Project 2318 | December 2023

Exploring Traffic Speed Patterns for the Implementation of Variable Speed Limit (VSL) Signs

Panick Kalambay, Ph.D.
Srinivas Pulugurtha, Ph.D., P.E., F.ASCE

MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the Mineta Consortium for Transportation Mobility (MCTM) and the Mineta Consortium for Equitable, Efficient, and Sustainable Transportation (MCEEST) funded by the U.S. Department of Transportation, the California State University Transportation Consortium (CSUTC) funded by the State of California through Senate Bill 1 and the Climate Change and Extreme Events Training and Research (CCEETR) Program funded by the Federal Railroad Administration. MTI focuses on three primary responsibilities:

Research

MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

Education and Workforce Development

To ensure the efficient movement of people and products, we must prepare a new cohort of transportation professionals who are ready to lead a more diverse, inclusive, and equitable transportation industry. To help achieve this, MTI sponsors a suite of workforce development and education opportunities. The Institute supports educational programs offered by the Lucas Graduate School of Business: a Master of Science in Transportation Management, plus graduate certificates that include High-Speed and Intercity Rail Management and Transportation Security Management. These flexible programs offer live online classes so that working transportation professionals can pursue an advanced degree regardless of their location.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

Report 23-29

Exploring Traffic Speed Patterns for the Implementation of Variable Speed Limit (VSL) Signs

Panick Kalambay, Ph.D.

Srinivas Pulugurtha, Ph.D., P.E., F.ASCE

December 2023

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
23-29		

4. Title and Subtitle
Exploring Traffic Speed Patterns for the Implementation of Variable Speed Limit (VSL) Signs

5. Report Date
December 2023

6. Performing Organization Code

7. Authors
Panick Kalambay, Ph.D. 0000-0002-0815-3074
Srinivas Pulugurtha, Ph.D., P.E., F.ASCE 0000-0001-7392-7227

8. Performing Organization Report
CA-MTI-2318

9. Performing Organization Name and Address
Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

10. Work Unit No.

11. Contract or Grant No.
69A3551747127

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Office of the Assistant Secretary for
Research and Technology
University Transportation Centers Program
1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report and Period

14. Sponsoring Agency Code

15. Supplemental Notes
10.31979/mti.2023.2318

16. Abstract
Traffic congestion is a prevalent issue during peak travel hours on roads in the United States. This study focuses on identifying suitable road links in Charlotte, North Carolina, for implementing variable speed limit (VSL) signs. Real-world traffic speed data collected over one year was analyzed to identify specific road links with favorable characteristics for VSL sign installations. The analysis considered weekdays, weekends, and specific times of the day to capture variations in speed patterns. The results revealed that roads with lower speed limits consistently experienced speeds exceeding the posted speed limits, suggesting additional enforcement or safety measures. For roads with higher speed limits, mean speeds were generally close to the speed limits, but the 85th percentile speeds exceeded them, indicating a potential need for speed management measures. Road links with a 45/50 mph speed limit display a unique pattern compared to other clusters. The mean speed on these roads decreases as the standard deviation increases. The findings contribute to understanding traffic speed patterns and provide valuable insights for transportation planning and management.

17. Key Words	18. Distribution Statement
Variable speed limit, Speed limit cluster, Traffic speed, Speed variation	No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	51	

Form DOT F 1700.7 (8-72)

DOI: 10.31979/mti.2023.2318

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2318

Acknowledgments

The authors sincerely thank the staff of the North Carolina Department of Transportation and the Regional Integrated Transportation Information System for their help with the traffic speed data used in this research. The National Performance Management Research Data Set used in this research is based upon work supported by the Federal Highway Administration under contract number DTFH61-17-C-00003. The authors also thank Sarvani Duvvuri, PhD, for her efforts during the initial stages of the project.

CONTENTS

LIST OF FIGURES

List of Tables

Executive Summary

Traffic congestion, bottlenecks, queuing of vehicles, and the resulting shockwaves are commonly observed phenomena during peak hours of travel on many roads across the United States. Researchers and practitioners are exploring sustainable and economic approaches to mitigate congestion and its associated effects by examining historical traffic patterns and exploring data-driven strategies.

Intelligent transportation system (ITS)-based solutions are being widely explored to address congestion-associated transportation problems. The application of advanced traveler information systems, like variable speed limit (VSL) signs, is one such ITS solution. VSL signs are being strategically implemented to improve mobility during extreme weather conditions, in work zones, and at locations with special events.

VSL signs promote speed harmonization of the road link or section at which they are implemented. Existing VSL systems typically use simulated algorithms to generate the speeds needed for specific times of the day and days of the week. Due to the dynamic nature of traffic conditions, selecting an algorithm or technique to improve the flow is one of the most common challenges. It requires a prior understanding of the existing traffic speed patterns for various timespans across the road. Some of the simplest algorithms used include the display of speeds in increments of 5 mph based on the 85th percentile speeds.

The traffic volumes and incidents during peak and off-peak hours are spatially dependent and result in speed variation. The level of variation depends on the time of the day, day of the week, and road functional class. Variable speed limits could play a pivotal role in addressing the challenges posed by spatially dependent speed variations, as they enable transportation authorities to dynamically adapt speed limits based on traffic conditions, enhancing safety and traffic flow on roads affected by varying factors such as the time of day, day of the week, and road functional class. Hence, it is important to identify the road links susceptible to higher variations of traffic speeds to mitigate congestion and improve mobility. Because simulation-based analysis has limitations in accounting for such variations, using real-world data and a data-driven approach is more suitable.

This study is aimed at identifying suitable road links in Charlotte, North Carolina, for implementing VSL signs. Traffic speed data collected from July 2021 to June 2022 at the link level were analyzed to identify specific road links, particularly freeways, with favorable characteristics for installing VSL signs. The analysis was conducted in two phases: an initial phase providing a general overview of the data and a second phase focusing on speed limit clusters. The analysis considered weekdays, weekends, and specific time periods throughout the day to capture variations in speed patterns.

Roads with speed limits of 25/30 mph consistently experience speeds that exceed the posted limits, with the 85th percentile speeds being twice as high. This indicates that safety concerns influenced the establishment of these speed limits. There were no discernible differences in speed measures between weekdays and weekends. For roads with speed limits of 35/40 mph and higher, mean speeds are generally close to the limits, but the 85th percentile speeds exceed them. This suggests a need for additional enforcement or speed management measures. Road links with a 45/50 mph speed limit display a unique pattern compared to other clusters. The standard deviations of speeds in these road links exhibit strong negative correlations with the mean speed, 15th percentile speed, 85th percentile speed, and reference speed (RSP). This negative correlation suggests that as the standard deviation of speeds increases, the average speed, lower percentile speeds, higher percentile speeds, and RSP tend to decrease. Conversely, a decrease in the standard deviation of speeds is associated with an increase in these speed measures.

In conclusion, this study effectively identified and listed road links and their speed variations. Furthermore, an illustrative example showcased the importance of selecting the appropriate traffic speed distribution for a road link with significant speed variation. This example demonstrated the practical implications of considering speed patterns and variations in implementing VSL signs. The findings of this study contribute to the understanding of traffic speed patterns and offer valuable insights for transportation planning and management.

1. Introduction

Since 1995, speed limits in the United States have been centralized at the state level (Albalate & Bel, 2012). The change followed the controversial debates that abolished the national speed limit of 55 mph (Speed Limits by State, 2022). With advancements in vehicle safety features and infrastructure, states have gradually raised their maximum speed limits. These limits are determined by general statutes and local and state ordinances and are enforceable even if the speed limit is not posted.

In North Carolina, the State Department of Transportation sets the statutory speed limit at 35 mph within cities and 55 mph outside cities (NCDOT, 2021). These speed limits are posted along different types of roads, including rural and urban freeways and divided and undivided roads. Also, speed limits are either regulatory or advisory. The regulatory speed limit sign serves as a legal requirement, indicating that drivers must not exceed the specified speed limit under any circumstances. On the other hand, advisory speed limits aim at improving safety at road alignments such as horizontal and vertical curves (Das et al., 2022). They are determined using engineering studies based on guidance from the Manual on Uniform Traffic Control Devices (FHWA, 2020). Traffic engineers use the 85th percentile of free-flow speed (FFS) distribution as a standard to set the speed limit for uniform traffic flow and to minimize crashes (Deardoff et al., 2011; Elvik, 2010).

In growing cities such as Charlotte, the efficient movement of people and goods is essential to avoid congestion. Maintaining speed variation below a certain level based on road functional class, time of day, and day of the week is crucial for smooth traffic flow. Furthermore, harmonizing vehicular speeds can promote better mobility, safer traffic, and improved operational performance. Intelligent transportation systems-based solutions such as variable speed limits (VSL) will make corridors within the city of Charlotte smarter and more efficient from a traffic operation perspective. In fact, a VSL solution can maintain speed variations below thresholds by dynamically adjusting speed limits in response to changing traffic conditions, thereby preventing excessive speed differences between vehicles. Additionally, these systems can harmonize vehicular speeds by encouraging all drivers to adhere to synchronized speed limits, reducing congestion and enhancing overall traffic flow.

Although simulation-based analysis is a valuable tool for studying traffic speed variation, it has inherent limitations in accounting for real-world factors. A data-driven approach using real-world data might be more appropriate, especially when examining traffic patterns from a macroscopic perspective. By relying on real-world data, this approach offers a more accurate and comprehensive understanding of traffic speed patterns, allowing for more effective planning and decision-making at the city level.

1.1 Research Objectives

This study aims to identify road links with abnormal (high) speed variation and indicate the likely need for a VSL control strategy, especially for freeways, to guarantee smooth traffic. To achieve this goal, a pattern recognition strategy using a data-driven approach is proposed to screen road links with different levels of speed variation. Road links whose traffic speed variation exceeds a predetermined threshold are considered suitable for VSL implementation.

The objectives of this study are:

1. to compute and evaluate traffic speed measures by day of the week and time of the day,

2. to explore their association with the speed limit or reference speed (RSP) by road functional class, and,

3. to provide guidance on identifying road links susceptible to variations in traffic speeds for implementing VSL signs.

1.2 Organization of the Report

This report is organized as follows. The second chapter reviews and discusses the relevant literature. The third chapter introduces the study area and describes the data used for analysis. The methodology is presented in Chapter 4. Chapters 5 and 6 focus on the exploratory data analysis of traffic speed data and the bivariate analysis of traffic speed measures, respectively. Chapter 7 focuses on identifying road links with a high speed variation. The study's findings are summarized in Chapter 8.

1.3 Contribution of the Study

This research has practical implications for transportation planning and policy. By understanding which road links experience consistently high speed variations, authorities can focus on improving the infrastructure, implementing traffic management measures, and designing more efficient transportation systems in those links. This can lead to reduced congestion and travel times, enhanced road safety, and improved traffic flow. Additionally, the findings of this study can aid in the development of targeted interventions and policies aimed at reducing speed variations and creating more consistent driving conditions on the identified road links.

2. Literature Review

This chapter discusses past literature on speed limit changes, the operational benefits of VSL implementation, and the main guiding principles of VSL strategies.

2.1 Incidence of Speed Limit Changes

In the United States, most research on the impact of speed limit changes on highways has been conducted at the federal level. In 1974, the maximum speed limit was reduced to 55 mph (Albalate & Bel, 2012). This legislation was prompted by the oil crisis affecting the overall economy in the '70s (Srinivasan et al., 2006). Thirteen years later, the maximum speed limits on rural interstates were increased to 65 mph, increasing average speeds between 1 mph and 5 mph (Srinivasan et al., 2006), which constitutes a benefit from a traffic operation standpoint.

In the literature, there are studies whose conclusions are somewhat opposed. Although some research found that speed limit reductions sometimes have an insignificant effect on crash frequencies (Parker, 1997; Vernon et al., 2004; Chen et al., 2013), many others indicate that the raised speed limits contribute to an increase in total crashes (Kockelman et al., 2006; Kwayu et al., 2020; Alhomaidat et al., 2020). Contrarily, Tagar and Pulugurtha (2021a) observed a decrease in the total, non-incapacitating and possible injury, and property damage only crash frequencies at entry ramp speed-change lanes after the increase in the freeway-posted speed limit. The predictor variables influencing the merging speed change lane crash severity risk are different for cloverleaf, diamond, and other interchange types (Tagar & Pulugurtha, 2021b).

Some other studies investigated the impacts of speed limit changes in speed zones including school and work zones. The speeds of vehicles are usually considered causal factors for work zone crashes (Daniel et al., 2000). For instance, 29 people were killed in work zone crashes in 2021 in North Carolina, and overall, speeding and distracted driving account for more than 50% of all work zone crashes in the state (NCDOT, 2022).

Fixed speed limits can unnecessarily decrease operating speeds, even when not needed (for example, during off-peak school hours), resulting in lower road performance. Therefore, VSL may help regulate traffic based on real-time traffic conditions or pre-determined speed control algorithms on different road links. Besides the operational benefits, past research shows that VSL signs reduce overall speeds and, therefore, crashes (Garber & Srinivasan, 1998; Ullman & Rose, 2005; Saha et al., 2015; De Pauw et al., 2018). Particularly, Ullman and Rose (2005) and Levin et al. (2019) found that VSL is an effective countermeasure for preventing speed-related crashes and controlling congestion, especially in work zones.

2.2 Operational Benefits of VSL Implementation

Research on congestion reduction is extensive in the literature. Pulugurtha et al. (2015) found evidence of the influence of travel time and traffic speeds on upstream and downstream road links on the speed of the link between them. Pulugurtha and Pasupuleti (2010) integrated travel time (traffic speed) data from the regional travel demand model and the crash data to assess link reliability as a function of congestion components.

Only a few recent studies have utilized a data-driven approach to examine VSL or speed variations. Some examples include the studies conducted by He (2016), Silvano et al. (2020), Yasanthi and Mehran (2020), and Duvvuri et al. (2020, 2021), which are summarized in Table 1, highlighting their specific areas of focus, the data and methodology employed, and their key conclusions.

Table 1. Recent Research on Speed Variation using a Data-Driven Approach

Authors	Focus	Data and Methodology	Key Conclusions
He (2016)	To investigate if higher FFS will lead to a less congested freeway; estimate the impact of variable FFS on the performance of a freeway system	**Data**: Numerical examples based on observation of the reality **Method**: Mathematical modeling/approach based on a numerical approximation model called Cell Transmission Model	With the increasing FFS, the average delay of vehicles decreases at the beginning and then increases; the actual bottleneck capacity increases at the beginning and then decreases with the continuous increase of FFS
Silvano et al. (2020)	To estimate the FFS and the impact of speed limit changes and road characteristics on FFS distribution	**Data**: Dataset of speed observations from urban roads with different characteristics **Method**: Parametric probabilistic latent approach	Several road characteristics such as land use, on-street parking and the presence of sidewalks influence FFS; changes in posted speed limit impacts the distribution of the free flow vehicles and the speed distribution of the constrained vehicles
Yasanthi and Mehran (2020)	To investigate driver behavior in terms of variations of the desired driving speeds under adverse road-weather conditions	**Data**: Road-weather data and traffic data including traffic speeds from weigh-in-motion traffic counter **Method**: Linear and non-linear regression models	Slight, moderate, and heavy snow will respectively reduce the FFS of light vehicles travelling in the shoulder lane by 0.2%, 3.4% and 0.8%, and by 0.3%, 0.4% and 1.5% when travelling in the median lane
Duvvuri et al. (2020)	To examine the influence of historical speed patterns on the degree of speed variations during peak hours	**Data**: Traffic speeds using probe data and road characteristics **Method**: K-means clustering and forest-based classification	AADT and average speeds of upstream and downstream road segments influence the average speed of the corresponding road segment

2.3 Main Guiding Principles of VSL Strategies

Traditional traffic control strategies and management (especially of freeways) include VSL tools, whereby changes in the speed limit are conveyed to drivers by displaying the current speed limit on overhead variable message signs (Arora & Kattan, 2022).

VSL systems have three different applications, namely, congestion, weather, and work zones. A congestion-related VSL system, which is the focus of this research, relies on changeable speed limit signs, speed sensors, and communications equipment to transmit data. Different VSL strategies are used to control congestion, decrease travel times, and improve operating speed. Khondaker and Kattan (2015) provided an overview of VSL control strategies. They divided these strategies into reactive rule-based and proactive approaches.

The former control strategies were mainly formulated as simple reactive rule-based logic to harmonize speed variations and stabilize traffic flow. These strategies adjust speed limits based on pre-selected thresholds of traffic flow, occupancy, or mean speed. VSL systems developed using these strategies were found effective in reducing speed variations and improving traffic safety. Early research in the '90s by Van de Hoogen and Smulders (1994) developed an efficient VSL strategy that contributed to reductions in both crash frequency and severity. Afterward, other researchers highlighted the mobility and safety benefits of implementing rule-based VSL control strategies (Lee et al., 2003; Abdel-Aty & Dhindsa, 2006; Allaby et al., 2007). Some other researchers observed reduced travel times of vehicles traveling in work zones controlled with these VSL strategies (Park & Yadlapati, 2003; Lavansiri, 2003). However, the reactive nature of rule-based VSL control strategies is their main limitation.

Proactive VSL control strategies are more advanced since they can predict future traffic, anticipating traffic breakdowns before they occur (Khondaker & Kattan, 2015). In addition, the closed-loop feedback control used in proactive VSL strategies better controls the discrepancy between demand prediction and real demand. Most advanced VSL control strategies extended Payne's second-order METANET and integrated traffic prediction and dynamic speed limit models. The following are examples of recently developed proactive VSL control strategies. Hegyi et al. (2009) developed a VSL control strategy, called Specialist, consisting of shock wave detection, control scheme generation, resolvability assessment, and control scheme application. Carlson et al. (2010) built on Payne's second-order model by incorporating their strategy into a MATLAB simulator. Lu et al. (2010) proposed a VSL control strategy based on a speed limit tracking model to consider the transient effects of VSL. They filled in the gaps of previous research that merely considered VSL effects on steady-state speed values. Other researchers developed VSL control strategies by modifying the traffic volume-to-density diagram of the cell transmission models (Hadiuzzaman & Qiu, 2012), using the mean space speed from vehicle probes constantly moving in the network (Kattan et al., 2014) or using a microscopic traffic prediction model (Zegeye et al., 2010).

2.4 Limitations of Past Research

As stated above, although simulation-based analysis is commonly used in studies on VSL or speed variations, this approach has limitations in capturing real-world factors. While simulations offer valuable insights into traffic speed variation, their ability to fully account for real-world complexities is inherently limited.

This study uses real-world traffic speed data, enabling a more accurate and comprehensive understanding of traffic speed patterns. Incorporating such data provides valuable insights into the actual behavior of vehicles on the road, allowing for more effective planning and decision-making at the city level. Consequently, transportation strategies can be better tailored to address specific challenges and optimize traffic flow, thereby improving urban mobility and enhancing overall transportation systems.

3. Study Area and Data

This study adopts the city of Charlotte as its study area. The city of Charlotte is located within Mecklenburg County, the most populous county in North Carolina. Figure 1 illustrates the boundaries of the city of Charlotte, along with all the road links considered for this study. Each link is identified with a unique 9-digit Traffic Message Channel (TMC) code (FHWA, 2017).

The city of Charlotte is encircled by the interstate highway I-485, as shown in Figure 1. This study includes the entire loop of I-485 as well as all the links located outside the boundaries of the city but within the circumference of I-485.

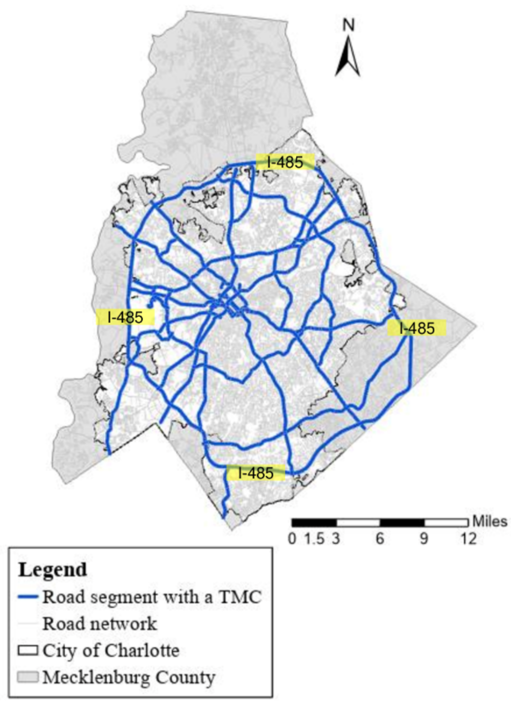


Figure 1. Study Area

An overview of the data used in this study, encompassing speed, road, and traffic characteristics at the link level, is presented in sections 3.1 to 3.3.

3.1 Traffic Speed Data

The link-level traffic speed data used in this study was obtained from the National Performance Management Research Data Set (NPMRDS) website. The data collection period is from July 2021 to June 2022. The raw traffic speed data collected for each link in this study includes a date-time stamp, recorded speeds at 5-minute intervals, and RSP. The RSP is an indicator of the FFS of the corresponding link.

As NPMRDS does not provide speed limit data, they are deduced from the road characteristics data gathered from the City of Charlotte Open Data Portal (City of Charlotte, 2022). This dataset contains the speed limits for most of the links in Mecklenburg County.

3.2 Road Characteristics

Data regarding road characteristics at the link level were obtained from shapefiles available on the NPMRDS website. These data include functional class, facility type (one-way or two-way road), link length, and the number of through lanes.

3.3 Traffic Characteristics

NPMRDS provides the annual average daily traffic (AADT) as the sole available traffic characteristic. This AADT data is obtained in a geospatial format (shapefile) and covers road links belonging to interstates, US and NC routes, secondary roads, ramps, and most non-state roads maintained in North Carolina.

4. Methodology

This chapter outlines the methodology employed for exploring traffic speed patterns with a view to implementing VSL signs. It includes the following key components.

1. Traffic speed data merging and clustering

2. Exploratory data analysis of traffic speed data

3. Bivariate analysis of traffic speed measures

4. Identifying and mapping road links susceptible to high speed variations

The analysis is divided into two phases. In the first phase, the analysis was conducted without clustering road links according to speed limits. This initial phase provided a general overview of the data and allowed for a broad understanding of the speed patterns. In the second phase, the analysis was conducted considering clusters of speed limits. This phase enabled a more detailed examination of speed patterns within those clusters.

Furthermore, the analysis considered variations across the days of the week by distinguishing between weekdays and weekends. Additionally, the analysis was conducted considering eight specific timespans (12 AM to 3 AM, 3 AM to 6 AM, 6 AM to 9 AM, 9 AM to 12 PM, 12 PM to 3 PM, 3 PM to 6 PM, 6 PM to 9 PM, 9 PM to 12 AM), allowing for a comprehensive understanding of speed patterns across time. By incorporating both temporal dimensions, the potential variations in speed behavior throughout the day and the week were captured.

4.1 Data Merging and Clustering

The data merging process involved combining the traffic speed data at the link level with all the relevant road and traffic characteristics. This merging was accomplished using the spatial join feature in ArcGIS Pro.

After the merging process, the resulting dataset was divided into different clusters based on speed limits. Five clusters were considered, categorized as follows: 25/30 mph, 35/40 mph, 45/50 mph, 55/60 mph, and 65/70 mph. This clustering facilitated a more focused analysis by grouping road links with similar speed limit ranges.

Subsequent analysis was conducted on both the entire dataset and the individual clusters. While a comprehensive understanding of the overall trends and patterns was obtained by examining the entire dataset, analyzing the clustered datasets provided insights into the specific characteristics and behaviors within each speed limit category.

4.2 Exploratory Data Analysis

Exploratory data analysis was conducted to gain insights into the main characteristics of the traffic speed data, such as central tendency, dispersion, and distribution. The analysis focused on the following summary statistics: mean, standard deviation (SD), minimum (Min), maximum (Max), 15th percentile speed (15%ile), and 85th percentile speed (85%ile).

15%ile and 85%ile speeds are commonly used measures in traffic engineering and road design. The 15%ile speed refers to the speed at or below which 15% of vehicles travel. In other words, it represents the maximum speed at which the slowest 15% of vehicles travel. The 15%ile speed is used to assess the lower end of the speed distribution and identify the slowest-moving vehicles on a given road link.

The 85%ile speed represents the speed at or below which 85% of vehicles are traveling. It indicates the maximum speed at which most (85%) of vehicles travel. The 85%ile speed is a widely used measure in determining appropriate speed limits, as it reflects the speed behavior of a large portion of drivers on a specific road link.

Both the 15%ile and 85%ile speeds are crucial in understanding the speed characteristics of traffic on a roadway. They provide insights into the relevant range of speeds and help inform decisions related to speed limit setting, road design, and traffic safety measures.

4.3 Bivariate Analysis

A bivariate analysis was conducted to assess the relationship between pairs drawn from the summary statistics mentioned in the previous section. Correlation coefficients were computed to quantify the strength and direction of the relationship between two variables.

Correlation coefficients range from -1 to 1, with values closer to -1 or 1 indicating a stronger correlation. Coefficients close to 0 indicate a weak or insignificant correlation. For the purposes of this study, strong correlations are indicated by coefficient values greater than 0.5 or lower than -0.5. A positive correlation coefficient greater than 0.5 suggests a strong positive relationship, implying that as one summary statistic increases, the other also tends to increase to a significant degree. On the other hand, a negative correlation coefficient lower than -0.5 indicates a strong negative relationship, implying that as one summary statistic increases, the other tends to decrease to a significant degree.

4.4 Identifying Road Links Suitable for the Implementation of VSL Signs

The primary objective of this task was to identify road links that consistently exhibit high or very high variations in traffic speed throughout the study period. To assess the level of speed variation, the difference between the average speed (referred to as the mean) and the speed limit was calculated.

In this study, the levels of speed variation were categorized into four distinct groups:

- **Low speed variation**: This category includes road links where the speed variation falls between 0 and 5 mph. Road links in this range exhibit relatively small deviations from the speed limit.

- **Moderate speed variation**: Road links with speed variations ranging from > 5 mph to ≤ 10 mph fall into this category. These links experience moderate fluctuations in speed compared to the speed limit.

- **High speed variation**: Road links with speed variations between > 10 mph and ≤ 15 mph are classified as having high speed variation. These links demonstrate significant deviations from the speed limit.

- **Very high speed variation**: This category encompasses road links with speed variations exceeding 15 mph. These links exhibit substantial variations from the speed limit, indicating a considerable level of speed fluctuation.

To visualize and analyze the speed variation patterns, maps were generated for the five clusters of road links. These maps provide an overview of speed variations during weekdays and weekends, covering eight specific timespans. By examining the maps for each cluster at different time periods, insights can be gained regarding the consistency and magnitude of speed variations across different days and times.

Lastly, for illustration purposes, the study explored fitting five candidate distributions to the traffic speeds of a road link exhibiting high speed variations. Through the analysis of different distribution models, valuable insights were obtained, aiding in selecting the distribution that most effectively captures the observed speed patterns. This comprehensive understanding enables improved management of traffic flow on similar road links, thereby facilitating enhanced traffic control and optimization strategies.

5. Exploratory Analysis of Traffic Speed Data

This chapter focuses on exploratory data analysis of traffic speeds in Charlotte. The data used for the exploratory data analysis is summarized in Table 2.

Table 2. Data Summary

Variable	Attribute	#	%
Roadway category			
Functional class	1: Interstate	307	37.81
	2: Other freeway/expressway	28	3.45
	3: Other principal arterial	409	**50.37**
	4: Minor arterial	48	5.91
	5: Major collector	7	0.86
	6: Minor collector	8	0.99
	7: Local	5	0.62
Facility type	1: One-way roadway	14	1.72
	2: Two-way roadway	798	**98.28**
Roadway geometry			
Length	1: <= 0.5 mile	397	**48.89**
	2: > 0.5 mile & <= 1 mile	229	28.20
	3: > 1 mile & <= 1.5 miles	112	13.79
	4: > 1.5 miles & <= 2 miles	48	5.91
	5: > 2 miles	36	4.43
# of through lanes	1	47	5.79
	2	429	**52.83**
	3	195	24.01
	4	124	15.27
	5	13	1.60
	6	4	0.49
Traffic-related			
AADT	1: <= 17,500	332	**40.89**
	2: > 17,500 & <= 35,000	187	23.03
	3: > 35,000 & <= 52,500	121	14.90
	4: > 52,500 & <= 70,000	101	12.44
	5: > 70,000	71	8.74
Speed-related			
Speed limit	1: 25 mph & 30 mph	78	9.61
	2: 35 mph & 40 mph	372	**45.81**
	3: 45 mph & 50 mph	154	18.97
	4: 55 mph & 60 mph	112	13.79
	5: 65 mph & 70 mph	96	11.82
Reference speed	1: <= 30 mph	5	0.62
	2: > 30 mph & <= 40 mph	24	2.96
	3: > 40 mph & <= 50 mph	213	**26.23**
	4: > 50 mph & <= 60 mph	194	23.89
	5: > 60 mph & <= 70 mph	204	25.12
	6: > 70 mph	169	20.81

Values in bold in Table 2 indicate the highest data share within sets of variable attributes. Regarding the categories of road links, 50.37% belong to the "Other principal arterials" road functional class, and 98.28% of all road links are two-way roadways. In terms of length, 48.89% of the data consists of road links that are at most 0.5 miles long, while 52.83% have two through lanes. The AADT of 40.89% of the road links is less than or equal to 17,500 vehicles per day. Moreover, 45.81% of the road links have speed limits of 35 or 40 mph. The RSP for 25.12% of the road links is between 60 and 70 mph.

5.1 Variation of Traffic Speeds across Months and Times of the Day

Figure 2 shows the variation of the mean speed for all road links across months and times of the day for both weekdays and weekends. Figure 2b highlights a higher frequency of mean speed variations during weekends than weekdays, particularly between 6 AM and 9 PM from September to April. Overall, for corresponding times of the day, the mean speeds are consistently higher by one increment (5 mph) on weekends compared to weekdays.

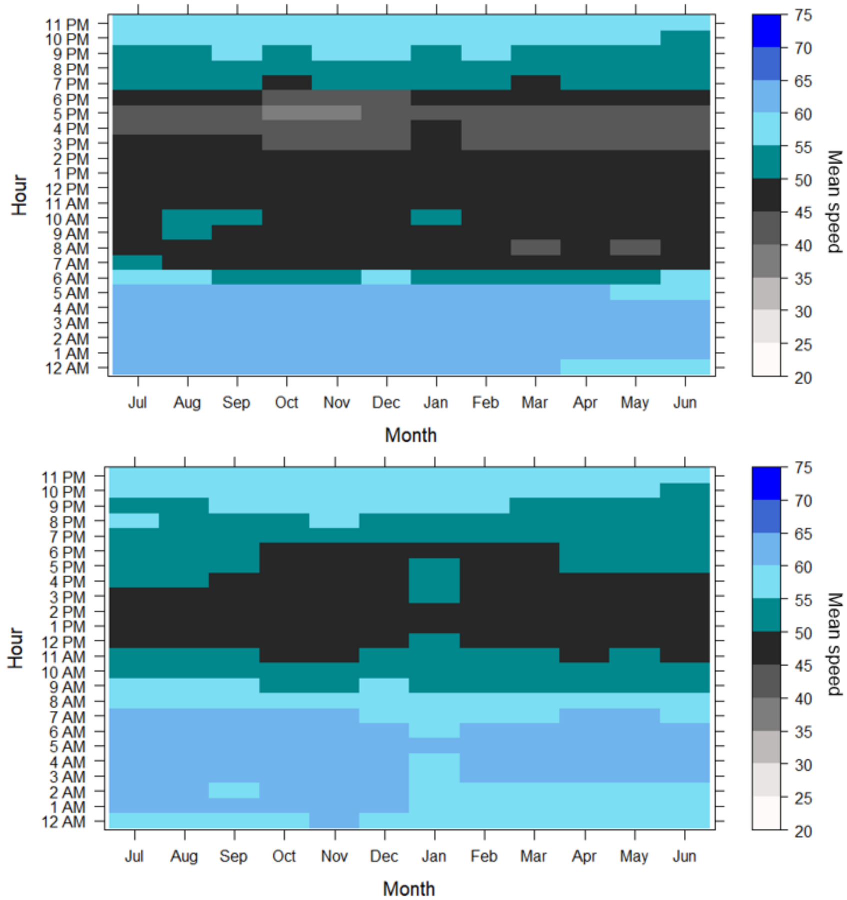
Similar to Figure 2, Figure 3 displays the variation of SDs for all road links across months and times of the day, considering both weekdays and weekends. The observations regarding the variations of SDs during weekdays and weekends align with those made in Figure 2 with respect to mean speed.

5.2 Exploratory Data Analysis of Traffic Speeds

Table 3 presents the summary statistical measures of traffic speeds, as outlined in Section 4.2. These statistics include the Mean, SD, Min, Max, 15%ile, and 85%ile for both weekdays and weekends across different times of the day. These measures are provided for all road links regardless of differences in the RSPs or speed limits of these road links.

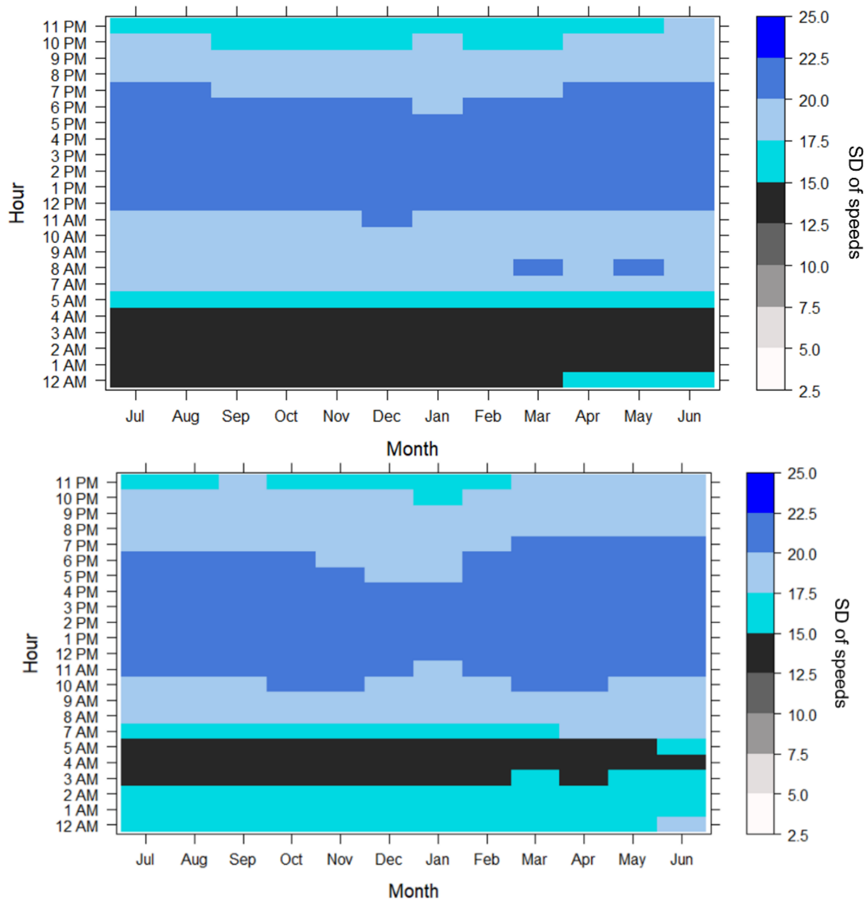
Table 3 shows that the lowest mean speeds were recorded from 3 PM to 6 PM and 12 PM to 3 PM for weekdays and weekends, respectively, measuring 39.6 mph and 47.3 mph. These speeds are associated with the highest SDs. Additionally, the lowest speeds (Min) were found to be for the same times of the day.

The 85%ile speeds across the different times of the day are quite uniform, particularly during weekends, ranging from 71 mph to 74 mph. The maximum speed of 99 mph was recorded from 3 PM to 6 PM and 12 AM to 3 AM for weekdays and weekends, respectively.



(a) Weekday (b) Weekend

Figure 2. Variation of the Mean Speed across Months and Times of the Day



(a) Weekday (b) Weekend

Figure 3. Variation of the Standard Deviation across Months and Times of the Day

Table 3. Summary Statistics of Traffic Speeds (mph)

Time of the day	Mean	SD	Min	Max	15%ile	85%ile
Weekday						
12 AM - 3 AM	63.2	8.6	30	90	55	71
3 AM - 6 AM	63.6	9.6	31	88	53	73
6 AM - 9 AM	48.0	17.9	13	93	26	69
9 AM - 12 PM	48.1	18.0	12	85	26	69
12 PM - 3 PM	44.7	19.1	9	90	22	68
3 PM - 6 PM	39.6	19.4	3	99	18	65
6 PM - 9 PM	48.0	18.2	12	89	26	69
9 PM - 12 AM	57.8	14.2	19	85	40	71
Weekend						
12 AM - 3 AM	61.4	11.8	24	99	48	72
3 AM - 6 AM	64.4	9.1	33	88	55	73
6 AM - 9 AM	60.9	14.1	23	84	43	74
9 AM - 12 PM	52.3	18.4	14	87	29	72
12 PM - 3 PM	47.3	19.7	9	93	24	71
3 PM - 6 PM	48.1	19.4	10	93	25	71
6 PM - 9 PM	52.0	17.9	14	86	30	71
9 PM - 12 AM	58.2	14.7	17	86	39	72

5.3 Exploratory Data Analysis of Traffic Speeds by Speed Limit Clusters

Tables 4-8 present the summary statistics of traffic speeds by speed limit clusters.

Table 4. Summary Statistics of Traffic Speeds (mph) for 25/30 mph Speed Limit Road Links

Speed limit cluster	Time of the day	Mean	SD	Min	Max	15%ile	85%ile
25/30 mph	Weekday						
	12 AM - 3 AM	51.7	9.6	30	66	40	62
	3 AM - 6 AM	50.8	9.3	31	64	39	61
	6 AM - 9 AM	36.0	11.9	14	57	23	51
	9 AM - 12 PM	36.4	13.0	13	59	22	53
	12 PM - 3 PM	32.8	13.0	10	57	19	50
	3 PM - 6 PM	29.6	11.7	9	53	17	44
	6 PM - 9 PM	35.8	12.1	14	58	22	51
	9 PM - 12 AM	42.8	12.2	19	62	28	57
	Weekend						
	12 AM - 3 AM	47.1	11.5	24	64.5	33	60
	3 AM - 6 AM	52.2	8.6	33	65	42	62
	6 AM - 9 AM	46.6	12.3	23	66	32	61
	9 AM - 12 PM	39.2	13.3	15	62	24	57
	12 PM - 3 PM	35.1	13.0	12	59	21	52
	3 PM - 6 PM	35.3	12.9	12	59	21	52
	6 PM - 9 PM	38.0	12.8	14	60	24	54
	9 PM - 12 AM	42.7	13.0	17	63	27	58

Table 5. Summary Statistics of Traffic Speeds (mph) for 35/40 mph Speed Limit Road Links

Speed limit cluster	Time of the day	Mean	SD	Min	Max	15%ile	85%ile
	Weekday						
35/40 mph	12 AM - 3 AM	60.4	7.4	43	71	51	68
	3 AM - 6 AM	59.9	9.3	39	73	48	70
	6 AM - 9 AM	39.4	14.2	14	64	23	57
	9 AM - 12 PM	39.0	14.9	12	65	22	58
	12 PM - 3 PM	35.2	14.8	9	63	19	55
	3 PM - 6 PM	30.2	13.1	7	57	16	46
	6 PM - 9 PM	39.3	15.2	12	66	22	59
	9 PM - 12 AM	51.5	13.8	24	71	34	67
	Weekend						
	12 AM - 3 AM	57.3	11.5	32	73	42	70
	3 AM - 6 AM	61.2	8.5	42	73	51	70
	6 AM - 9 AM	54.7	13.9	27	74	37	70
	9 AM - 12 PM	43.1	16.1	14	70	25	63
	12 PM - 3 PM	37.1	15.7	9	66	20	58
	3 PM - 6 PM	38.3	15.7	10	67	21	58
	6 PM - 9 PM	43.1	15.5	15	69	25	62
	9 PM - 12 AM	51.9	14.4	23	72	34	68

Table 6. Summary Statistics of Traffic Speeds (mph) for 45/50 mph Speed Limit Road Links

Speed limit cluster	Time of the day	Mean	SD	Min	Max	15%ile	85%ile
	Weekday						
45/50 mph	12 AM - 3 AM	61.2	9.6	39	75	48	71
	3 AM - 6 AM	61.0	10.3	39	75	47	72
	6 AM - 9 AM	44.8	18.0	13	74	25	69
	9 AM - 12 PM	45.3	17.9	13	74	26	69
	12 PM - 3 PM	42.0	18.9	9	74	22	68
	3 PM - 6 PM	35.7	17.7	5	70	18	61
	6 PM - 9 PM	42.8	16.6	14	71	25	65
	9 PM - 12 AM	55.9	15.0	26	77	37	72
	Weekend						
	12 AM - 3 AM	59.4	12.6	33	77	43	72
	3 AM - 6 AM	62.2	10.0	40	76	49	73
	6 AM - 9 AM	58.8	15.6	27	80	39	75
	9 AM - 12 PM	50.8	19.2	15	80	29	74
	12 PM - 3 PM	46.0	20.2	10	78	24	73
	3 PM - 6 PM	46.8	19.8	11	78	25	73
	6 PM - 9 PM	50.3	18.8	15	79	29	73
	9 PM - 12 AM	56.4	15.7	25	78	37	73

Table 7. Summary Statistics of Traffic Speeds (mph) for 55/60 mph Speed Limit Road Links

Speed limit cluster	Time of the day	Mean	SD	Min	Max	15%ile	85%ile
	Weekday						
55/60 mph	12 AM - 3 AM	63.9	6.4	46	81	58	70
	3 AM - 6 AM	64.4	5.9	49	79	58	71
	6 AM - 9 AM	55.1	13.5	18	93	39	67
	9 AM - 12 PM	58.8	9.4	31	85	49	67
	12 PM - 3 PM	55.3	12.8	20	90	40	67
	3 PM - 6 PM	47.8	17.6	3	99	26	65
	6 PM - 9 PM	58.5	11.1	27	89	46	68
	9 PM - 12 AM	63.1	7.0	43	81	56	70
	Weekend						
	12 AM - 3 AM	64.3	7.0	45	83	58	71
	3 AM - 6 AM	65.2	7.0	46	84	58	72
	6 AM - 9 AM	65.8	7.0	46	84	59	73
	9 AM - 12 PM	62.7	8.8	36	87	54	71
	12 PM - 3 PM	58.1	12.4	23	93	44	69
	3 PM - 6 PM	58.1	12.4	23	93	44	69
	6 PM - 9 PM	61.5	9.1	35	86	52	70
	9 PM - 12 AM	63.6	6.9	44	82	57	70

Table 8. Summary Statistics of Traffic Speeds (mph) for 65/70 mph Speed Limit Road Links

Speed limit cluster	Time of the day	Mean	SD	Min	Max	15%ile	85%ile
	Weekday						
65/70 mph	12 AM - 3 AM	69.2	7.0	47	90	63	76
	3 AM - 6 AM	71.2	6.2	53	88	64	77
	6 AM - 9 AM	70.2	5.5	52	87	65	75
	9 AM - 12 PM	70.1	4.9	54	84	65	75
	12 PM - 3 PM	70.0	4.9	54	84	65	75
	3 PM - 6 PM	68.0	7.0	43	89	62	74
	6 PM - 9 PM	70.6	5.7	52	87	65	76
	9 PM - 12 AM	70.8	5.6	55	85	65	76
	Weekend						
	12 AM - 3 AM	69.8	8.6	31	99	63	77
	3 AM - 6 AM	71.1	6.3	53	88	64	77
	6 AM - 9 AM	73.5	4.5	62	84	69	78
	9 AM - 12 PM	72.7	4.6	58	85	68	77
	12 PM - 3 PM	72.0	4.7	56	86	67	76
	3 PM - 6 PM	72.3	4.6	58	85	68	77
	6 PM - 9 PM	72.0	5.1	56	86	67	77
	9 PM - 12 AM	71.6	5.3	56	86	66	77

Mean, SD, Min, Max, 15%ile, and 85%ile are commensurate with the speed limit clusters. From Table 4, the mean speeds consistently exceed the 25/30 mph speed limit throughout the day. Furthermore, the 85%ile speeds are much higher, indicating that drivers on 25/30-mph speed limit roads tend to drive at speeds twice as high as the posted speed limit. Safety considerations, rather than traffic operation considerations, may have been the primary factors influencing the determination of the speed limits on these roads. Moreover, no statistical differences were observed in these traffic speed measures between weekdays and weekends.

The mean speeds for roads with speed limits of 35/40 mph, 45/50 mph, 55/60 mph, and 65/70 mph in Tables 5–8 are relatively close to the posted speed limits. However, the 85%ile speeds are higher than the speed limits on these roads. This indicates that many drivers exceed the speed limits, suggesting a need for additional enforcement or speed management measures to align these drivers with the intended speed limits. Also, this observation suggests that speed limits should be increased for certain road links to better accommodate drivers, albeit on the condition that their safety is maintained.

While the mean speeds generally align closely with the speed limits, certain road links display significant deviations in their mean speeds. These deviations, whether exceptionally low or exceptionally high, can go unnoticed when examining the aggregated mean speeds presented in Tables 5–8.

The variations in mean speeds on specific road links can provide valuable insights into the effectiveness of current speed limits. If certain road links consistently exhibit significantly low mean speeds, it could indicate potential issues such as congestion, road conditions, or other factors impeding traffic flow. Conversely, road links with consistently high mean speeds might signal a need for stricter enforcement or speed management measures to ensure the safety of road users.

It is crucial to consider and analyze individual road links separately to understand their speed patterns and identify any areas where the existing speed limits might require adjustments. By examining the data at an increasingly granular level, transportation authorities can make better-informed decisions regarding speed limit modifications or targeted interventions to address specific road links that deviate significantly from the aggregated mean speeds.

6. Bivariate Analysis of Traffic Speed Measures

The bivariate analysis consisted of pairwise correlations of traffic speed measures, including Mean, SD, 15%ile, 85%ile, RSP, and a speed limit referred to as SPL in the following figure. The bivariate analysis was conducted with and without considering clusters of road links based on their speed limits.

6.1 Bivariate Analysis of Traffic Speed Measures

Figure 4 displays the correlation coefficients of the six traffic speed measures for weekdays and different times of the day.

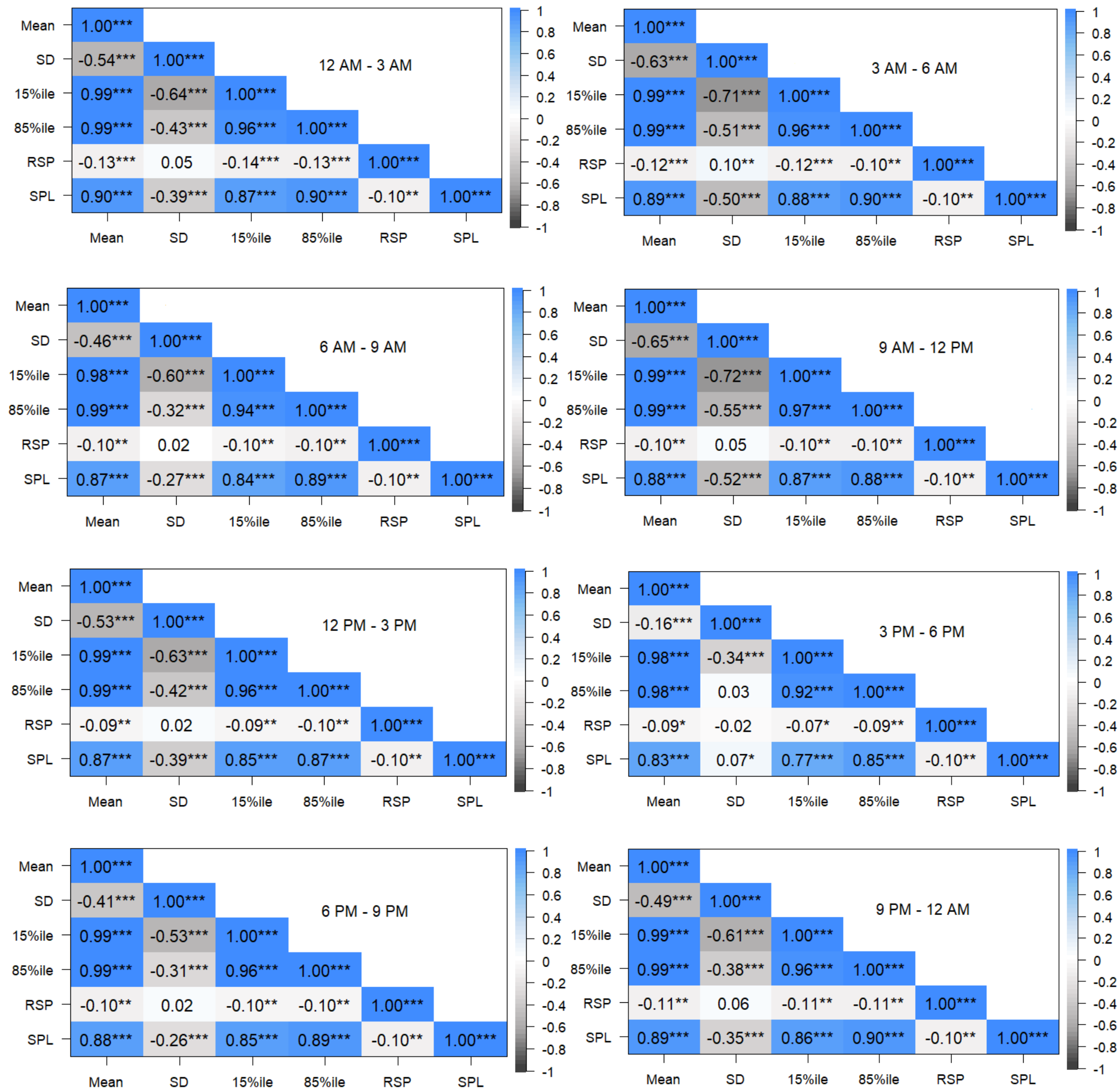


Figure 4. Correlations of Traffic Speed Measures for Weekdays

Note: *, **, and *** indicate that the corresponding coefficients are significant at 95%, 99%, and 99.9% confidence levels, respectively.

The bivariate analysis for weekends exhibits similarities to weekdays in terms of correlation coefficients and statistical significance levels. Figure 4 can be extended to include weekends on this basis. Also, Figure 4 shows that correlation coefficients and their statistical significance levels are quite similar all throughout the day.

The analysis reveals significant correlations between the mean speeds and several other factors. A strong correlation exists between the mean speed and the 15%tile speed, indicating a relationship between the overall mean speed and the lower end of the speed distribution. Similarly, a strong correlation exists between the mean speed and the 85%tile speed, indicating a relationship between the mean speed and the upper end of the speed distribution. Additionally, a strong correlation is observed between the mean speed and the speed limit, suggesting that the imposed speed restrictions influence the mean speed. These findings highlight the importance of considering these factors when assessing and analyzing traffic patterns and speed-related dynamics.

A weak correlation was observed between the mean speed and the SD of speeds. This suggests that the mean speed has a limited influence on the variation or dispersion of speeds within the traffic flow. Furthermore, a weak correlation was observed between the mean speed and RSP. This implies that the mean speed does not strongly dictate the speed at which traffic flows under uncongested conditions. In fact, a weak correlation was observed between the SD of speeds and any other traffic speed measure. This suggests that the variation in speeds within the traffic flow does not strongly correspond to other measured speed parameters.

It is important to note that this first bivariate analysis draws on a heterogeneous traffic speed dataset that does not differentiate road links based on their characteristics. This lack of distinction introduces potential limitations in interpreting the correlation coefficients and their corresponding statistical significance levels.

For instance, the analysis combines data from road links with varying speed limits, ranging from very low speed to very high speed. As a result, the correlations observed may be influenced by the inherent characteristics of the road links rather than solely reflecting the relationships between the traffic speed measures.

6.2 Bivariate Analysis of Traffic Speed Measures by Speed Limit Clusters

Table 9 presents the correlation coefficients between traffic speed measures for weekdays from 12 PM to 3 PM. These correlation coefficients provide insights into the relationships between different speed measures and the speed limits assigned to particular clusters.

After computing the correlations for different days of the week and times of the day, it was observed that the levels or magnitudes of the correlations and their significance are generally consistent across weekdays and weekends, regardless of the time of day. This suggests that the relationship between traffic speed measures and speed limit clusters remains relatively stable throughout the different days of the week, including weekends.

Table 9. Correlations between Traffic Speed Measures for Weekdays (12 PM to 3 PM)

Measure 1	Measure 2	Speed limit cluster (mph)				
		25/30	35/40	45/50	55/60	65/70
Mean	SD	-0.24*	-0.11*	-0.64***	-0.40***	-0.13
Mean	15%ile	0.99***	0.98***	0.99***	0.97***	0.95***
Mean	85%ile	0.98***	0.98***	0.99***	0.98***	0.96***
Mean	RSP	0.69***	0.87***	0.83***	0.82***	0.78***
Mean	SPL	-0.06	-0.08	0.17*	0.21*	0.17
SD	15%ile	-0.37***	-0.27	-0.73***	-0.58***	-0.41***
SD	85%ile	-0.08	0.06	-0.54***	-0.20*	0.15
SD	RSP	-0.10	0.02	-0.50***	-0.07	-0.17
SD	SPL	0.16	-0.05	-0.11	-0.28***	0.05
15%ile	85%ile	0.95***	0.93***	0.97***	0.91***	0.83***
15%ile	RSP	0.68***	0.83***	0.82***	0.74***	0.75***
15%ile	SPL	-0.07	-0.07	0.16*	0.25**	0.14
85%ile	RSP	0.68***	0.86***	0.83***	0.86***	0.75***
85%ile	SPL	-0.07	-0.09	0.16*	0.17	0.19
RSP	SPL	-0.07	-0.03	0.17*	-0.03	0.28***

≥ 0.5 > 0 & <0.5
≤ - 0.5 > -0.5 & <0

Note: *, **, and *** indicate that the corresponding coefficients are significant at the 95%, 99%, and 99.9% confidence levels, respectively.

Significant correlations were observed between each of the mean, 15%ileand 85%ile speeds, and the RSP, regardless of the speed limit cluster. These correlations indicate a robust relationship among these traffic speed measures and are statistically significant, confirming their reliability. When the mean speed is high, both the 15%ile and the 85%ile speeds are likely to be high as well. This indicates a general trend for speeds to align and vary together within a given speed limit cluster.

Road links subject to a 45/50 mph speed limit display a distinct pattern when compared to the road links that fall within the other speed limit clusters. Specifically, these road links demonstrate a notable finding: the SDs of speeds exhibit strong statistical correlations with the mean speed, the 15%ile speed, the 85%ile speed, and the RSP. However, what sets these correlations apart is the fact that they are negative, rather than positive.

Strong negative correlations between the SDs of speeds and the mean speed, 15%ile speed, 85%ile speed, and RSP indicate an inverse relationship between these variables on road links with a 45/50 mph speed limit. This means that as the SD of speeds increases, the mean speed, speeds at the lower 15%ile and the higher 85%ile points, and the RSP tend to decrease. Conversely, these speed measures tend to increase when the SD of speeds decreases.

Understanding the implications of these negative correlations can offer valuable insights for traffic management and road safety. The strong negative correlation between the SD of speeds and the mean speed suggests that road links with higher speed variations tend to have lower mean speeds. This indicates a potential discrepancy in driving behaviors and a higher likelihood of speed fluctuations within this speed limit cluster.

Additionally, the negative correlations between the SDs of speeds and the 15%ile and 85%ile speeds and the RSP can provide useful information about the speed distribution within the 45/50 mph speed limit cluster. These correlations suggest that as the variation in speeds increases, the speeds at the lower and higher percentiles and the RSP tend to decrease. This insight can help identify areas where speed management interventions may be necessary to address the speed distribution and potential risks associated with this speed limit cluster.

7. Identifying Road Links Suitable for the Implementation of VSL Signs

7.1 Identifying Road Links with High Speed Variations

A specific category of speed variation is assigned to each road link based on the difference between its speed limit and its mean speed at different times of the day and days of the week. Section 4.4 explained how different groups of speed variation were categorized.

Figure 5 presents road link maps exhibiting various speed variations during weekdays from 9 AM to 12 PM, divided according to speed limit clusters. A negative speed variation indicates that the mean speed falls below the specified speed limit.

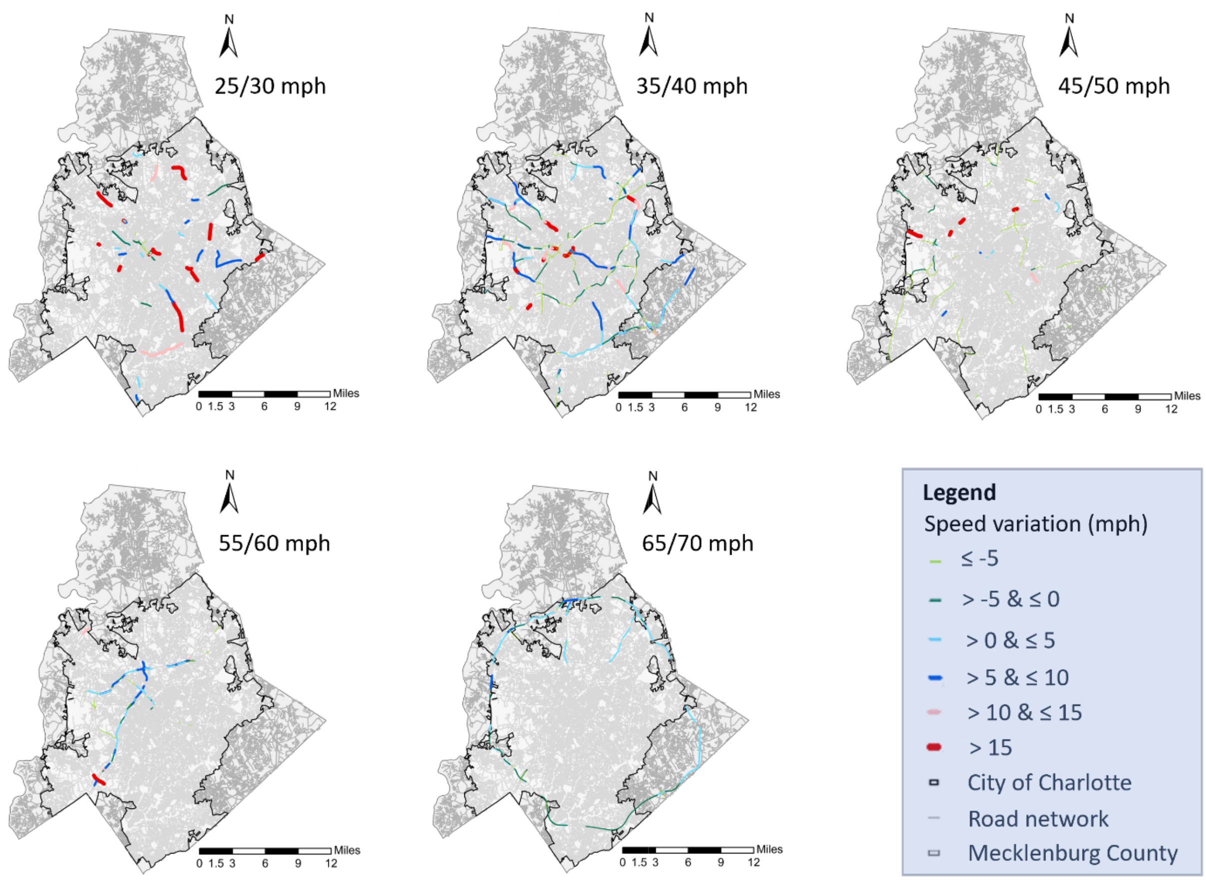


Figure 5. Speed Variations for Weekdays between 9 AM and 12 PM

This section examines road links that display significant variations in speed, specifically those categorized as high and very high speed variations. High speed variations refer to speed fluctuations exceeding 10 mph and up to 15 mph, while very high speed variations encompass fluctuations exceeding 15 mph.

In this study, an important assumption asserts that road links, particularly freeway sections, exhibiting consistently high or very high speed variations are prime candidates for VSL implementation. Table 10 showcases road links within the 65/70 mph speed limit cluster. These road links are of particular interest as they represent crucial sections of freeways that require careful analysis and potential consideration for VSL implementation.

Table 10. 65/70 mph Speed Limit Road Links of High Speed Variations

Time of the day	TMC code
	Weekday
12 AM - 3 AM	N/A
3 AM - 6 AM	125N10200
6 AM - 9 AM	125N16944
9 AM - 12 PM	N/A
12 PM - 3 PM	N/A
3 PM - 6 PM	N/A
6 PM - 9 PM	N/A
9 PM - 12 AM	N/A
	Weekend
12 AM - 3 AM	N/A
3 AM - 6 AM	N/A
6 AM - 9 AM	125N10200, 125N16944
9 AM - 12 PM	125P10200, 125N16944
12 PM - 3 PM	125N10200, 125P10200, 125N16944
3 PM - 6 PM	125N10200, 125P10200, 125N16944
6 PM - 9 PM	125N10200, 125N16944
9 PM - 12 AM	N/A

Note: N/A indicates the absence of any road link exhibiting high speed variation.

The analysis of road links with high speed variations aims to identify sections of the road network where drivers experience notable changes in speed. These variations can be attributed to many factors, such as traffic congestion, road design, intersections, or other localized conditions. By pinpointing these areas, transportation authorities and urban planners can gain insights into the factors contributing to speed fluctuations and devise strategies to improve traffic flow, enhance road safety, and optimize overall transportation efficiency.

Moreover, the examination extends to road links with very high speed variations, which exhibit even more pronounced changes in speed. Such variations often indicate the presence of critical bottlenecks, hazardous conditions, or other factors that significantly impact traffic. Identifying road links with very high speed variations is crucial for targeted interventions and engineering solutions to mitigate potential risks and enhance the overall quality of road infrastructure.

7.2 Fitting Candidate Distributions to Traffic Speeds

This section applies five candidate distributions to the traffic speeds of a road link with high speed variations. By analyzing different distribution models, valuable insights are gained on selecting the most appropriate distribution that accurately represents the observed speed patterns, facilitating better understanding and management of traffic flow on such road links.

Figure 6 exhibits the skewness-kurtosis graph, generated using the "fitdistrplus" package (Delignette-Muller & Dutang, 2015) in the R programming language for the speeds observed on road link 125N10200 (I-485 S/I-85 Exit 10) during the weekend interval of 3 PM to 6 PM. A nonparametric bootstrap procedure was implemented to address the uncertainty surrounding the estimated values of kurtosis and skewness derived from the computed speeds. The procedure involved computing skewness and kurtosis on 1,000 bootstrap samples, with the resulting values presented on the skewness-kurtosis plot as depicted in Figure 6.

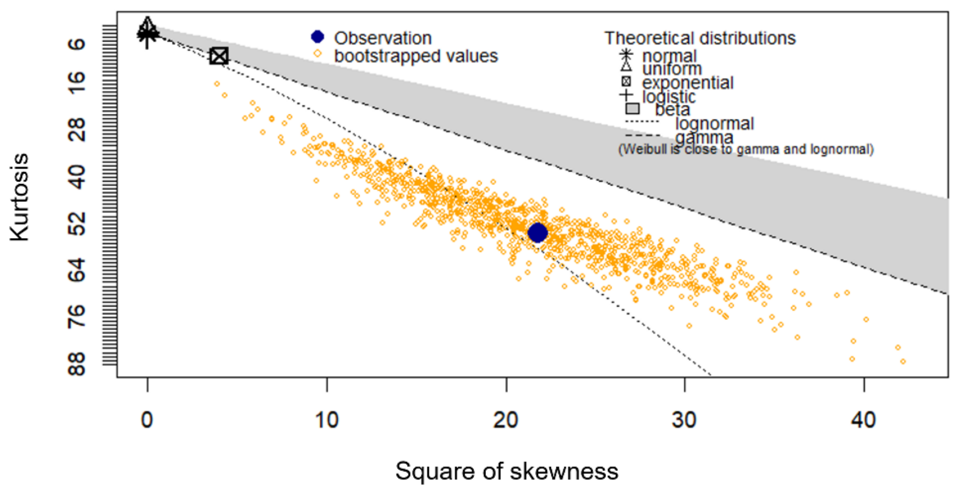
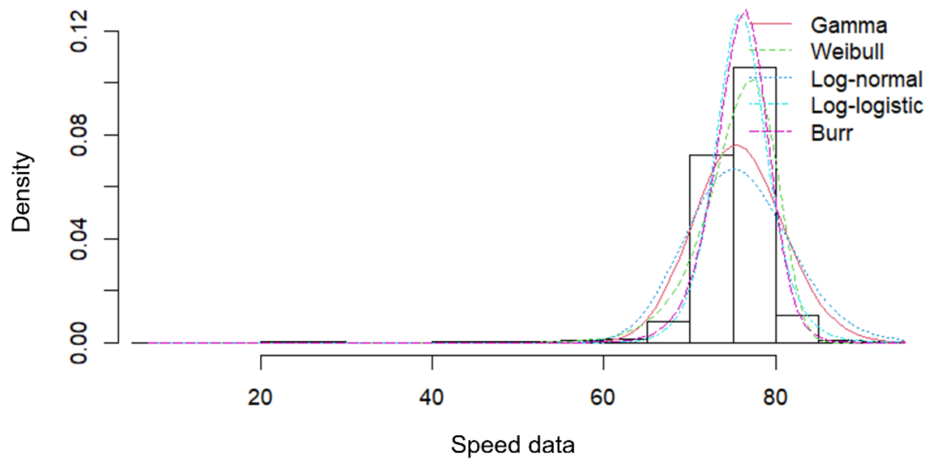
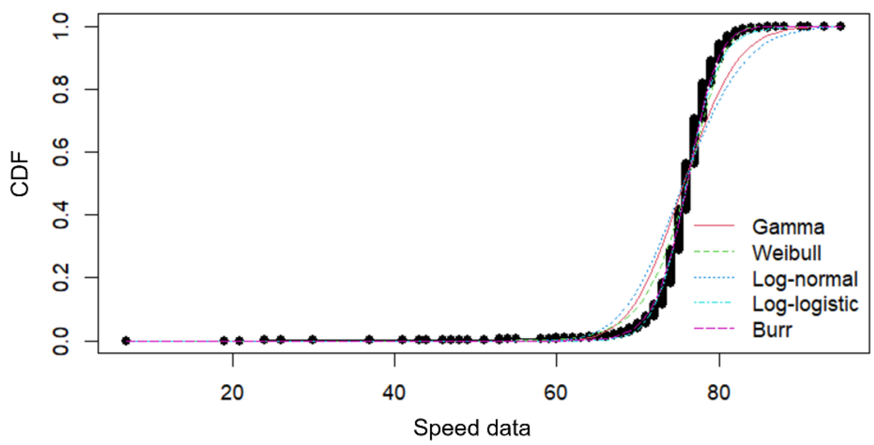


Figure 6. Skewness-Kurtosis Plot for Traffic Speeds on the Road Link "125N10200" during the Weekend Time Interval of 3 PM to 6 PM

The related goodness-of-fit plots, i.e., the density plot and the cumulative distribution function (CDF), are presented in Figures 7(a) and 7(b), respectively.



(a) Histogram and theoretical densities



(b) Empirical and theoretical CDF

Figure 7. Goodness-of-fit Plots of the Candidate Distributions Fitted to the Weekend Time Interval (3 PM to 6 PM) Traffic Speeds on the Road Link "125N10200"

Table 11 presents the goodness-of-fit results of the five candidate distributions. The Kolmogorov-Smirnov and Cramer-von Mises goodness-of-fit statistics, Akaike's Information Criterion, and the Bayesian Information Criterion were used in this study. The goodness-of-fit statistics measure the distance between the fitted parametric and the empirical distributions. Therefore, the lower the parameter listed in Table 11, the better the distribution's fit. Taking the outputs of the goodness-of-fit statistics into account, the Burr distribution is the best-fitted distribution of the case study.

Table 11. Comparison of Goodness-of-fit Results of the Weekend Time Interval (3 PM to 6 PM) Traffic Speeds on the Road Link "125N10200"

Good-of-fit statistic	Gamma	Weibull	Log-normal	Log-logistic	Burr
Kolmogorov-Smirnov statistic	0.20	0.14	0.22	0.09	0.09
Cramer-von Mises statistic	40.86	17.09	55.17	5.81	5.20
Good-of-fit criteria	Gamma	Weibull	Log-normal	Log-logistic	Burr
AIC	22756.19	20477.35	23731.25	20176.99	19938.96
BIC	22768.62	20489.78	23743.68	20189.42	19957.61

8. Conclusions

This study is aimed at identifying road links in Charlotte, North Carolina suitable for implementing VSL signs. Traffic speed data collected at the link level over a period spanning from July 2021 to June 2022 were used. The objective was to analyze the data and pinpoint specific road links, especially freeways, that exhibit characteristics conducive to installing VSL signs.

The study's methodology for exploring traffic speed patterns to guide VSL sign implementation involves data preprocessing, exploratory data analysis, bivariate analysis, identification of suitable road links, and a case study that showcases the selection of the right traffic speed distribution for a road link that exhibited high speed variation. The analysis was divided into two phases: an initial phase providing a general overview of the data and a second phase focusing on speed limit clusters. The analysis also distinguished between weekdays and weekends, as well as specific timespans (12 AM to 3 AM, 3 AM to 6 AM, 6 AM to 9 AM, 9 AM to 12 PM, 12 PM to 3 PM, 3 PM to 6 PM, 6 PM to 9 PM, 9 PM to 12 AM) to capture variations in speed patterns.

The speed patterns for roads with speed limits of 25/30 mph consistently exceed the posted limits, with the 85th percentile speeds being twice as high. This suggests that the assignment of these speed limits to these roads was motivated by safety concerns. There were no differences in speed measures between weekdays and weekends. For roads with speed limits of 35/40 mph and higher, mean speeds are close to the limits, but the 85th percentile speeds exceed them.

The mean, 15th percentile, 85th percentile, and RSP are significantly correlated regardless of speed limit cluster. Higher mean speeds are associated with higher 15th and 85th percentile speeds, suggesting a general trend of speeds aligning and varying within a given speed limit cluster.

Road links with a 45/50 mph speed limit exhibited a distinct pattern compared to the road links that belong to the other clusters. The SDs of speeds in these road links show strong negative correlations with the mean speed, 15th percentile speed, 85th percentile speed, and RSP. This negative correlation implies that as the SD of speeds increases, the mean speed, lower percentile speeds, higher percentile speeds, and RSP tend to decrease. Conversely, a decrease in the SD of speeds is associated with an increase in these speed measures.

The negative correlations between the SDs of speeds and the mean speed, 15th percentile speed, 85th percentile speed, and RSP provide valuable insights for traffic management and road safety. Higher variations in speeds in road links with a 45/50 mph speed limit indicate lower mean speeds and a higher likelihood of speed fluctuations within this speed limit cluster. Furthermore, the negative correlations suggest that increasing speed variations are associated with lower speeds at the lower and higher percentiles and the RSP. This information can help identify areas that require speed management interventions to address the speed distribution and potential risks associated with this specific speed limit cluster.

In conclusion, this study examined road links and their speed variations. Additionally, an illustrative example was presented, highlighting the significance of selecting the appropriate traffic speed distribution for a road link with significant speed variation. This example demonstrated the practical implications of considering speed patterns and variations in implementing VSL signs. The study's findings contribute to understanding traffic speed patterns and provide valuable insights for transportation planning and management.

Abbreviations and Acronyms

15%ile	15th Percentile
85%ile	85th Percentile
AADT	Annual Average Daily Traffic
CDF	Cumulative Distribution Function
FFS	Free-Flow Speed
GIS	Geographic Information System
ITS	Intelligent Transportation System
Max	Maximum
Min	Minimum
NPMRDS	National Performance Management Research Data Set
RSP	Reference Speed
SD	Standard Deviation
SPL	Speed Limit
TMC	Traffic Message Chanel
VSL	Variable Speed Limit

Bibliography

Abdel-Aty, M., Dilmore, J., & Dhindsa, A. (2006). Evaluation of variable speed limits for real-time freeway safety improvement. *Accident Analysis & Prevention*, *38*(2), 335–345.

Albalate, D., & Bel, G. (2012). Speed limit laws in America: The role of geography, mobility and ideology. *Transportation Research Part A: Policy and Practice*, *46*(2), 337–347.

Alhomaidat, F., Kwigizile, V., Oh, J. S., & Van Houten, R. (2020). How does an increased freeway speed limit influence the frequency of crashes on adjacent roads? *Accident Analysis & Prevention, 136*, 105433.

Allaby, P., Hellinga, B., & Bullock, M. (2007). Variable speed limits: Safety and operational impacts of a candidate control strategy for freeway applications. *IEEE Transactions on Intelligent Transportation Systems*, *8*(4), 671–680.

Arora, K., & Kattan, L. (2022). Operational and safety impacts of integrated variable speed limit with dynamic hard shoulder running. *Journal of Intelligent Transportation Systems*, 1–30.

Carlson, R. C., Papamichail, I., Papageorgiou, M., & Messmer, A. (2010). Optimal mainstream traffic flow control of large-scale motorway networks. *Transportation Research Part C: Emerging Technologies, 18*(2), 193–212.

City of Charlotte Open Data Portal. (2022). Retrieved December 20, 2022, from https://data.charlottenc.gov/datasets/charlotte::streets-2/explore.

Chen, L., Chen, C., Ewing, R., McKnight, C. E., Srinivasan, R., & Roe, M. (2013). Safety countermeasures and crash reduction in New York City—Experience and lessons learned. *Accident Analysis & Prevention, 50*, 312–322.

Daniel, J., Dixon, K., & Jared, D. (2000). Analysis of fatal crashes in Georgia work zones. *Transportation Research Record*, *1715*(1), 18–23.

Das, S., Geedipally, S., Fitzpatrick, K., Park, E., Wu, L., Wei, Z., & Paal, S. (2022). Develop a real-time decision support tool for rural roadway safety improvements. *Texas Department of Transportation, Austin*. http://tti.tamu.edu/documents/0-7051-R1.pdf.

De Pauw, E., Daniels, S., Franckx, L., & Mayeres, I. (2018). Safety effects of dynamic speed limits on motorways. *Accident Analysis & Prevention*, *114*, 83–89.

Deardoff, M. D., Wiesner, B. N., & Fazio, J. (2011). Estimating free-flow speed from posted speed limit signs. *Procedia-Social and Behavioral Sciences*, *16*, 306–316.

Delignette-Muller, M. L., & Dutang, C. (2015). fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, *64*, 1–34.

Duvvuri, S. V., Mathew, S., Gouribhatla, R., & Pulugurtha, S. S. (2021). Investigating road link-level data during peak hours to identify potential areas for implementing variable speed limit signs. In *International Conference on Transportation and Development 2021*, 50–61.

Duvvuri, S. V., Mathew, S., Gouribhatla, R., & Pulugurtha, S. S. (2020). Identifying road links and variables influencing the applicability of variable speed limits using supervised machine learning and travel time data. *Journal of Modern Mobility Systems*, 1, 125–130.

Elvik, R. (2010). A restatement of the case for speed limits. *Transport Policy*, *17*(3), 196-204.

Federal Highway Administration (FHWA). (2017). *National travel time data processing and utilization*. Retrieved December 3, 2022, from https://www.fhwa.dot.gov/policyinformation/presentations/hisconf/mon04_national_travel_time_data_processing_and_utilization_wenjing_pu.pdf.

Federal Highway Administration (FHWA). (2020). *Speed limit basics*. Report FHWA-SA-16-076. Washington, DC. Retrieved November 3, 2022, from https://safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa16076/fhwasa16076.pdf.

Garber, N. J., & Srinivasan, S. (1998). Influence of exposure duration on the effectiveness of changeable-message signs in controlling vehicle speeds at work zones. *Transportation Research Record*, *1650*(1), 62–70.

Hadiuzzaman, M., & Qiu, T. Z. (2013). Cell transmission model based variable speed limit control for freeways. *Canadian Journal of Civil Engineering, 40*(1), 46–56.

He, S. X. (2016). Will a higher free-flow speed lead us to a less congested freeway? *Transportation Research Part A: Policy and Practice*, *85*, 17–38.

Hegyi, A., De Schutter, B., & Hellendoorn, J. (2005). Optimal coordination of variable speed limits to suppress shock waves. *IEEE Transactions on Intelligent Transportation Systems, 6*(1), 102–112.

Kattan, L., Khondaker, B., Derushkina, O., & Poosarla, E. (2015). A probe-based variable speed limit system. *Journal of Intelligent Transportation Systems, 19*(4), 339–354.

Khondaker, B., & Kattan, L. (2015). Variable speed limit: An overview. *Transportation Letters*, *7*(5), 264–278.

Kockelman, K., Bottom, J., Kweon, Y. J., Ma, J., & Wang, X. (2006). Safety impacts and other implications of raised speed limits on high-speed roads (Vol. 90). Washington, DC, USA: *Transportation Research Board*.

Kwayu, K. M., Kwigizile, V., & Oh, J. S. (2020). Assessing the safety impacts of raising the speed limit on Michigan freeways using the multilevel mixed-effects negative binomial model. *Traffic Injury Prevention, 21*(6), 401–406.

Lavansiri, D. (2003). *Evaluation of variable speed limits in work zones* (Publication No. 3115994) [Doctoral dissertation, Michigan State University]. ProQuest Dissertations Publishing.

Lee, C., Hellinga, B., & Saccomanno, F. (2003). Real-time crash prediction model for application to crash prevention in freeway traffic. *Transportation Research Record*, *1840*(1), 67–77.

Levin, M. W., Chen, R., Liao, C. F., & Zhang, T. (2019). *Improving intersection safety through variable speed limits for connected vehicles* (No. CTS 19–12). Roadway Safety Institute.

Lu, X. Y., Qiu, T. Z., Varaiya, P., Horowitz, R., & Shladover, S. E. (2010). Combining variable speed limits with ramp metering for freeway traffic control. *In Proceedings of the 2010 American Control Conference*, 2266–2271.

North Carolina Department of Transportation (NCDOT). (2021). Speed limits in North Carolina. Retrieved December 3, 2022, from https://safety.transportation.org/wp-content/uploads/sites/17/2022/05/17-North-Carolina-Speed-Limits-Brian-Mayhew.pdf.

North Carolina Department of Transportation (NCDOT). (2022). *Speed limits*. Retrieved November 3, 2022, from https://www.ncdot.gov/initiatives-policies/Transportation/safety-mobility/speed-limits/Pages/default.aspx.

Park, B., & Yadlapati, S. (2003). Development and testing of variable speed limit logics at work zones using simulation. In *82nd Annual Meeting of the Transportation Research Board, Washington, DC*.

Parker Jr, M. R., & Parker, M. R. (1997). *Effects of raising and lowering speed limits on selected roadway sections* (No. FHWA-RD-97-084). United States. Federal Highway Administration.

Pulugurtha, S. S., & Pasupuleti, N. (2010). Assessment of link reliability as a function of congestion components. *Journal of Transportation Engineering*, *136*(10), 903–913.

Pulugurtha, S. S., Pinnamaneni, R. C., Duddu, V. R., & Reza, R. M. (2015). *Commercial remote sensing & spatial information (CRS & SI) technologies program for reliable transportation systems planning: Volume 1 – Comparative evaluation of link-level travel time from different technologies and sources* (No. RITARS-12-H-UNCC-1). United States. Dept. of Transportation. Office of the Assistant Secretary for Research and Technology.

Saha, P., Ahmed, M. M., & Young, R. K. (2015). Safety effectiveness of variable speed limit system in adverse weather conditions on challenging roadway geometry. *Transportation Research Record*, *2521*(1), 45–53.

Silvano, A. P., Koutsopoulos, H. N., & Farah, H. (2020). Free flow speed estimation: A probabilistic, latent approach. Impact of speed limit changes and road characteristics. *Transportation Research Part A: Policy and Practice*, *138*, 283–298.

Speed limits by state. Retrieved December 3, 2022, from https://www.speed-limits.com/.

Srinivasan, R., Parker, M., Harkey, D., Tharpe, D., & Sumner, R. (2006). Expert system for recommending speed Limits in speed zones final report. *Transportation Research Board: Washington, DC, USA*, 39–42.

Tagar, S., & Pulugurtha, S. S. (2021a). Effect of increasing the freeway posted speed limit on entry ramp speed-change lane crash frequency. *Transportation Engineering Journal*, 4, 100067.

Tagar, S., & Pulugurtha, S. S. (2021b). Predictor variables influencing merging speed change lane crash risk by interchange type in urban areas. *Transportation Research Interdisciplinary Perspectives Journal*, 10, 100375.

Ullman, G. L., & Rose, E. R. (2005). Evaluation of dynamic speed display signs. *Transportation Research Record*, *1918*(1), 92–97.

Van den Hoogen, E., & Smulders, S. (1994). Control by variable speed signs: Results of the Dutch experiment. *Seventh International Conference on Road Traffic Monitoring and Control*, *1994.*, 145–149.

Vernon, D. D., Cook, L. J., Peterson, K. J., & Dean, J. M. (2004). Effect of repeal of the national maximum speed limit law on occurrence of crashes, injury crashes, and fatal crashes on Utah highways. *Accident Analysis & Prevention, 36*(2), 223–229.

Yasanthi, R. G., & Mehran, B. (2020). Modeling free-flow speed variations under adverse road-weather conditions: Case of cold region highways. *Case Studies on Transport Policy*, *8*(1), 22–30.

Zegeye, S. K., De Schutter, B., Hellendoorn, J., & Breunesse, E. A. (2011). Variable speed limits for green mobility. In *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 2174–2179.

About the Authors

Panick Kalambay, Ph.D., recently graduated with his doctoral degree in Civil Engineering at the University of North Carolina at Charlotte. His areas of interest are traffic operations and safety, and transportation planning.

Srinivas S. Pulugurtha, Ph.D., P.E., F.ASCE, is currently working as a Professor & Research Director of the Department of Civil and Environmental Engineering at the University of North Carolina at Charlotte.

MTI FOUNDER

Hon. Norman Y. Mineta

MTI BOARD OF TRUSTEES

Directors

MTI MINETA TRANSPORTATION INSTITUTE