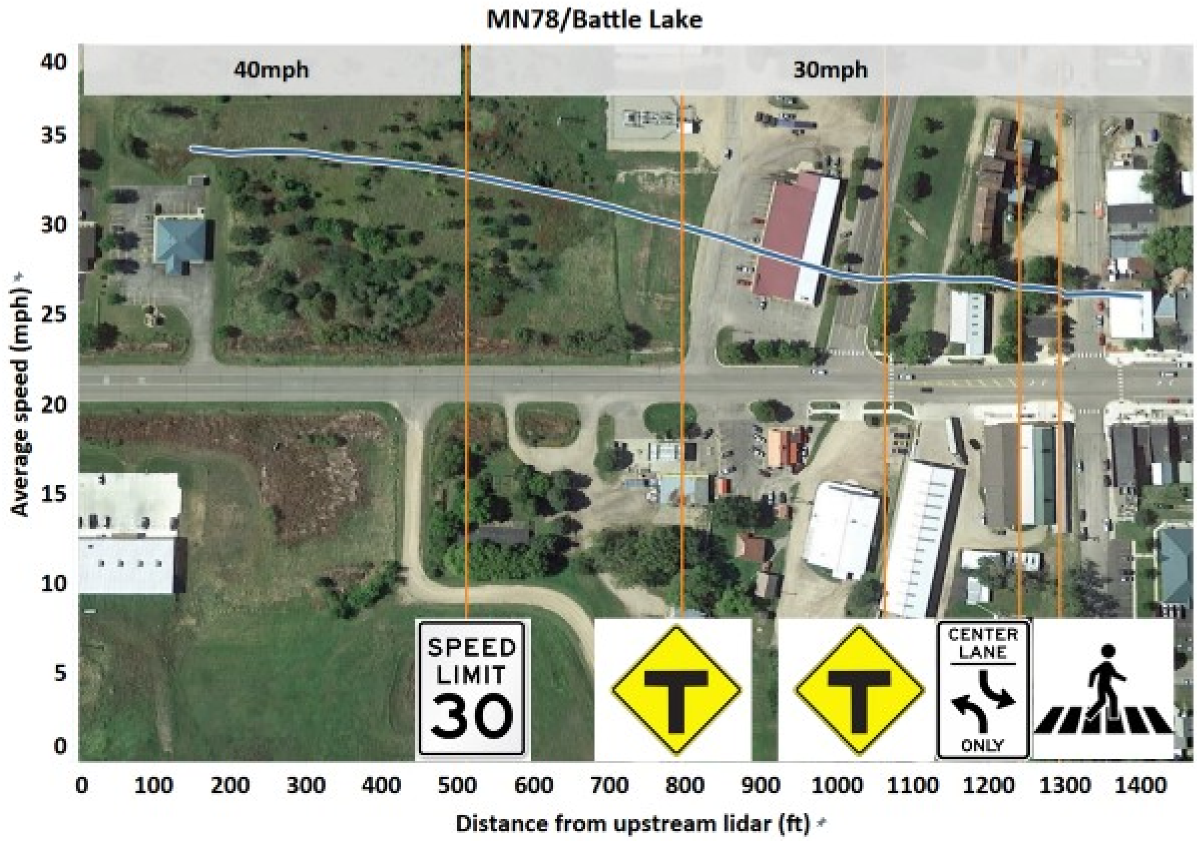
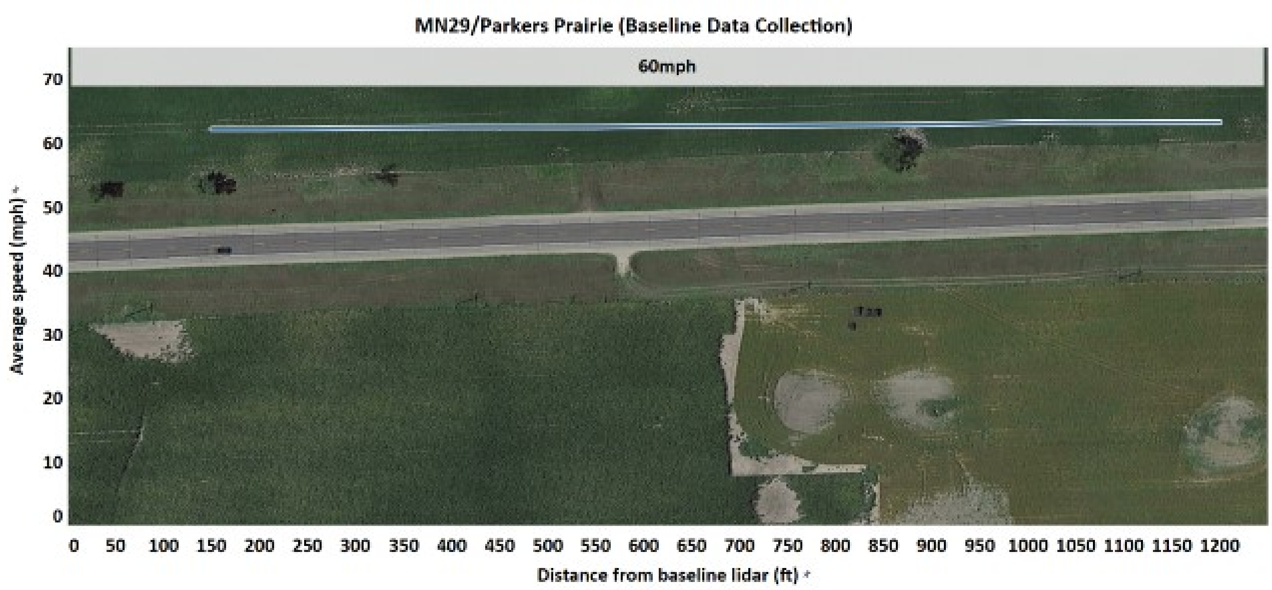
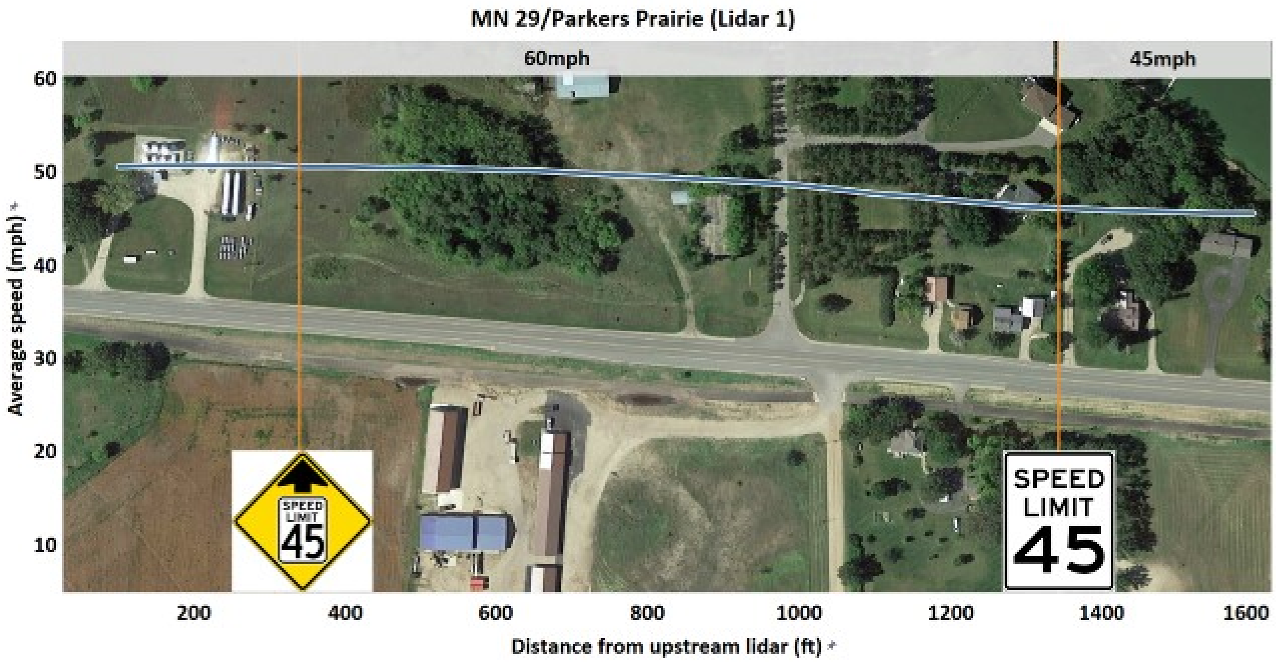


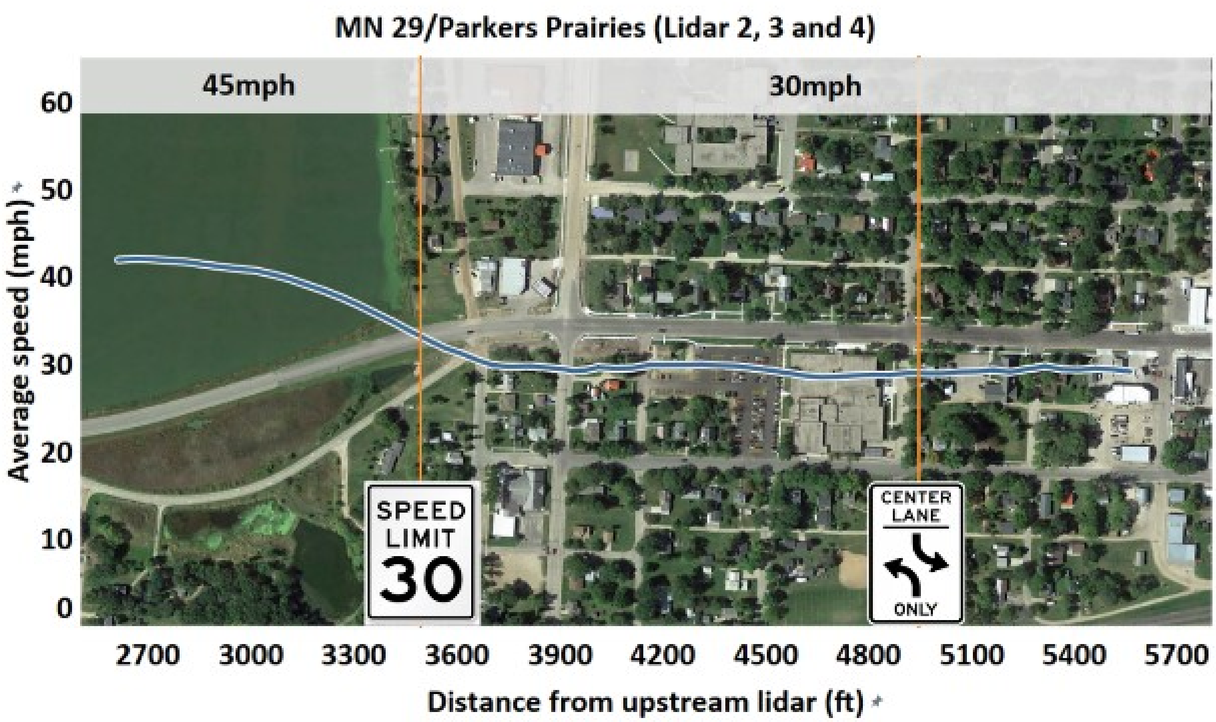
Figure 27 Average Speed Profile as Vehicles Transit from 40-30 mph on MN78/Battle Lake Corridor



(28a)



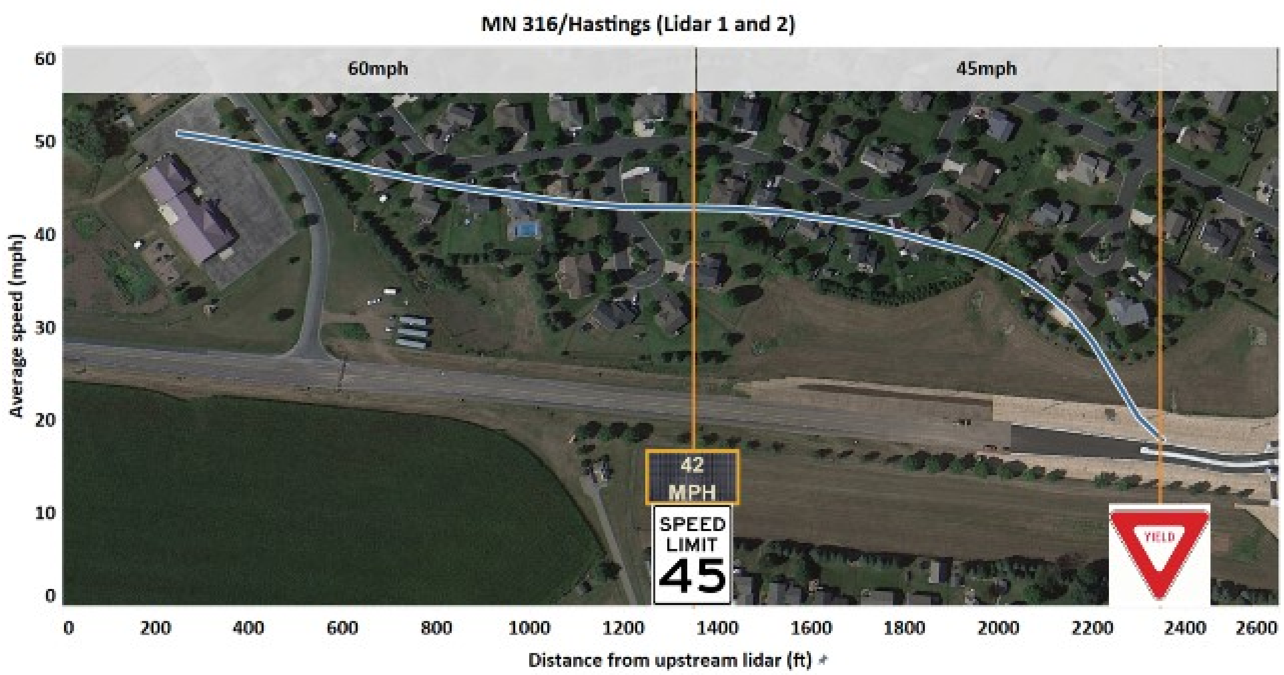
(28b)



(28c)

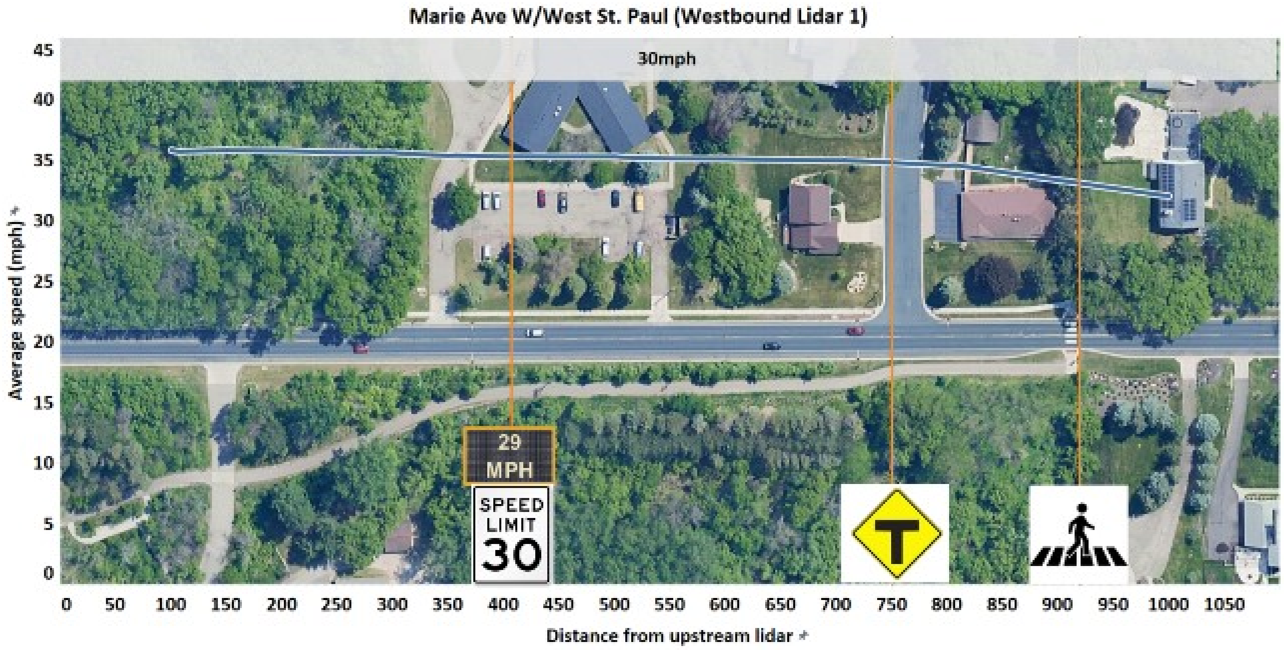
Figure 28 Average Speed Profile as Vehicles Transit from 40-30 mph on MN78/Battle Lake Corridor

(29a)

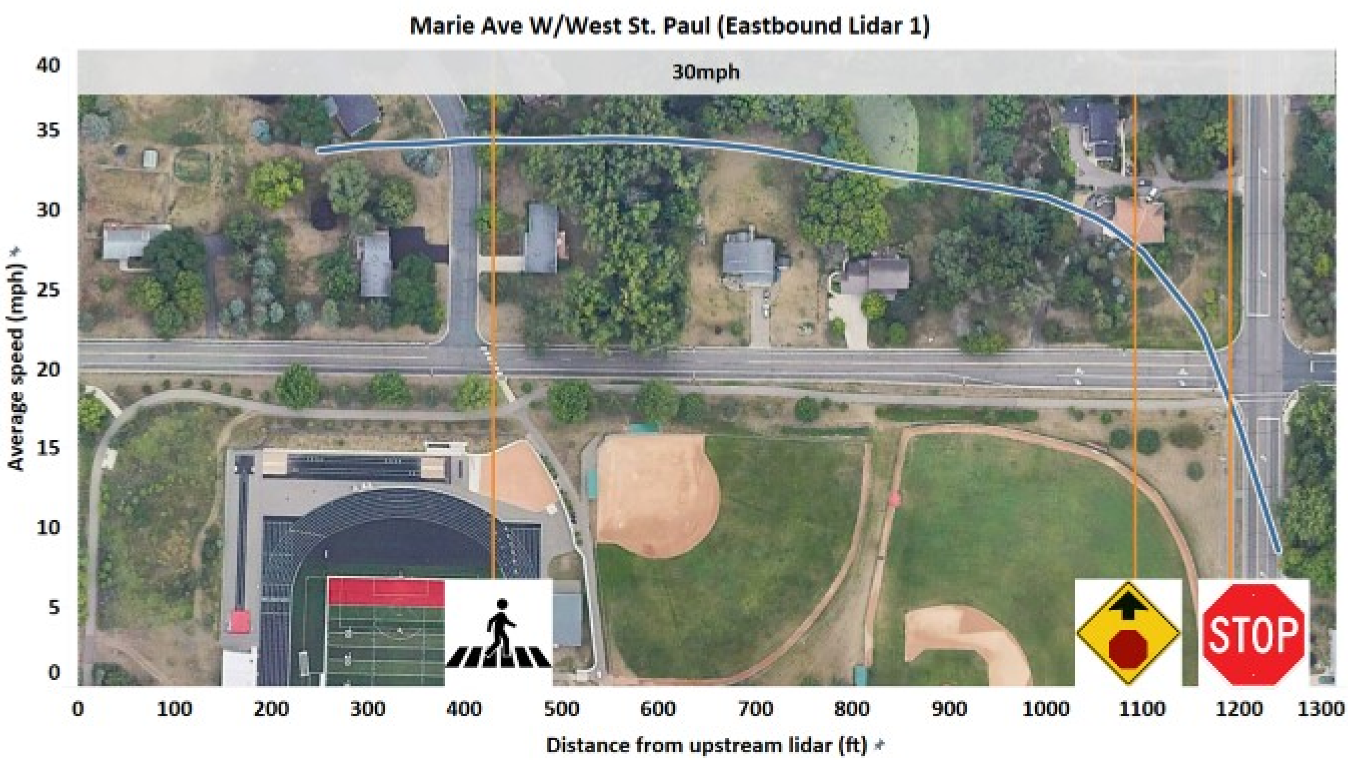


(29b)

Figure 29 Average Speed Profile as Vehicles Transit from 60-45 mph on MN316/Hastings Corridor



(30a)



(30b)

Figure 30 Average Speed Profile as Vehicles Transit through the Marie Ave W/West St. Paul (East and Westbound)

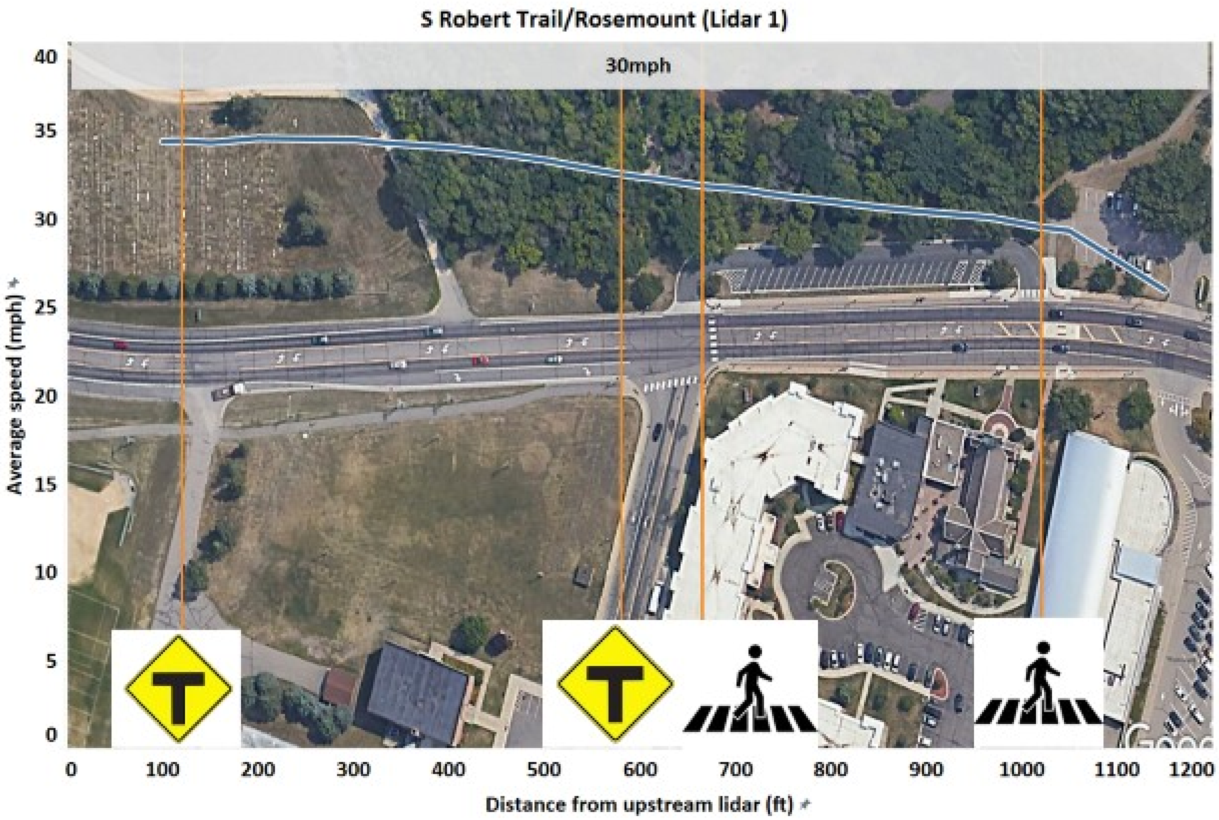


Figure 31 Average Speed Profile as Vehicles Transit through the S Robert Trail/Rosemount Corridor

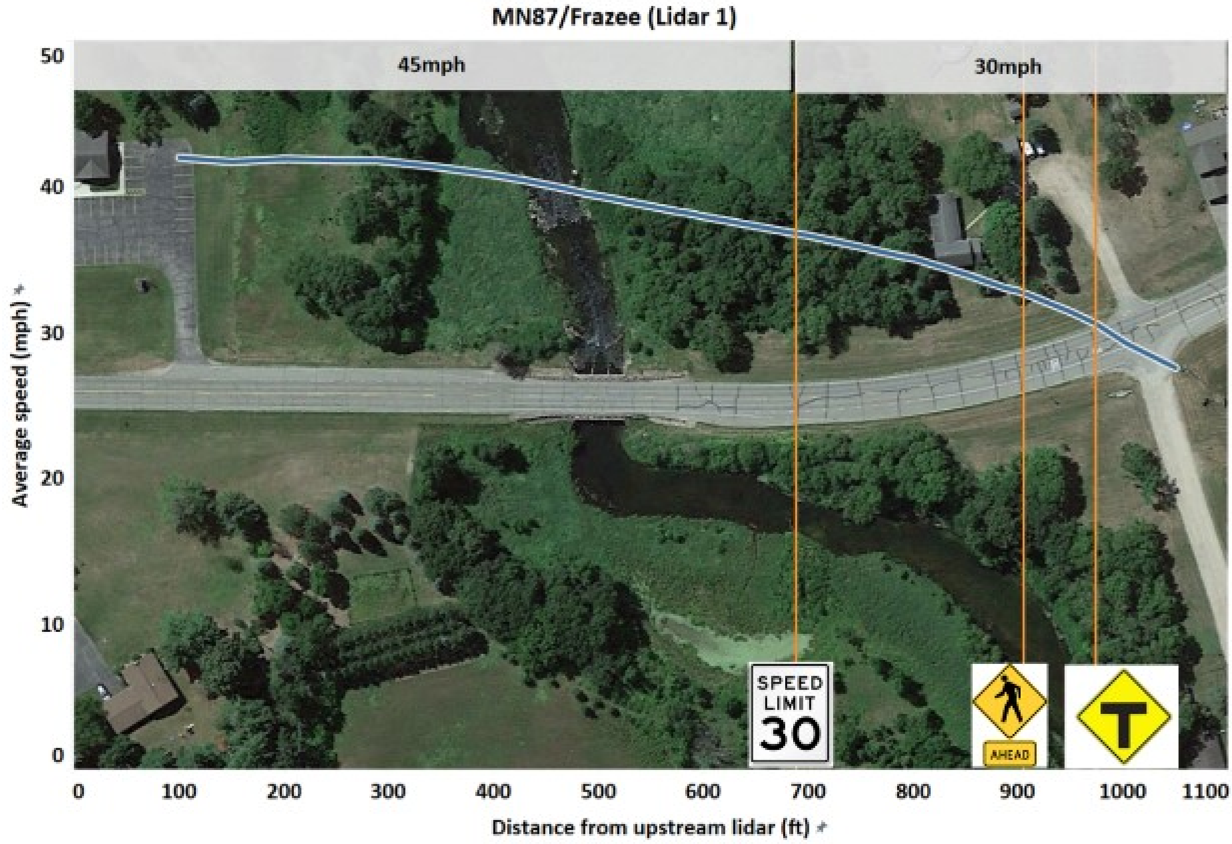


Figure 32 Average Speed Profile as Vehicles Transit from 45-30 mph on MN87/Frazee Corridor

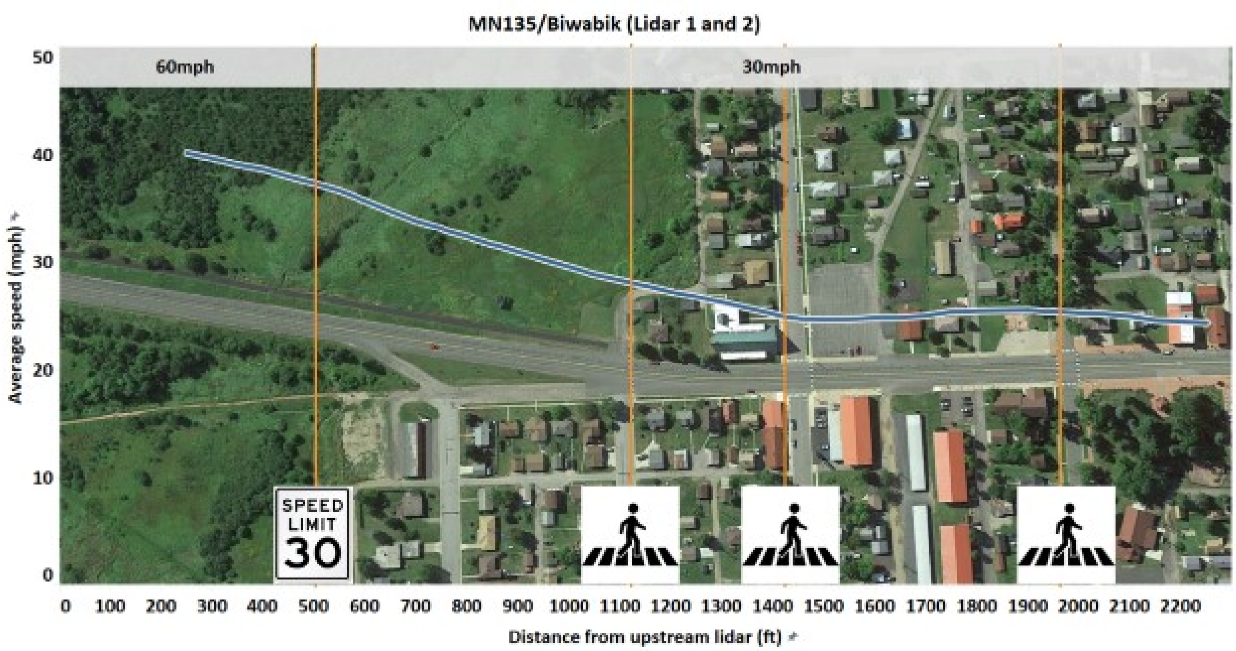


Figure 33 Average Speed Profile as Vehicles Transit from 60-30 mph on MN87/Frazee Corridor