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Urban Arterial Lane Width Versus Speed and Crash Rates: A Comprehensive Study of Road Safety

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Abstract: Reducing vehicle lane widths has been proposed as an effective strategy to decrease vehicle speeds and enhance road safety. However, the safety benefits of narrower travel lanes remain a topic of debate due to mixed findings in the literature. This study examines the relationship between lane width, vehicle speed, and crash occurrence to comprehensively understand their impact on road safety and transportation planning. Using data from 320 urban arterial sections in Utah, the analysis reveals that narrower lane widths are associated with reduced vehicle speeds. For every additional foot of lane width, 85th and 95th percentile speeds increase by 1.012 mph and 1.088 mph, respectively. Furthermore, injury crash modeling indicates that a one-foot increase in lane width is associated with a 38.3% increase in the odds of an injury crash on a roadway section. These findings contribute to the growing evidence supporting the implementation of narrower lane widths as a strategy to improve road safety, foster multimodal infrastructure, and promote sustainable urban transportation systems. We recommend that UDOT adopt a minimum lane width of 10 or 11 feet for arterials in highly urbanized areas, such as downtowns and major activity centers.

Keywords: lane width; speed; crash likelihood; cross-sectional road design; urban arterial; safety modeling

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1. Introduction

Road traffic injuries are a significant global public health and development concern, with the World Health Organization (WHO) estimating that 1.19 million people lose their lives annually due to traffic collisions [1]. Additionally, between 20 and 50 million more people suffer non-fatal injuries, with many incurring a disability [1]. These incidents rank among the leading causes of death globally, highlighting the urgent need for effective interventions to mitigate their impact. Addressing the relationship between road design and traffic safety is crucial in reducing the societal and economic burdens associated with road traffic collisions.

This study is motivated by the pressing need to improve urban road safety and sustainably enhance transportation efficiency. Urban arterial roads, which carry significant traffic volumes, are critical for urban mobility but also present substantial safety challenges.

As traffic volumes and their distribution can vary significantly across different times of day or days of the week, these temporal variations are widely known as crucial for understanding the dynamics of road safety and traffic efficiency [2]. Despite extensive research, the impact of lane width on traffic speed and crash rates remains a subject of debate, particularly in urban settings.

Lane width standards vary across developed and developing countries, influenced by road classification, design guidelines, and policies. In the U.S., AASHTO Green Book (2018) recommends a 12 feet (3.66 m) width for highways and 9 feet (2.74 m) for lower-grade roads). Germany specifies 12.3 feet (3.75 m) for mixed traffic and 11.5 feet (3.5 m) for passenger car lanes in the Guidelines for the Design of Motorways (2008). In the UK, highway lane widths are 12 feet (3.65 m) to 12.1 feet (3.7 m) in Design Manual for Roads and Bridges (2020), while Canada prescribes 11.5–12.1 feet (3.5–3.7 m) according to Geometric Design Guide for Canadian Roads (1999). In China, the Design Specification for Highway Alignment (2017) mandates 12.3 feet (3.75 m) for highways, reduced to 11.5 feet (3.5 m) for roads primarily used by passenger cars. A recent study of Chinese roads found that the effective lane width at the 95th, 90th, and 85th percentiles are 3.2 m, 3.0 m, and 2.8 m, respectively, based on high-precision trajectory data collected using an integrated radar shorter video system (IRVS) [3]. Although new evidence and project-based claims increasingly support the use of relatively narrower lane widths, the discussion remains limited, particularly in the context of U.S. roads [4].

The street design guidelines, formulated by the American Society of Civil Engineers (ASCE), the Institute of Transportation Engineers (ITE), the National Association of Home Builders (NAHB), and the Urban Land Institute (ULI), advocate for selecting minimum lane widths that fulfill fundamental requirements without superfluity. This method reduces construction and maintenance expenses while producing a more sustainable and livable society. Additionally, narrower lanes can create space for infrastructure that facilitates active mobility.

The effect of narrower travel lanes on safety remains contentious, as research presents inconclusive results about the consistent enhancement of road safety through narrower lane widths. An initial study by Swift et al. (1997) indicated that narrower lanes on residential streets were associated with reduced injury-related accidents [5]. Recent studies suggest that the safety implications of narrower lanes can differ based on the traffic volume and roadway type. Narrow lanes have been shown to enhance safety on rural roads, but on urban arterial roads, they are frequently associated with an increased risk of collisions [6–9]. In particular, the relationship between lane width and driving speeds is complex and not entirely understood. There is a dearth of research on the subject, largely due to lack of speed data for large samples of urban roadways.

Studies that do address urban arterials often fail to control for critical confounding variables, such as road markings, roadside objects, the presence (or absence) of medians, the number of travel lanes, and the visual environment ahead, such as the proportion of visible sky, which affects drivers' perceptions of lane width and speed, particularly on curved sections compared to straight highways [10]. These factors can significantly influence both vehicle speeds and the likelihood of crashes, yet they are rarely incorporated into analyses of lane width effects. This highlights the importance of carefully considering multiple factors—such as the traffic volume, capacity, level of service, speed, cross-sectional alignment, development type, and other geometric characteristics—when examining the relationship between lane width and vehicle speeds [11].

Our study aims to address these gaps in the literature by providing a more comprehensive analysis of the relationship between lane width, speed, and crash rates on urban arterial roads while considering confounding variables. This research introduces a novel approach by emphasizing a diverse set of environmental factors, enabling a more accurate assessment of how lane width affects road safety in urban areas. By analyzing a substantial dataset of 320 urban arterial sections in Utah, we aim to provide empirical evidence to guide road design practices. The findings of this research have the potential to inform policymakers and transportation engineers, offering practical recommendations for optimizing lane widths to enhance road safety, reduce construction costs, and improve community livability.

This paper is organized as follows: Section 2 provides a detailed review of the relevant literature on lane width, speed, and crash rates, highlighting existing gaps in research. Section 3 outlines the methodology used for data collection and analysis, including the selection of urban arterial sections in Utah and the variables considered in the study. Section 4 presents the results of the analysis, including statistical relationships between lane width, speed, and crash rates, and discusses the findings in the context of road safety. Finally, Section 5 concludes the study by summarizing key insights and suggesting directions for future research.

2. Literature Review

2.1. Safety

2.1.1. Lane Width

As used in this article, the term narrow applies to 9 and 10 ft lanes, 13 and 14 ft lanes are wide, and 11 and 12 ft lanes are the widely accepted standard for urban arterials. Reducing lane widths on urban arterials can create additional space for pedestrians and bicycles, including wider sidewalks, landscaped medians, shorter pedestrian crossings, and dedicated bike lanes. It can also facilitate the development of supplementary on-street parking areas. Nevertheless, safety must be considered when determining adequate lane widths for these routes. Prior research has yielded inconclusive findings concerning the correlation between lane width and road safety on urban arterials, suggesting that this relationship may be contingent upon several confounding factors [11,12].

Studies indicate that the impact of lane width on safety outcomes varies across urban and rural environments. Research in rural regions has demonstrated a significant correlation between accident risk and road design features, including lane, shoulder, and median widths [13–15]. Nonetheless, other research indicates that lane and shoulder widths exert negligible effects on crash severity, whereas the type of shoulder plays a more crucial role, decreasing crashes by 30–70% [16]. These findings contrast with previous studies on two-lane rural roadways, which linked wider shoulders to heightened crash severity [17].

Likewise, studies examining the correlation between lane width and safety in metropolitan environments yield inconclusive findings. A study investigating non-freeway urban roads found an association between wider vehicle lanes, narrower shoulders, and a decreased incidence of roadside and midblock crashes [18]. Conversely, several studies on urban streets demonstrated that narrower lanes reduce collisions [12,19,20]. The contradictory results emphasize the intricacy of assessing the effect of lane width on safety in urban environments.

Manuel et al. [11] investigated the impact of road width on safety for urban collector highways using negative binomial (NB) safety performance functions (SPFs). Their findings revealed that longer segments, elevated traffic volumes, increased access-point density, and midblock alterations (such as crossroads or driveways) were positively associated with higher collisions. In contrast, roadway width showed a negative and statistically significant correlation with crashes, indicating that narrower roadways may be linked to decreased crash frequency.

Lane width, route curvature, roadside development, and traffic control also affect vehicle speed. A previous study identified the following two principal methodologies for measuring this relationship: quasi-experimental studies (before and after) of individual roadway segments and comparative studies of various routes with differing lane widths [21]. The research determined that the literature lacks consensus on the correlation between lane width and speed.

In the NCHRP 330 report, Douglas Harwood [22] analyzed the efficient application of roadway width on urban arterials at 35 locations in five states [22]. The study emphasized assessing several options for employing streets with identical curb-to-curb dimensions. Harwood accounted for other variables that could affect efficacy to guarantee precise outcomes, including traffic volume, vehicle composition, capacity (level of service), prevailing speeds, cross-sectional alignment, the kind of development, and access to neighboring properties. The research was specifically confined to urban arterials with speed limits of 45 mph or lower, and its findings were predominantly associated with lane width.

- A lane width narrower than 11 feet can be used effectively for urban arterial improvements.
- A 10 foot lane width is widely accepted by engineers with reduced or unchanged crash rates.
- Based on its impact on the crash rate, a lane width of less than 10 feet should be used cautiously.

Roadside elements, such as street trees and nearby parking, significantly influence traffic management and give drivers a sense of spatial orientation. The positioning and visibility of roadside objects are crucial for traffic safety. In addition to establishing a safe zone for roadside elements, several geometric designs are linked to road safety [23]. Hauer’s study indicates that wide lanes do not correlate with safety, asserting that the threshold for safer roads is 11 feet [3]. Dumbaugh [18] found that 11 ft lanes have 11% fewer mid-block collisions than 12.5 ft lanes. This contrast is far more pertinent for harmful and lethal collisions [18]. The driver’s assessment of the road environment and response to associated dangers is the most important aspect of enhancing safety. The study suggests that wider lanes with clear zones reduce the driver’s perception of risk, creating an inflated but deceptive sense of security that may contribute to behaviors increasing the likelihood of a crash. In addition, reallocating road space after reducing lane widths may serve as an effective and low-cost strategy for creating recovery areas for steering errors [24], while maintaining capacity and conserving road space [25].

It has been suggested that roadway design should prioritize “drivers’ perception of risk” over rigid compliance with traditional technical requirements. When drivers assess the safe speed as exceeding the posted speed limit, they are more inclined to exceed it. Moreover, integrating practical road design elements and enacting traffic calming strategies can substantially improve safety, promoting driver conduct that more closely aligns with traffic safety goals.

2.1.2. Shoulders

One of the critical variables that influence crashes is the shoulder. Roads with shoulders can indirectly influence crash frequencies by affecting the average vehicle speed [26–28]. This suggests that the presence of shoulder lanes may increase vehicle speeds, which, in turn, produce higher crash frequencies. Removing or narrowing shoulder lanes is likely a more effective way of managing speeds and, consequently, reducing collisions than narrowing lane widths [28].

Increasing the shoulder width is directly associated with higher crash rates [27,29]. For instance, Bamzai et al. [29] suggested that shoulders narrower than 2.44 m could potentially reduce shoulder-related crashes [29]. Additionally, Gitelman et al. [30] discovered that widening unpaved shoulders beyond 0.9 m increased the risk of crashes, particularly injuries and total crashes, with a 5% increase in crash risk for each additional 0.1-m extension [30]. However, the lowest crash risks were observed with total shoulder widths of around 3 m or wider, and narrower shoulders of less than 1 m.

On the other hand, another body of literature found that roads with shoulders are likely to have lower crash frequencies [30–32]. For example, Gitelman et al. [30] found that widening the shoulder to 2.2 m increased the crash risk. However, crash frequency decreased when the shoulder was expanded beyond this point. A driving simulation study also indicated that shoulders could reduce head-on collisions, as drivers tend to steer farther away from oncoming traffic [26].

2.1.3. Number of Lanes

Previous studies have also shown that the number of lanes plays a significant role in road safety [33–35]. For instance, Abdel-Aty and Radwan [33] found that crash rates increased as the number of lanes on urban road sections increased [33]. This is likely because a higher number of lanes often leads to more frequent lane changes, increasing vehicle conflicts and the likelihood of crashes [35]. In contrast, other studies suggest that roads with more than two lanes tend to have lower crash rates across all levels of crash severity [36,37]. One explanation is that wider roads provide more space for vehicles to maneuver and avoid crashes in potentially hazardous situations [38]. Another contributing factor is that many crashes analyzed occurred on undivided, single-carriageway roads, which are more prone to risky vehicle interactions, such as head-on collisions, leading to severe outcomes [38].

2.1.4. Parking

On-street parking is another variable that can impact crash frequency. It is highly correlated with average speeds and, consequently, crash frequency. On-street parking provides safe environments, as identified by Dumbaugh and Gattis [23], who found that 11% fewer crashes occurred on livable streets with high roadside activities, including on-street parking, than in comparison road sections [23]. The authors attributed this to drivers' consciousness when driving through a crowded area, causing fewer collisions.

On-street parking serves the following two essential functions: it acts as a traffic calming measure and provides a protective barrier between pedestrians and vehicles [39]. Research shows that on-street parking is effective in calming traffic in areas with speed limits of 40 kph or lower [40]. It also enhances pedestrian safety and comfort by creating a physical separation from vehicle traffic [41,42]. Additionally, on-street parking offers cyclists protection from high-speed vehicles, which can help reduce the occurrence of bicycle crashes [43].

However, road segments with one-sided or two-sided parking may increase the risk of pedestrian–vehicle crashes compared to those without on-street parking, particularly under specific road conditions [19,23,44]. In urban environments, this heightened risk is often linked to driver behavior influenced by the presence of parked vehicles. On roads with parked cars, drivers tend to experience higher stress, reduce their speed, and position their vehicles farther from the centerline to avoid oncoming traffic [45]. A review by Biswas et al. [39] also emphasized that the impact of on-street parking varies depending on the type of road [39]. On major roads, on-street parking is considered unsafe, with recommendations to limit parking near pedestrian crossings and intersections. In contrast, parallel parking (as opposed to angled parking) may be more suitable for minor streets with lower traffic volumes and slower speeds.

2.1.5. Enclosure

In urban design, the obstruction of the visible sky in a specific location is typically termed the degree of street "enclosure". Street enclosure refers to the cumulative impact of substantial objects, such as buildings and trees, that delineate the spatial boundaries of a streetscape and limit extended sight lines [46]. Figure 1 depicts an open streetscape (left) compared to an enclosed streetscape (right).

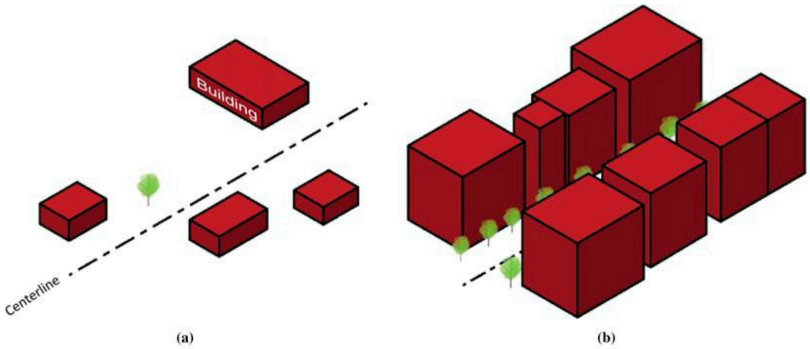


Figure 1. Examples of an open streetscape (**a**) and an enclosed streetscape (**b**) (sourced from Aultman-hall and Harvey [46]).

Aultman-Hall and Harvey [46] suggest that streetscapes with more open views and less enclosure often encourage higher speeds and riskier driving behaviors, resulting in more traffic crashes, particularly on urban arterials [46]. On the other hand, certain roadside landscapes or objects, often perceived as unpleasant or visually cluttered, can also contribute to collisions, injuries, and fatalities [47,48].

Crashes in urban environments are less severe in smaller, more confined streetscapes. In such conditions, drivers typically navigate at reduced speeds, owing to the visual limitations imposed by tighter or more confined spaces, especially in urban settings characterized by intricate traffic patterns and varied road users [49]. This suggests that, instead of presuming that dense and intricate urban roadside settings intrinsically diminish traffic safety, the safety of urban arterials is primarily affected by promoting moderate speeds and discouraging hazardous behaviors within these confined areas. The urban design quality of enclosure involves streets or public areas delineated by vertical structures, such as uninterrupted sequences of buildings, walls, or trees, which foster a sense of enclosure or a room-like quality [50]. Ewing and Handy [50] define enclosure by parameters including the ratio of street walls on either side of the street segment, the extent of visible sky both ahead and across the roadway, and the existence of long sightlines [50]. In 1965, Don Appleyard and his associates suggested an alternative correlation between the roadside environment and travel velocity in their work *The View from the Road*. It was proposed that, when objects like trees, buildings, and parked cars are situated near the driver, they serve as reference points that assist the driver in assessing their speed, thus typically decreasing their driving velocity. When immovable objects are positioned farther from the road, drivers lack visual cues and are more inclined to speed. Drivers frequently experience this phenomenon on highways, particularly in open areas.

2.2. Capacity and Speed

Several studies have examined the relationship between lane width, geometric features, and saturation flow rates [12,51–54]. Many of these studies identified a positive correlation between lane width and saturation flow rates [12,52,53]. Specifically, Shao et al. [52] proposed a straightforward model linking the lane width, saturation flow, and curve radius, demonstrating that increasing both the lane width and curve radius results in higher saturation flow rates [46]. Chandra [55] used field data to examine the impact of the lane width on roadway capacity. The findings indicate that the capacity and carriageway width adhere to a quadratic relationship. Furthermore, an effective lane width is influenced by shoulder conditions and can affect the roadway capacity [55].

The Highway Capacity Manual (HCM) states that a 1-foot reduction in lane width at signalized crossings results in a 3.33% decrease in capacity; however, for lanes narrower than 10 feet, there is no substantial drop in capacity [52]. Given that lane width affects the saturation flow rate, a study by Potts et al. [12] examined the actual saturation flow rates at signalized crossings. It contrasted them with the estimations provided by the Highway Capacity Manual (HCM) [8]. The statistical analysis performed in the study revealed a correlation between the lane width and the average saturation flow rate, with the comprehensive results reported in the following section. Compared to 11 and 12 ft lanes, 9.5 ft lanes have 4.3% lower saturation flow rates, while 11 or 12-ft lanes have 4.3 to 4.4% lower saturation flow rates than 13-ft lanes. The results of this study indicated that actual saturation flow rates are generally lower than the values suggested by the HCM. It is worth noting that, besides the actual lane width, side friction factors, including, but not limited to, parking, pedestrians, and bus stops, play a significant role in the road capacity and average speed.

A recent study by Patkar and Dhamaniya [56] has shown a linear relationship between increased side friction factors and reduced effective lane width and capacity, correspondingly [56]. Similarly, it was observed that the stream speed would be reduced. Later, it was shown that a 3.2% capacity reduction followed a 2% increase in side friction factors [54]. After reviewing the literature on the relationship between the lane width and speed, most studies suggest no significant relationship between the two. Even though narrower lanes (9 ft) experience a lower average speed than 10 ft lanes, the difference is insignificant. However, narrower lanes will reduce lateral movements, which, as a result, increases safety. Road markings and medians can also affect drivers' perceived lane width and driving speed. These factors influence curves more than straight road segments [6].

2.3. Pedestrian Volume

The relationship between lane width and pedestrian volume has been addressed cursorily. Nonetheless, pedestrian volume is more frequently analyzed in connection with the number of lanes affected by a road diet. Numerous municipal, regional, and state agencies have evaluated road diets that facilitate various travel modes instead of conventional roadway designs by reducing vehicle traffic lanes and redistributing the right-of-way for alternative modes. A road diet generally denotes an economic safety intervention for a roadway with an average daily traffic volume of 25,000 or less, transforming an existing four-lane undivided road into a three-lane configuration, with one lane in each direction and a center two-way left-turn lane [57]. The surplus width resulting from eliminating a lane can be used for bicycle lanes or expanded walkways. Numerous studies have sought to evaluate the effect of a road diet on pedestrian traffic. Most studies suggest a significant rise in pedestrian volume following the implementation of road diet programs.

Gudz et al. [58] examined bicycle and pedestrian traffic alterations following a road diet initiative in Davis, California [58]. The number of bikers surged by 243% at a statistically significant level following the implementation of the road diet, whereas pedestrian counts showed a negligible reduction that lacked statistical significance. Ntonifor [59] examined alterations in pedestrian volume along a section of Wilson Blvd in Arlington County, Virginia, before and after executing a road diet project that decreased driving lanes from four to two, incorporating a two-way center left-turn lane [59]. The counts before and after were analyzed at the AM and PM peak hours, coinciding with several customer complaints. The assessment of pedestrian volume had a minor decline relative to other traffic metrics, including the traffic volume, trip time, and speed.

Conversely, it is unsurprising that the volume of bicycles markedly rose following the implementation of the road diet, which was mainly attributable to the introduction of bike lanes on the roadway. Anderson et al. [60] analyzed alterations in the pedestrian volume through a case study in Orlando, Florida [60]. Pedestrian traffic fell by 23 percent at the crossings during peak hours. However, bicycle counts increased by 30 percent. This outcome aligns with the findings of Ntonifor [59]. Conversely, varying directional outcomes from the road diet initiative in New York indicated that pedestrian traffic rose following the 4th Avenue, Sunset Park Traffic Calming project. This project modified optimal lane lengths and expanded medians at intersections to facilitate safer pedestrian crossings. Moreover, a recent study found that pedestrian volume is likely to increase the crash frequency of dockless e-scooters, with this relationship becoming stronger in the TAZs with higher average vehicle speeds [61].

However, no research has investigated the correlation between lane width and pedestrian volume. Although one study examined the impact of modifying the lane width and expanding the median width, it remains inadequate to definitively establish a relationship. Consequently, research on the correlation between lane width and pedestrian volume is essential for enhancing road safety.

In conclusion, the relationship between lane width and road safety remains unclear, especially in urban areas. While narrow lanes may improve safety on rural roads, they are often linked to higher crash risks on urban arterials. The connection between lane width and vehicle speeds is complex and not well understood, partly due to a lack of sufficient data for urban roads. Moreover, studies on urban roads often overlook important factors like road markings, medians, roadside objects, traffic volume, and driver perception of the road ahead. These factors can greatly affect vehicle speeds and crash risks but are rarely considered in analyses. This highlights the need to consider a wider range of factors when studying lane width effects.

3. Methods

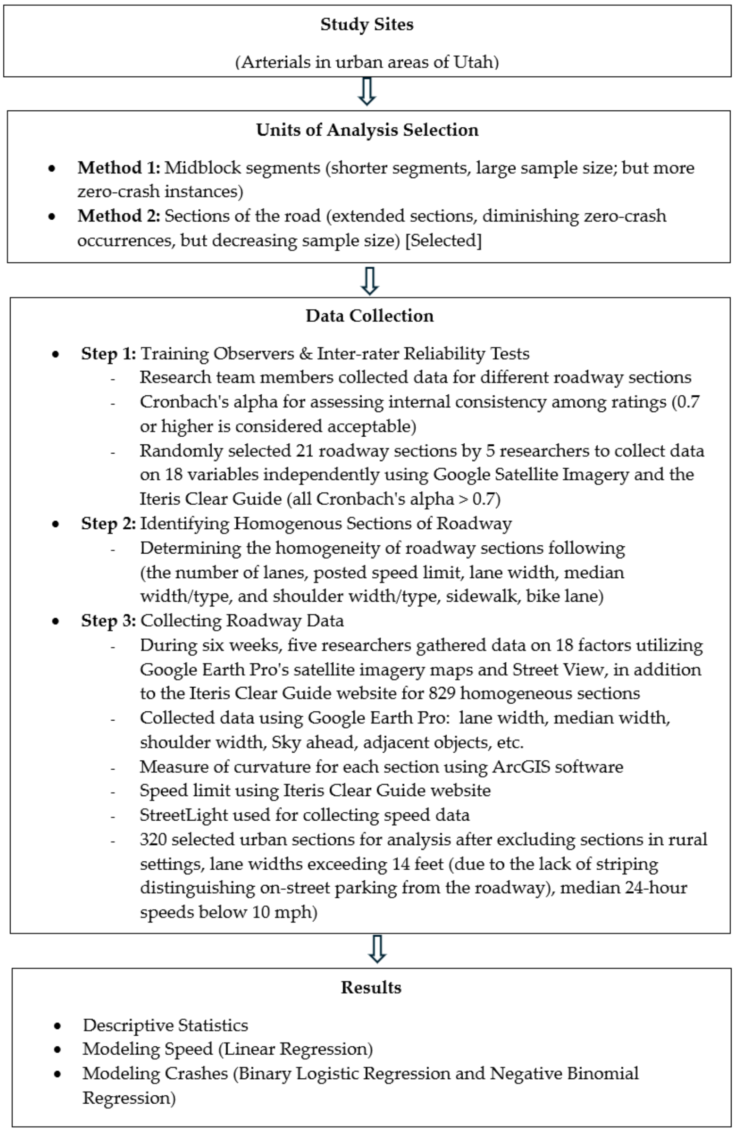
The following flowchart shows the steps followed in this research.

3.1. Study Sites

This study investigated arterials in urban areas of Utah. According to the Highway Safety Manual, AASHTO Greenbook (2018), an area is considered urban if 50,000 or more people live there. While inconsistent with the U.S. Census, this has become our definition of urban (the census would define an area with 50,000 people as urbanized and classify small towns as urban). Table 1 presents descriptive statistics for roadway study sections in urban areas of Utah. The average length is 0.79 miles, with a standard deviation of 0.63. In addition, the average lane width is 11.9 feet, with a standard deviation of 0.75 feet. Figure 2 shows the locations of principal and minor arterials in urban areas of Utah.

Table 1. Descriptive statistics of roadway study sections.

Count	Mean	Median	Min.	Max.	S.D.
Average Length (Miles)	0.79	0.63	0.05	5.13	0.56
Average Lane Width (ft)	11.90	11.98	9.5	21.11	0.75



Study Sites

(Arterials in urban areas of Utah)

Units of Analysis Selection

- **Method 1:** Midblock segments (shorter segments, large sample size; but more zero-crash instances)
- **Method 2:** Sections of the road (extended sections, diminishing zero-crash occurrences, but decreasing sample size) [Selected]

Data Collection

- **Step 1:** Training Observers & Inter-rater Reliability Tests
  - Research team members collected data for different roadway sections
  - Cronbach's alpha for assessing internal consistency among ratings (0.7 or higher is considered acceptable)
  - Randomly selected 21 roadway sections by 5 researchers to collect data on 18 variables independently using Google Satellite Imagery and the Iteris Clear Guide (all Cronbach's alpha > 0.7)
- **Step 2:** Identifying Homogenous Sections of Roadway
  - Determining the homogeneity of roadway sections following (the number of lanes, posted speed limit, lane width, median width/type, and shoulder width/type, sidewalk, bike lane)
- **Step 3:** Collecting Roadway Data
  - During six weeks, five researchers gathered data on 18 factors utilizing Google Earth Pro's satellite imagery maps and Street View, in addition to the Iteris Clear Guide website for 829 homogeneous sections
  - Collected data using Google Earth Pro: lane width, median width, shoulder width, Sky ahead, adjacent objects, etc.
  - Measure of curvature for each section using ArcGIS software
  - Speed limit using Iteris Clear Guide website
  - StreetLight used for collecting speed data
  - 320 selected urban sections for analysis after excluding sections in rural settings, lane widths exceeding 14 feet (due to the lack of striping distinguishing on-street parking from the roadway), median 24-hour speeds below 10 mph)

Results

- Descriptive Statistics
- Modeling Speed (Linear Regression)
- Modeling Crashes (Binary Logistic Regression and Negative Binomial Regression)

Figure 2. Research flow.

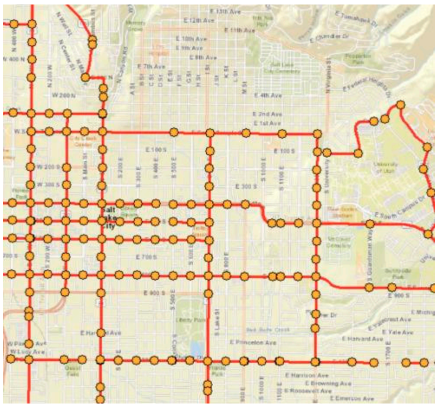
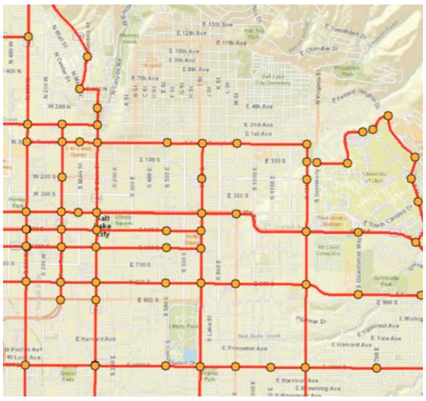
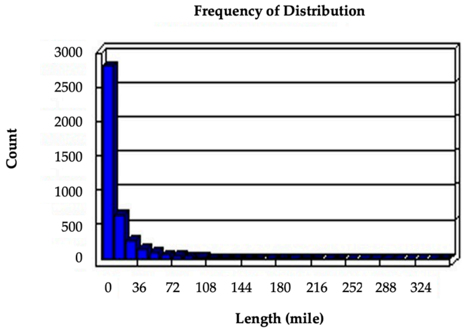
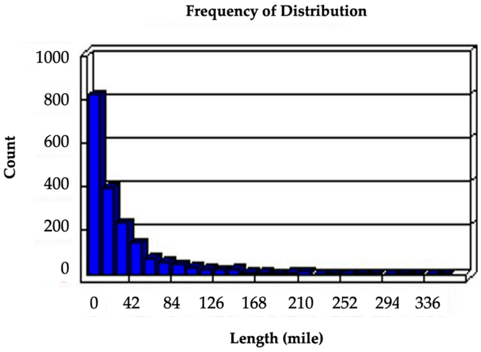
3.2. Units of Analysis

Roadway units are generally characterized in two principal manners for analytical purposes. The initial strategy emphasizes segments situated between junctions [12,62], wherein midblock segments run from one intersection to the subsequent one or to a location where the roadway type changes. These segments are anticipated to exhibit uniformity in attributes such as Average Annual Daily Traffic (AADT) and design specifications (e.g., the lane count and median type). The Highway Safety Manual recommends that segment lengths be a minimum of 0.10 miles to enhance the efficiency and accuracy.

The second method examines extended sections of roadway, frequently integrating many segments [11,37,63]. The Highway Capacity Manual categorizes these as urban street facilities, generally extending 1–2 miles, characterized by uniform attributes like the lane configuration, shoulder width, and Average Annual Daily Traffic (AADT).

Although both strategies pursue sample homogeneity, they diverge in their statistical effects. Method 1 uses shorter segments, enabling a larger sample size; nevertheless, this may lead to an increased number of zero-crash instances, occasionally misleadingly attributed to the brevity of the segments. Method 2 employs extended sections, diminishing zero-crash occurrences but perhaps decreasing the sample size and statistical power due to the incorporation of many segments with diverse designs. Table 2 delineates the segmentation outcomes for the UDOT arterials employing both methodologies.

Table 2. Units of analysis and characteristics.

Analysis Units	Method 1: Midblock Segments	Method 2: Sections of Road
Unit characteristics	- Total number of units: 4125 - Mean length: 0.9 mi. - Range: 0.1 to 35 mi. 	- Total number of units: 1869 - Mean length: 2.0 mi. - Range: 0.1 to 49.3 mi. 
Data collection time	- Relatively shorter time per sample	- Relatively longer to examine multiple midblock segments
Number of crashes	- Zero-crash samples: 16% (644 out of 4125) of the total cases - Mean crashes per unit: 14 - Range: 0 to 355 	- Zero-crash samples: 5% (85 out of 1869) of the total cases - Mean crashes per unit: 31 - Range: 0 to 355 

This study designated road sections as the units of analysis. Identifying homogenous portions, however time-consuming, and resulting in a reduced sample size, decreased the incidence of zero-crash occurrences. Additionally, road segments that traverse many intersections are frequently prioritized in local highway enhancement initiatives and generally align with regions where AADT data are readily obtainable from UDOT. Utilizing road sections instead of segments diminished the interdependence across nearby sections, thereby maintaining the independence assumption that is essential for regression analysis.

3.3. Data Collection

Although UDOT supplies secondary data for certain road design variables, many other variables require manual observation. To address this, we employed Google Street map imagery to augment the database. We instituted the following procedure to ensure the reliability of data collected by different personnel and to accurately delineate uniform roadway sections.

Step 1: Training Observers and Conducting Inter-rater Reliability Assessments

To ensure consistency and reliability in measurements across different research team members, we used Cronbach's alpha, a statistical method for assessing internal consistency among ratings. Cronbach's alpha values range from 0 to 1, with values closer to 1 indicating a higher consistency and reliability in the data and values closer to 0 suggesting a lower consistency. A value of 0.7 or higher is considered acceptable, indicating a high consistency even with varying effect sizes.

Twenty-one roadway sections were randomly selected from the total sample pool, and five researchers independently collected data on 18 variables for these sections. After two weeks of data collection using Google Satellite Imagery and the Iteris Clear Guide, the statistical analysis showed Cronbach's alpha values of 0.7 or higher for all 18 variables, confirming strong consistency in the ratings (see Figure 3). As a result, the pilot test validated that the raters could proceed independently with the data collection for the entire sample, following the established protocol.

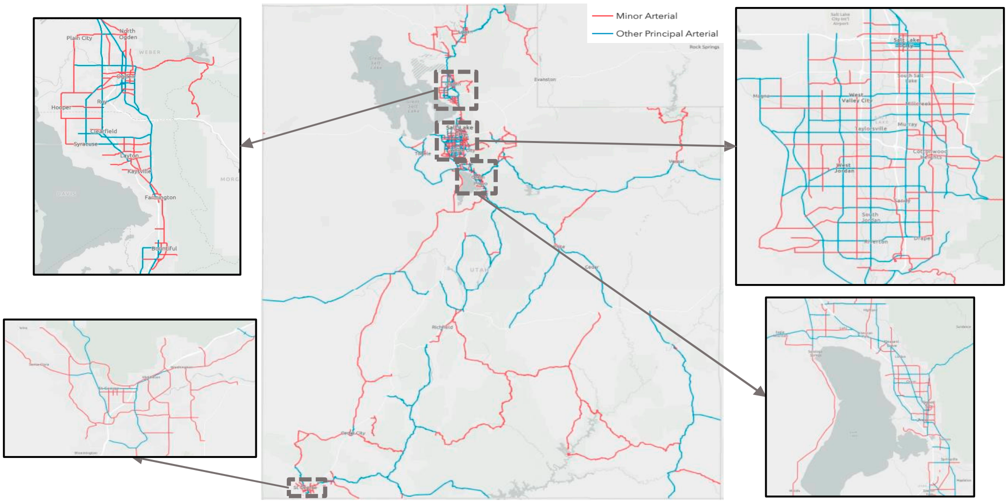


Figure 3. Geographic map of the study sections.

Step 2. Identifying Homogenous Segments of Roadway

In the next phase, the researchers were responsible for determining the homogeneity of the roadway sections. Each data collector was assigned a sample of approximately 380 roadway sections from 1883 urban road segments in Utah. The team analyzed the cross-sectional road attributes using Google Satellite Imagery and Clear Guide to assess the homogeneity, focusing on seven specific criteria (see Table 3). The findings were recorded as the following binary variables: "1" for sections meeting the criteria for further data collection and "0" for those that did not.

Step 3. Collecting Roadway Data

In the concluding phase, an extensive database was established, consisting of roughly 700 uniform roadway sections. During a six-week period, five researchers gathered data on 18 factors utilizing Google Earth Pro's satellite imagery maps and Street View, in addition to the Iteris Clear Guide website. We employed Google Earth Pro's distance measurement tool to ascertain the lane width, median width, shoulder width, and the Euclidean distance between the starting and ending points of the section. At three reference positions within each section, the mean values for the lane width, median width, and shoulder width were recorded. The aerial perspective in Google Earth Pro additionally furnished data concerning the number of through lanes and the varieties of medians, shoulders, sidewalks, bike lanes, crossroads, and parking lanes. Minor discrepancies in the roadway sections were omitted throughout the data analysis. Bus stops were located utilizing the search tool in Google Earth Pro, while the Street View feature evaluated the route environment, concentrating on factors such as “sky ahead” and “adjacent objects”. For the “sky ahead” variable, if less than 50% of the view from the horizon upward was obscured, it was assigned a value of 1; otherwise, it was assigned a value of 0. The “objects” variable was quantified by calculating the percentage of the area within 50 feet of the pavement edge that included entities such as buildings, trees, and bus shelters. If over 50% of the section had such objects, it was recorded as 1; otherwise, it was recorded as 0.

Table 3. Observation protocol for identifying homogenous roadway sections.

Criteria	Observation Protocol
Number of lanes	The count of through lanes in both directions was tracked, eliminating flush medians and turning lanes adjacent to intersections. Any alteration in the number of lanes was recorded as “0”, but a consistent lane design was recorded as “1”.
Posted speed limit	A change in the speed limit was recorded as “0” and a uniform speed limit was recorded as “1”.
Lane width	Lane width was measured at multiple random points along the section. A difference greater than 1 ft was recorded as “0” and a uniform lane width was recorded as “1”.
Median width/type	Any significant changes in median width (e.g., from 12 ft to 13 ft) or changes in median type (e.g., from traversable to non-traversable) have been recorded as “0”. A constant median was recorded as “1”.
Shoulder width/type	Any significant changes in shoulder width (e.g., from 2 ft to 3 ft) or shoulder type (e.g., present in one direction and absent in the other) were recorded as “0”. A consistent shoulder was recorded as “1”.
Sidewalk	Any significant changes in the presence of sidewalks (e.g., from present to absent) were recorded as “0”. Consistency in sidewalk presence was recorded as “1”.
Bike lane	For the presence of bike lanes, if there was any significant change (e.g., from present to absent), it was recorded as 0. If the condition remained uniform across the section, it was recorded as 1.

Along with Google Earth Pro v7.3.3, ArcGIS Desktop 10.8.2 software was used to generate shapefiles for the selected samples and to calculate the total length of each roadway segment. We then divided this length by the Euclidean distance to derive a measure of the curvature for each section. To obtain speed limit information for each roadway, we utilized the Iteris Clear Guide website along with UDOT’s speed limit shapefile. Additionally, the block length, representing the average distance between consecutive intersections (or intersection frequency), was measured. This was determined using the number of intersections and the segment length, as outlined in Equation (1), with an additional 1 subtracted from the denominator to account for the section’s start and endpoints.

$$Block\ Length = \frac{Section\ Length}{Intersections - 1} \tag{1}$$

We also estimated the Annual Average Daily Traffic (AADT) per lane to gauge the average traffic flow in each lane, as it may correlate with speed. This metric was included in our dataset to account for the effect of normalized traffic in our model. For crash data, we used a similar approach. Since roadway section lengths vary, we adjusted crash and injury crash counts on a per-mile basis. To maintain these values as count data suitable for analysis with count regression models (commonly applied in crash analysis), we rounded the crash rates to the nearest integer. We also factored in the influence of on-street parking and parked cars on safety and traffic speed by normalizing parked car counts relative to the length of each section. All of the data for each roadway section were compiled into an Excel spreadsheet, creating a comprehensive database that was used for our modeling analysis.

The width of a roadway lane is commonly thought to influence both the safety and speed for a given section. Previous research, expert insights, and real-world applications have produced varying and sometimes conflicting results regarding the association between the lane width, speed, and safety (refer to Literature Review). To clarify this relationship, our analysis aimed to quantify the connection between the lane width, speed, and crashes while considering various roadway designs and other factors. We gathered data on these variables across 829 homogeneous sections, using the traffic volume, speed, and crash data from 2021. Speed data were obtained from StreetLight, which provided daily measures for the 50th, 85th, and 95th percentile speeds. Crash data, sourced from the Utah Department of Public Safety (UDPS), were limited to non-intersection crashes and included records of all crashes, injury crashes, and fatal crashes occurring in 2021.

We chose StreetLight data because they met the requirements of this study and have proven to be reliable in analyzing transportation behavior for over a decade, utilized by DOTs, MPOs, and other agencies across North America. StreetLight data have also been validated by various third parties, including government agencies such as the FHWA and academic institutions like Texas A&M.

During data collection, we encountered roadways with lane widths exceeding 14 feet. Upon review, we found that this anomaly was due to the lack of striping distinguishing on-street parking from the roadway. We opted to exclude these sections from our dataset, since an ambiguous roadway definition could influence driver behavior and thus affect our analysis.

After removing these sections and conducting data preprocessing to address errors and inconsistencies, 389 sections were included in the final dataset. To enhance the model accuracy regarding road classification, we categorized the data into urban databases, with 325 of the 389 sections located in urban areas. Another challenge involved potentially unreliable speed data. StreetLight data show that five urban roadway sections had median 24-h speeds below 10 mph. Such low speeds seem improbable over 24 h, even for roads with traffic control devices like signals or stop signs. Whether accurate or not, outliers of this nature could skew the results by disproportionately influencing the regression coefficients. Consequently, we removed these five sections from the urban sample, resulting in 320 urban sections with median speeds exceeding 10 mph. Overall, StreetLight's speed values seem reasonable.

The correlation coefficient between the posted speed limit and the 85th percentile speed—a measure typically aligned with speed limit determinations—is 0.701 for urban sections. This indicates a reasonable level of correlation that supports the validity and reliability of StreetLight's speed data. Our primary independent variable of interest is lane width. As illustrated in Figure 4, the most prevalent roadway width in Utah is between 11 feet and less than 12 feet, with the next most common range being 12 feet to less than 13 feet.

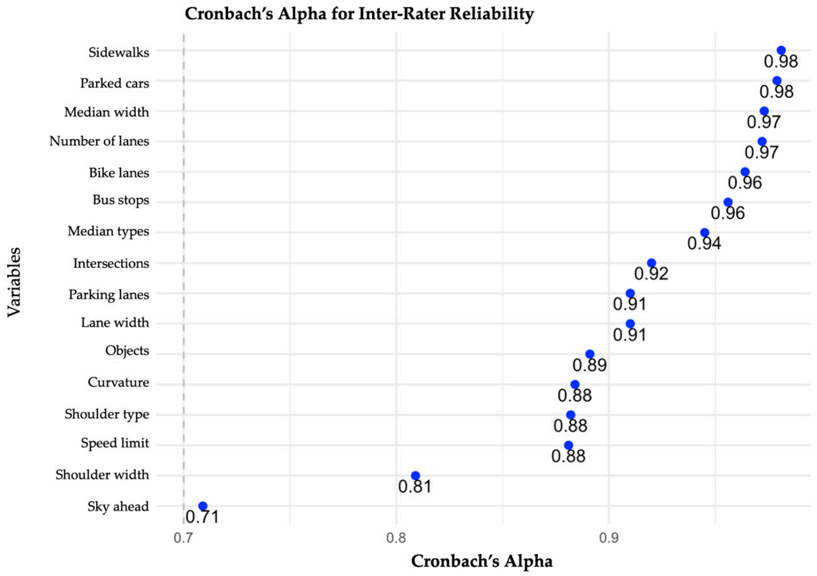


Figure 4. Inter-rater reliability test results for Cronbach's Alpha.

4. Results

4.1. Descriptive Statistics

To gain deeper insights into the database, we generated descriptive statistics, as shown in Table 4. In addition to the collected data, we added various dummy variables to the dataset to aid in the modeling. These variables assume a value of one if present and zero if absent. We also included and tested the natural logarithm of the lane width, hypothesizing that the average speed may be nonlinearly related to these variables.

Table 4. Statistical distribution of collected data for arterial sections in urban areas.

Variable	Mean	STD	Min	25%	50%	75%	Max
Length (miles)	0.57	0.29	0.13	0.32	0.51	0.80	1.51
Lane Width (ft)	11.62	0.90	9.43	11.01	11.63	12.11	14.91
Lane $\geq$ 12 ft (dummy)	0.34	0.47	0.0	0.0	0.0	1.0	1.0
Ln (Lane Width)	2.45	0.08	2.24	2.40	2.45	2.49	2.70
Num. Lanes	3.96	1.38	2.0	4.0	4.0	4.0	8.0
Median (dummy)	0.80	0.40	0.0	1.0	1.0	1.0	1.0
Non-traversable Median (dummy)	0.19	0.40	0.0	0.0	0.0	0.0	1.0
Median Width (ft)	10.86	7.02	0.00	8.97	12.30	14.07	41.73
Shoulder (dummy)	0.68	0.47	0.0	0.0	1.0	1.0	1.0
Shoulder Width (ft)	6.43	5.40	0.00	0.00	6.71	10.61	31.62
Sidewalk (dummy)	0.93	0.26	0.0	1.0	1.0	1.0	1.0
Bike Lane (dummy)	0.19	0.39	0.0	0.0	0.0	0.0	1.0
Bus Stop (dummy)	0.60	0.49	0.0	0.0	1.0	1.0	1.0
Parking Lane (dummy)	0.03	0.18	0.0	0.0	0.0	0.0	1.0
Num. Parked Cars	6.04	15.68	0.00	0.00	0.00	4.25	169.00
Parked Cars (/Mile)	12.84	33.11	0.00	0.00	0.00	9.76	362.02
Curve Length (ft)	3041.70	1548.27	699.61	1705.15	2682.23	4334.57	7995.77
Euclidean Length (ft)	3017.45	1528.49	700.83	1639.08	2677.24	4268.39	8036.47
Curvature (degree)	1.01	0.14	0.79	1.00	1.00	1.00	3.37
Sky Ahead	0.75	0.44	0.0	0.0	1.0	1.0	1.0
Roadside Objects	0.79	0.41	0.0	1.0	1.0	1.0	1.0
Intersections	3.56	2.96	0.0	1.0	3.0	5.0	15.0
Block Length (mi)	0.16	0.13	0.02	0.09	0.13	0.18	1.04
Speed Limit (mph)	38.30	6.54	25.0	35.0	40.0	40.0	70.0
AADT (in 1000s)	22.85	11.37	0.99	14.42	20.80	30.08	61.09
AADT (in 1000s per lane)	5.80	2.15	0.25	4.44	5.55	7.06	13.63
50th Percentile Speed	29.69	8.75	3.00	24.35	29.67	34.49	62.90
85th Percentile Speed	38.56	8.66	13.00	33.65	38.38	42.79	80.00
95th Percentile Speed	43.70	8.29	23.81	38.56	43.07	47.05	89.00

Table 4. *Cont.*

Variable	Mean	STD	Min	25%	50%	75%	Max
All Crash Count	6.06	6.61	0.0	1.0	4.0	8.0	41.0
Injury Crash Count	1.88	2.45	0.0	0.0	1.0	3.0	16.0
Fatal Crash Count	0.04	0.21	0.0	0.0	0.0	0.0	2.0
All Crash Count (/Mile)	11.01	11.72	0.0	3.0	7.5	15.0	83.0
Injury Crash Count (/Mile)	3.34	3.95	0.0	0.0	2.0	4.3	26.0
Fatal Crash Count (/Mile)	0.05	0.028	0.0	0.0	0.0	0.0	2.0

4.2. Modeling Speed

4.2.1. Linear Regression

Linear regression is a statistical method used to represent the relationship between a dependent variable and one or more independent variables. It assumes that a linear relationship exists between the dependent and independent variables. Linear regression seeks to identify the optimal line or plane that characterizes the connection, facilitating the prediction of the dependent variable's value based on the values of the independent variables. This research utilized a multiple linear regression model to examine and predict the speed. The model allowed us to analyze the correlation between the speed and several independent variables, including the lane width, geometric factors, annual average daily traffic, and roadside elements. The association between each independent variable and the dependent variable is established by holding all of the other variables in the regression equation constant.

4.2.2. Urban Arterial Speeds

The speed modeling started with a histogram of the lane width distribution of urban arterials (see Figure 5) and a scatterplot of the lane width vs. the 85th percentile speed for the UDOT urban arterials (see Figure 6). This dataset includes 320 roadway sections. There appears to be a weak but upward-sloping relationship between the two. The simple correlation coefficient between the two is 0.105, which is statistically significant at 0.065, but does not meet the conventional significance level of 0.05. We would expect a correlation coefficient as large as the lane width's by chance 6.5 percent of the time. The conventional significance level used in most statistical studies is 0.05, suggesting we would expect an effect this large by chance only 5 percent of the time (or for only 1 out of 20 random samples if there is no relationship between the lane width and speed). Of course, this disregards the effect of any confounding variables, such as the number of lanes or the presence of a non-traversable median.

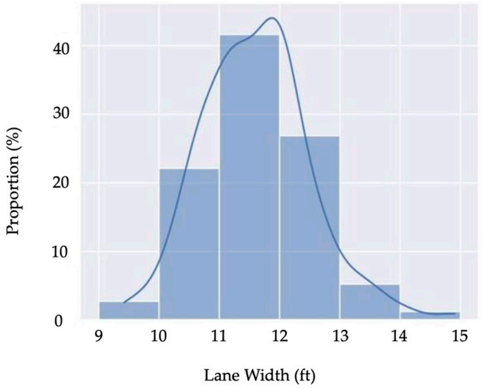


Figure 5. Lane width distribution of urban arterials and in the collected database.

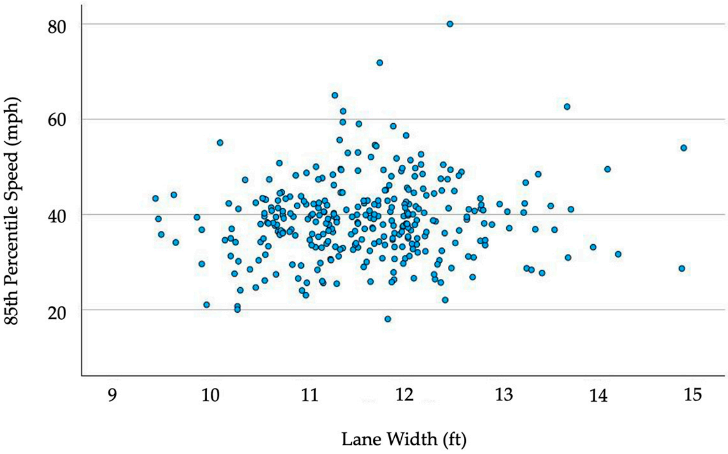


Figure 6. Scatterplot of lane width (in ft) vs. the 85th percentile speed (in mph) for the UDOT urban arterials.

We then estimated multiple regression models using the urban area dataset. We found the most significant variables after estimating numerous regression models with different sets of variables available in our dataset.

We began by modeling the 50th percentile using StreetLight speed data. The 50th percentile speed is at or below the speed at which 50 percent of the drivers travel on a road section. It is the median speed of travel. The 50th percentile speed is taken from data collected during a 24-h weekday. Controlling for other variables, the 50th percentile speed for our sample had a weak relationship to the lane width. While the variable lane width had a positive sign, implying faster speeds with wider lanes (as expected), the significance level of the lane width was 0.149, short of the standard 0.05 level.

Next, we modeled the 85th percentile speed for our independent variables, following the same procedure as for the 50th percentile or median speed, testing different independent variables. Traffic engineers and planners often use the 85th percentile speed to represent the upper end of the speed range. Posted speed limits are usually based on 85th percentile speeds. The results demonstrate that several variables, including the lane width, significantly impact the 85th percentile speed driven on a given roadway section. In the final model, only statistically significant independent variables were retained.

The R^2 is 0.405, meaning that the model explains more than 40 percent of the variance in the 85th percentile speed. We tested for multicollinearity, and there was none. The highest variance inflation factor (VIF) is 1.334, where values greater than 5.0 signal multicollinearity. We tested the logged forms of the dependent and independent variables (the non-binary variables) with no significant change in the results. We conducted diagnostic tests to assess the presence of heteroscedasticity in the residuals of our regression model. The results indicated no significant evidence of heteroscedasticity ($p > 0.05$), suggesting that the assumption of homoscedasticity was satisfied.

The lane width's significance level for the 85th percentile speed is 0.02, a result that would not be expected by chance. With a regression coefficient value of 1.012 compared to 0.674 in the 50th percentile speed model, the lane width appears to have more of an impact on higher-speed traffic than on typical-speed traffic. Table 5 presents the best-fit regression model for the 85th percentile speed on the UDOT urban arterials.

Table 5. Linear regression model for the 85th percentile speeds on the UDOT urban arterials.

Variable	Coefficient	Std. Error	t-Statistic	*p*-Value
(Intercept)	16.689	5.666	2.945	0.003 ***
Lane width (ft)	1.012	0.431	2.346	0.020 ***
Number of lanes	1.090	0.303	3.602	<0.001 ***
Non-traversable median (dummy)	−3.720	1.060	−3.508	0.001 ***
Parked cars (/mile)	−0.041	0.011	−3.607	<0.001 ***
Sky ahead (dummy)	2.004	0.937	2.139	0.033 **
Roadside objects *	−2.789	0.985	−2.832	0.005 ***
Block length (ft)	0.005	0.001	8.919	<0.001 ***
AADT (in 1000s per lane)	0.650	0.172	3.779	<0.001 ***
R^2		0.405		

Significance < 0.01 ***, <0.05 **, and 0.1 *.

Following this logic, we decided to model the 95th percentile speed for our sample of UDOT urban arterials. The 95th percentile speed represents the uppermost end of the speed range and is also used by traffic engineers and transportation planners, though not as pervasively as the 85th percentile speed. The regression coefficient of the lane width is 1.088, and the significance level is 0.011, showing again that lane width significantly impacts the vehicle speed at the upper end of the speed range. Table 6 presents the best-fit regression model for the 95th percentile speeds on urban arterials.

Table 6. Linear regression model for the 95th percentile speeds on the UDOT urban arterials.

Variable	Coefficient	Std. Error	t-Statistic	*p*-Value
(Intercept)	20.809	5.620	3.703	<0.001 ***
Lane width (ft)	1.088	0.428	2.543	0.011 **
Number of lanes	1.282	0.300	4.271	<0.001 ***
Non-traversable median (dummy)	−3.953	1.052	−3.759	<0.001 ***
Parked cars (/mile)	−0.041	0.011	−3.621	<0.001 ***
Sky ahead (dummy)	1.808	0.929	1.947	0.052 *
Objects (dummy)	−3.282	0.977	−3.360	0.001 ***
Block length (ft)	0.005	0.001	8.982	<0.001 ***
AADT (in 1000s per lane)	0.591	0.170	3.467	0.001 ***
R^2		0.421		

Significance < 0.01 ***, <0.05 **, and 0.1 *.

Controlling for other variables, each additional foot of lane width increases the 85th percentile speed and the 95th percentile speed by more than one mph. The difference between a roadway with 14-foot lanes and 10-foot lanes would be more than four mph. This conclusion comes with some limitations. First, our sample is substantial but not that large. Second, our sample consists solely of state-owned and operated arterials in Utah. There is almost certainly less variance in the dataset than there would be if collectors or locally owned arterials were included. On its arterials, Salt Lake City has been experimenting with many more narrow lanes than has UDOT. Third, while we tested for inter-rater reliability, there was an element of subjectivity in the different raters' estimates of independent variables.

StreetLight speed data are also based on a sample, albeit a large one. Regarding the other variables, the number of lanes positively impacts the speed. Specifically, the 85th percentile speed increases by 1.09 mph for each additional lane. Therefore, adding two lanes to a roadway (one in each direction) will increase the 85th percentile speeds by about the same amount as increasing the lane width by two feet. This observation has also been shown in road diet projects, where fewer lanes result in lower speeds, since the prudent driver sets the pace on the roadway with only one lane in each direction. A similar relationship is observed for the block length within the roadway section. The results indicate that the longer the blocks along the roadway, the higher the midblock speed.

Conversely, non-traversable medians in a roadway can significantly reduce the speed. Non-traversable medians are the most influential variable in reducing the 85th percentile speeds by 3.72 mph. The roadside objects variable has about the same effect on 85th percentile speeds as does a non-traversable median. Hence, it can be concluded that more buildings, trees, and other objects alongside a roadway section can reduce drivers' speed by more than 3 mph. Sky ahead has about two-thirds of this size effect. Additionally, the coefficient of on-street parking shows that the user's perception of the road can be influenced by side friction. Therefore, the "width" of the road is mainly influenced by drivers' perceptions, which affect the speed at which they drive.

It is important to note that the variables included in this model were selected after a thorough review of all of the collected variables. The excluded variables that either exhibited unexpected signs or which were insignificant in the roadway speed model. There was one exception: the AADT per lane in thousands was among those variables with a positive sign and a statistically significant p-value. It was expected that the sign would be negative due to congestion. Across 24 h, congestion does not influence state urban arterials. Indeed, possibly due to platooning, faster vehicles set the pace for slower vehicles.

4.3. Modeling Crashes

4.3.1. Count Regression Models

Traffic safety studies have employed various statistical models to analyze the relationship between cross-section design features and crash frequency, including Poisson and negative binomial models [33,35,64–69], zero-inflated negative binomial models [68,70,71], negative binomial models with random effects [68], Conway–Maxwell–Poisson generalized linear models [66], negative binomial models with random parameters [72], and dual-state negative binomial Markov-switching models [73,74].

Our dependent variable is the crash count on a roadway section, excluding intersection crashes, as these are primarily influenced by conflicting movements at intersections rather than midblock speeds. When the outcome variable is a count with non-negative integer values, many small values, and few large ones, the following two main analysis methods are used: Poisson regression and negative binomial regression.

The Poisson and negative binomial models differ in their assumptions regarding the distribution of the dependent variable. Negative binomial regression is preferred when the dependent variable exhibits overdispersion, meaning the variance of the counts exceeds the mean. Overdispersion is commonly assessed using the Pearson and $\chi 2$ statistics, divided by the degrees of freedom, known as dispersion statistics. If these statistics exceed 1.0, the frequency distribution is considered overdispersed. Based on these indicators, our data on crash counts show overdispersion, making the negative binomial model more suitable than the Poisson model for our analysis.

We started with three outcome variables—total crashes, injury crashes, and fatal crashes—but reduced it to two because fatal crashes are so rare. Only 3 percent of roadway sections in our sample experienced fatal crashes in 2021. Another statistical complication results from the fact that the variables of interest, crash counts and injury crash counts, were initially count variables for an entire section of roadway, each of varying length. Upon converting it to a total crash rate per mile and an injury crash rate per mile, the resultant output consisted of decimal values, which were subsequently rounded to restore the variable to its original count format, representing the total number of crashes and injury crashes per mile. This allowed us to apply a count model to the resulting dependent variable, the crash analysis norm.

A fourth statistical challenge is the excess of zero values in the injury count variable. While total crash counts on urban arterials generally follow a negative binomial distribution, 32% of urban sections report no injury crashes. To address this "zero inflation", a two-stage hurdle model is often used. The first stage estimates a binary logistic regression to differentiate between sections with and without injury crashes. The second stage applies a negative binomial regression to estimate injury crashes for sections with any injury crashes. Each model was finalized after a thorough variable selection process, ensuring the expected signs were obtained.

4.3.2. Urban Arterial Crashes

The crash modeling started by estimating multiple models using the urban area dataset. This dataset includes 320 roadway sections, and the most significant variables were found after estimating numerous regression models with different sets of variables available in our dataset.

We began by modeling total crashes per mile, including property damage-only crashes (level 1 crashes on a scale of 1 to 5). Using negative binomial regression, the only variables that proved significant were the number of travel lanes and AADT per lane in thousands of vehicles. More travel lanes suggest more weaving in and out of traffic, as aggressive drivers change lanes often carelessly. The preceding discussion of road diets applies here. More AADT per lane in thousands suggests more exposure to potential crashes and less space between vehicles for crash avoidance. Notably, neither the lane width nor the 85th percentile speed (nor, parenthetically, the 95th percentile speed) proved to be significant predictors of total crashes per mile. One could certainly imagine that lower-speed environments and the stop-and-go traffic accompanying them lead to more fender benders that offset more serious crashes in higher-speed environments. One could also imagine that narrower lanes cause drivers to exercise greater caution, since the driving environment is less forgiving, with one effect offsetting the other.

We next estimated a two-stage hurdle model for injury crashes per mile (crash levels 2 through 5). Hurdle modeling is a statistical technique for analyzing count data with many zero values. In such cases, traditional count models like Poisson or negative binomial regression may be inappropriate, since they assume that the count variable follows a particular distribution and does not account for the excess zeros [75]. Hurdle modeling addresses this issue by breaking down the count data into two parts. A binary part represents the presence or absence of the event of interest (i.e., whether the count is zero), and a counting part represents the number of such events (i.e., positive counts). The binary part is modeled using binary logistic regression, while the count part is modeled using a truncated count model (e.g., zero-truncated Poisson or negative binomial regression). By separately modeling the binary and counting parts of the data, we attempt to account for the excess zeros in our crash data and improve the accuracy of the statistical analysis.

4.3.3. Binary Logistic Regression of Injury Crash Occurrence

Binary logistic regression is a statistical method that models the relationship between a binary dependent variable (with two possible outcomes) and one or more independent variables. The dependent variable is represented as a function of the independent variables by a logit function, which converts any real-valued input into a value ranging from zero to one. The logit function calculates the likelihood that the dependent variable assumes a specific value contingent upon the independent variables. Our hurdle model employs this methodology to analyze the correlation between the incidence or absence of crashes and other predictor factors.

Using the urban dataset, our optimal model for predicting injury crash occurrences incorporates the lane width and the 85th percentile speed, together with the variables that demonstrated significance for total collision counts (refer to Table 7). Both are statistically significant at the 0.05 level and have positive coefficients. The correlation between speed and injury-related collisions is evident. The negative correlation between the lane width and injury crashes may be attributed to more prudent driver behavior when vehicles have reduced the clearance in multilane cross-sections.

Table 7. Binary model of injury crash occurrence in urban areas.

Variable	Coefficient	Std. Error	Wald Statistic	*p*-Value	Exp (Coeff)
(Constant)	−7.674	1.891	16.464	<0.001 ***	0.000
Lane width (ft)	0.325	0.145	5.025	0.025 **	1.383
Number of lanes	0.331	0.102	10.477	0.001 ***	1.393
AADT per lane	0.295	0.069	18.195	<0.001 ***	1.343
85th percentile speed	0.046	0.018	6.282	0.012 **	1.047
pseudo-R^2			0.204		

Significance < 0.01 ***, and <0.05 **.

The coefficient of the lane width in the binary logistic model is 0.325, indicating that a one-unit (ft) increase in lane width correlates with an odds increase of a crash occurring by a factor of e raised to the power of 0.325, or 1.383. This is known as an odds ratio. A 1 ft increase in lane width correlates with a 38.3 percent rise in the probability of a road segment experiencing an injury crash. The *p*-value for this coefficient is 0.025, signifying statistical significance at a high confidence level.

The coefficient for the 85th percentile speed in the binary logistic model is 0.046, indicating that a one-unit increase in speed (mph) correlates with an increase in the probabilities of a crash by a factor of e raised to the power of 0.046, or 1.047. This is again termed an odds ratio. A one mph increases in the 85th percentile speed correlates with a 4.7 percent rise in the odds of an injury crash. The *p*-value for this coefficient is 0.012, signifying statistical significance at a high confidence level.

Additional critical factors in the binary crash model are the number of lanes and the Average Annual Daily Traffic (AADT) per lane, measured in thousands. Both exhibit the anticipated relationship. An increase in travel lanes suggests a heightened weaving in traffic, as aggressive drivers frequently change their lanes. A higher AADT per lane indicates increased exposure to potential collisions and reduced spacing between vehicles for accident prevention.

4.3.4. Negative Binomial Regression

This analysis of injury crashes uses negative binomial regression within our hurdle model, following the adjustment for zero inflation (Table 8). We analyzed the positive values of injury collisions. Only the following two independent variables demonstrated statistical significance: AADT (in thousands) and a non-traversable median. Both the lane width and the 85th percentile speed were not statistically significant in this count model. This contradicts our previous finding that the incidence of injury crashes, treated as a binary variable, is associated with both the lane width and the 85th percentile speed. The fundamental concept of a hurdle model is that various processes may influence the occurrence of an event, and, if it occurs, different processes may influence the frequency of similar events. The anticipated number of crashes is just the product of the chance of a collision and the expected number of crashes, if applicable, that occur. Consequently, it can be asserted with certainty that wider lanes on urban arterials correlate with increased injury crashes.

Table 8. Negative binomial regression model of urban injury crashes.

Variable	Coefficient	Std. Error	Z-Value	*p*-Value
(Constant)	−0.91	2.90	−0.31	0.750
AADT (in 1000)	0.03	0.00	6.30	<0.001 ***
85th percentile speed (mph)	0.04	0.07	0.48	0.630
Lane width (ft)	0.17	0.24	0.71	0.480
Non-traversable median	−0.39	0.12	−3.29	<0.001 ***
Number of lanes	0.07	0.05	1.58	0.111

Significance < 0.01 ***.

5. Discussion

These results suggest that narrower travel lanes significantly affect the speed and traffic safety, decreasing vehicle speeds and reducing severe crashes. Narrowing lane widths can also provide a more balanced roadway environment, where vehicle speeds are moderated, and the risk of severe crashes is reduced. This study offers several implications supporting the feasibility and safety benefits of reducing lane widths on urban arterials.

First, reducing lane widths can serve as an effective strategy to improve road safety on urban arterials. Narrower lanes encourage drivers to slow down, thereby reducing the likelihood and severity of crashes. These results align with some studies [18,22]. This reduction in vehicle speeds is particularly beneficial in areas with high pedestrian or cyclist activity, where the risk of severe accidents is more pronounced.

Secondly, road safety is affected by the aggregated effect of many road design attributes. No single attribute can be identified as the exclusive cause of crashes [76]. Road design attributes, including lane width and traffic volume, interact to impact safety outcomes. For example, although parameters like road curvature [77–79] and lane width [28,80,81] are important, the safety implications of these factors can vary depending on traffic conditions, including vehicle volume and speeds. Understanding these interactions is critical for developing comprehensive and context-sensitive safety measures.

Third, enhancing the infrastructure for safety measures or multimodal transportation is another key benefit of reducing lane widths. By reallocating roadway space, narrower lanes provide opportunities for adding bike lanes, sidewalks, and median refuge islands. For instance, the Utah Department of Transportation (UDOT) implemented traffic safety countermeasures, such as high-intensity activated crosswalk (HAWK) signals, overhead warning flashers with HAWK signals, and Rectangular Rapid Flashing Beacons (RRFBs), all of which effectively reduced crash rates [82]. Younes et al. [83] suggest a secondary benefit of bicycle lanes. By having a traffic-calming effect, delineated bicycle lanes may decrease the risk and severity of crashes for pedestrians and other road users [83]. These changes not only improve the safety and convenience of non-motorized users but also contribute to more sustainable transportation systems by encouraging walking and cycling.

Overall, this study contributes to the growing body of evidence suggesting that reducing lane widths can improve road safety, enhance multimodal infrastructure, and promote more sustainable urban transportation systems. The inference is as follows: the State of Utah should adopt a minimum lane width of 10 or 11 feet on arterials running through highly urbanized areas to reduce speeds and crashes, and make room for bike lanes, planted medians, wider sidewalks, and other pedestrian and bicyclist countermeasures.

6. Conclusions

In conclusion, this paper comprehensively studied the relationship between the lane width, speed, and crash rates on urban arterial sections throughout Utah. The study comprised the following two key components: a thorough literature review investigating the effects of narrower travel lanes and other geometric design features on speed, safety, and transportation impacts, and statistical analyses examining various factors affecting roadway performance.

Using data from 320 urban arterial sections in Utah, the analysis revealed that narrower lane widths are associated with reduced vehicle speeds. For every additional foot of lane width, the 85th and 95th percentile speeds increase by 1.012 mph and 1.088 mph, respectively. Furthermore, injury crash modeling indicates that a one-foot increase in lane width is associated with a 38.3% increase in the odds of an injury crash on a roadway section.

The literature review confirmed the potential effects of narrower travel lanes on speed, safety, and other transportation aspects. The statistical analyses provided significant implications for urban arterials. In urban areas, narrowing the lane width leads to substantial reductions in vehicle speeds without increasing the crash rates. The additional space gained from narrower lanes offers opportunities to implement various safety and pedestrian-friendly enhancements. Consequently, we recommend revising the current minimum lane width standard of the Utah DOT, particularly in low-speed, highly urbanized areas, and potentially exploring further reductions in specific cases while considering exceptions for areas with heavy truck traffic. Several other state DOTs have adopted this best practice [51,80].

Furthermore, the speed models demonstrate the significant influence of the lane width on speed for urban arterials, with narrower lanes associated with lower speeds. Other factors, such as the number of lanes, non-traversable medians, on-street parking density, roadside objects, and average block length, also impact speed on urban arterials.

Despite the meaningful findings, certain limitations must be acknowledged. First, some subjectivity measurement of road design attributes may have influenced the results. For instance, coding road design attributes, such as roadside objects and sky ahead, involved a degree of subjectivity. Second, the findings limit the generalizability to urban arterials owned and operated by a single state DOT. Although we modeled rural arterials in Utah, we decided to focus on the urban model due to the relatively small sample size of the rural cases. In addition, while the Abbreviated Injury Scale (AIS) is one of the most widely known measurements for injury severity, this study could not consider the AIS scoring system for evaluating injury crash models, since the data collection unit of the Utah Department of Public Safety (UDPS) does not follow this scoring system. Lastly, theoretically significant variables, such as driver behavior, real-time weather conditions, vehicle speeds of off-peak hours, and daily variations in traffic volume, were not included as predictors, which may limit the comprehensiveness of the findings. Regarding the driver characteristics, as we have aggregated crash information at the section level, it was inevitable to omit the individual driver characteristics. The data availability also limits the analysis of driver characteristics.

Therefore, incorporating real-time variables and addressing the subjectivity in road design measurement will enhance the robustness and applicability of future studies. Regarding injury severity measurements, future studies should consider more reliable measurement methods, such as the Abbreviated Injury Scale (AIS). Additionally, increasing the sample size of rural arterial cases will improve the generalizability of the findings across different contexts. Moreover, future research should explore factors such as off-peak hour speeds, seasonal variations, detailed traffic flow, pedestrian safety, and infrastructure costs to better understand the interplay between road design and broader transportation outcomes.

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References

1. World Health Organization (WHO) Road Traffic Injuries. Available online: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries (accessed on 24 December 2024).
2. Macioszek, E.; Kurek, A. Road Traffic Distribution on Public Holidays and Workdays on Selected Road Transport Network Elements. *Transp. Probl.* **2021**, *16*, 127–138. [CrossRef]
3. Hauer, E. *Safety in Geometric Design Standards*; University of Toronto: Toronto, ON, Canada, 1999.
4. Liu, J.; Guo, Z.; Shan, D.; Liu, X. Effective Lane Width for Cars Considering Lateral Oscillation Characteristics Based on High-Precision Field Data. *Int. J. Transp. Sci. Technol.* **2023**, *16*, 18–33. [CrossRef]
5. Swift, P.; Painter, D.; Goldstein, M. *Residential Street Typology and Injury Accident Frequency*; Congress for the New Urbanism: Denver, CO, USA, 1997.
6. Abdel-Rahim, A.; Sonnen, J. *Potential Safety Effects of Lane Width and Shoulder Width on Two-Lane Rural State Highways in Idaho*; University of Idaho: Moscow, ID, USA, 2012; 52p.
7. Pokorny, P.; Jensen, J.K.; Gross, F.; Pitera, K. Safety Effects of Traffic Lane and Shoulder Widths on Two-Lane Undivided Rural Roads: A Matched Case-Control Study from Norway. *Accid. Anal. Prev.* **2020**, *144*, 105614. [CrossRef] [PubMed]
8. Rahman, Z.; Memarian, A.; Madanu, S.; Iqbal, G.; Anahideh, H.; Mattingly, S.P.; Rosenberger, J.M. Assessment of the Impact of Lane Width on Arterial Crashes. *J. Transp. Saf. Secur.* **2018**, *10*, 229–250. [CrossRef]
9. Rista, E.; Goswamy, A.; Wang, B.; Barrette, T.; Hamzeie, R.; Russo, B.; Bou-Saab, G.; Savolainen, P.T. Examining the Safety Impacts of Narrow Lane Widths on Urban/Suburban Arterials: Estimation of a Panel Data Random Parameters Negative Binomial Model. *J. Transp. Saf. Secur.* **2018**, *10*, 213–228. [CrossRef]
10. Godley, S.T.; Triggs, T.J.; Fildes, B.N. Perceptual Lane Width, Wide Perceptual Road Centre Markings and Driving Speeds. *Ergonomics* **2004**, *47*, 237–256. [CrossRef]
11. Manuel, A.; El-Basyouny, K.; Islam, M.T. Investigating the Safety Effects of Road Width on Urban Collector Roadways. *Saf. Sci.* **2014**, *62*, 305–311. [CrossRef]
12. Potts, I.B.; Harwood, D.W.; Richard, K.R. Relationship of Lane Width to Safety on Urban and Suburban Arterials. *Transp. Res. Rec.* **2007**, *2023*, 63–82. [CrossRef]
13. Ahmed, M.; Huang, H.; Abdel-Aty, M.; Guevara, B. Exploring a Bayesian Hierarchical Approach for Developing Safety Performance Functions for a Mountainous Freeway. *Accid. Anal. Prev.* **2011**, *43*, 1581–1589. [CrossRef]
14. Pande, A.; Abdel-Aty, M. A Novel Approach for Analyzing Severe Crash Patterns on Multilane Highways. *Accid. Anal. Prev.* **2009**, *41*, 985–994. [CrossRef]
15. Zhu, H.; Dixon, K.K.; Washington, S.; Jared, D.M. Predicting Single-Vehicle Fatal Crashes for Two-Lane Rural Highways in Southeastern United States. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2147*, 88–96. [CrossRef]
16. Nowakowska, M. Logistic Models in Crash Severity Classification Based on Road Characteristics. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2148*, 16–26. [CrossRef]
17. Gårder, P. Segment Characteristics and Severity of Head-on Crashes on Two-Lane Rural Highways in Maine. *Accid. Anal. Prev.* **2006**, *38*, 652–661. [CrossRef]
18. Dumbaugh, E. Design of Safe Urban Roadsides. *Transp. Res. Rec. J. Transp. Res. Board* **2006**, *1961*, 74–82. [CrossRef]
19. Hauer, E.; Council, F.M.; Mohammedshah, Y. Safety Models for Urban Four-Lane Undivided Road Segments. *Transp. Res. Rec.* **2004**, *1897*, 96–105. [CrossRef]
20. Strathman, J.G.; Dueker, K.J.; Zhang, J.; Williams, T. *Analysis of Design Attributes and Crashes on the Oregon Highway System*; Oregon Department of Transportation: Salem, OR, USA, 2001; Volume 2.

21. Parsons Transportation Group. *Relationship Between Lane Width and Speed Review of Relevant Literature*; Columbia Pike Street Space Planning Task Force: Arlington, VA, USA, 2003; pp. 1–6.
22. Harwood, D.W. *Effective Utilization of Street Width on Urban Arterials*; Transportation Research Board: Washington, DC, USA, 1990; ISBN 0-309-04853-2.
23. Dumbaugh, E.; Gattis, J.L. Safe Streets, Livable Streets. *J. Am. Plan. Assoc.* **2005**, *71*, 283–300. [CrossRef]
24. Mecheri, S.; Rosey, F.; Lobjois, R. The Effects of Lane Width, Shoulder Width, and Road Cross-Sectional Reallocation on Drivers' Behavioral Adaptations. *Accid. Anal. Prev.* **2017**, *104*, 65–73. [CrossRef]
25. Zheng, J.; Sun, J.; Yang, J. Relationship of Lane Width to Capacity for Urban Expressways. *Transp. Res. Rec.* **2015**, *2483*, 10–19. [CrossRef]
26. Bobermin, M.P.; Silva, M.M.; Ferreira, S. Driving Simulators to Evaluate Road Geometric Design Effects on Driver Behaviour: A Systematic Review. *Accid. Anal. Prev.* **2021**, *150*, 105923. [CrossRef]
27. Ewan, L.; Al-Kaisy, A.; Hossain, F. Safety Effects of Road Geometry and Roadside Features on Low-Volume Roads in Oregon. *Transp. Res. Rec.* **2016**, *2580*, 47–55. [CrossRef]
28. Gargoum, S.A.; El-Basyouny, K. Exploring the Association between Speed and Safety: A Path Analysis Approach. *Accid. Anal. Prev.* **2016**, *93*, 32–40. [CrossRef] [PubMed]
29. Bamzai, R.; Lee, Y.; Li, Z. *Safety Impacts of Highway Shoulder Attributes in Illinois*; Illinois Department of Transportation: Springfield, IL, USA, 2011.
30. Gitelman, V.; Doveh, E.; Carmel, R.; Hakkert, S. The Influence of Shoulder Characteristics on the Safety Level of Two-Lane Roads: A Case-Study. *Accid. Anal. Prev.* **2019**, *122*, 108–118. [CrossRef] [PubMed]
31. Arévalo-Támara, A.; Orozco-Fontalvo, M.; Cantillo, V. Factors Influencing Crash Frequency on Colombian Rural Roads. *Promet-Traffic-Traffico* **2020**, *32*, 449–460. [CrossRef]
32. Gross, F.; Jovanis, P.P. Estimation of the Safety Effectiveness of Lane and Shoulder Width: Case-Control Approach. *J. Transp. Eng.* **2007**, *133*, 362–369. [CrossRef]
33. Abdel-Aty, M.A.; Radwan, A.E. Modeling Traffic Accident Occurrence and Involvement. *Accid. Anal. Prev.* **2000**, *32*, 633–642. [CrossRef]
34. Council, F.M.; Stewart, J.R. Safety Effects of the Conversion of Rural Two-Lane to Four-Lane Roadways Based on Cross-Sectional Models. *Transp. Res. Rec.* **1999**, *1665*, 35–43. [CrossRef]
35. Milton, J.; Mannering, F. The Relationship among Highway Geometrics, Traffic-Related Elements and Motor-Vehicle Accident Frequencies. *Transportation* **1998**, *25*, 395–413. [CrossRef]
36. Ma, J.; Kockelman, K.M. Bayesian Multivariate Poisson Regression for Models of Injury Count, by Severity. *Transp. Res. Rec. J. Transp. Res. Board* **2006**, *1950*, 24–34. [CrossRef]
37. Park, J.; Abdel-Aty, M.; Wang, J.-H.; Lee, C. Assessment of Safety Effects for Widening Urban Roadways in Developing Crash Modification Functions Using Nonlinearizing Link Functions. *Accid. Anal. Prev.* **2015**, *79*, 80–87. [CrossRef]
38. Imprialou, M.I.M.; Quddus, M.; Pitfield, D.E.; Lord, D. Re-Visiting Crash-Speed Relationships: A New Perspective in Crash Modelling. *Accid. Anal. Prev.* **2016**, *86*, 173–185. [CrossRef]
39. Biswas, S.; Chandra, S.; Ghosh, I. Effects of On-Street Parking in Urban Context: A Critical Review. *Transp. Dev. Econ.* **2017**, *3*, 10. [CrossRef]
40. Krieger, A.; Lennertz, W. *Andres Duany and Elizabeth Plater-Zyberk: Towns and Town-Making Principles*; Harvard University Graduate School of Design: Cambridge, MA, USA, 1991.
41. De Cerreño, A.L.C. Dynamics of On-Street Parking in Large Central Cities. *Transp. Res. Rec.* **2004**, 130–137. [CrossRef]
42. Ossenbruggen, P.J.; Pendharkar, J.; Ivan, J. Roadway Safety in Rural and Small Urbanized Areas. *Accid. Anal. Prev.* **2001**, *33*, 485–498. [CrossRef] [PubMed]
43. Søren, B.; Jensen, U. Road Safety and Perceived Risk of Cycle Facilities in Copenhagen. In *Presentation to AGM of European Cyclists Federation*; 2007; pp. 1–9. Available online: https://www.researchgate.net/publication/235358599_Road_safety_and_perceived_risk_of_cycle_facilities_in_Copenhagen (accessed on 14 September 2024).
44. Kraidi, R.; Evdorides, H. Pedestrian Safety Models for Urban Environments with High Roadside Activities. *Saf. Sci.* **2020**, *130*, 104847. [CrossRef]
45. Edquist, J.; Rudin-Brown, C.M.; Lenné, M.G. The Effects of On-Street Parking and Road Environment Visual Complexity on Travel Speed and Reaction Time. *Accid. Anal. Prev.* **2012**, *45*, 759–765. [CrossRef]
46. Harvey, C.; Aultman-hall, L. Urban Streetscape Design and Crash Severity. *Transp. Res. Rec.* **2015**, *2500*, 1–8. [CrossRef]
47. Moradi, A.; Saeed, S.; Nazari, H.; Rahmani, K. Sleepiness and the Risk of Road Traffic Accidents: A Systematic Review and Meta-Analysis of Previous Studies. *Transp. Res. Part F Psychol. Behav.* **2019**, *65*, 620–629. [CrossRef]
48. Young, K.L.; Salmon, P.M. Examining the Relationship between Driver Distraction and Driving Errors: A Discussion of Theory, Studies and Methods. *Saf. Sci.* **2012**, *50*, 165–174. [CrossRef]

49. Naderi, J.R. Landscape Design in Clear Zone Effect of Landscape Variables on Pedestrian Health and Driver Safety. *Transp. Res. Rec. J. Transp. Res. Board* **2003**, *1851*, 119–130. [CrossRef]
50. Ewing, R.; Handy, S. Measuring the Unmeasurable: Urban Design Qualities Related to Walkability Measuring the Unmeasurable: Urban Design Qualities Related to Walkability. *J. Urban Des.* **2009**, *14*, 65–84. [CrossRef]
51. Ewing, R.; Yang, W.; Promy, N.S.; Kaniewska, J.; Tabassum, N. Selective State DOT Lane Width Standards and Guidelines to Reduce Speeds and Improve Safety. *Infrastructures* **2024**, *9*, 141. [CrossRef]
52. Shao, C.Q.; Rong, J.; Liu, X.M. Study on the Saturation Flow Rate and Its Influence Factors at Signalized Intersections in China. *Procedia Soc. Behav. Sci.* **2011**, *16*, 504–514. [CrossRef]
53. Susilo, B.H.; Solihin, Y. Modification of Saturation Flow Formula by Width of Road Approach. *Procedia Soc. Behav. Sci.* **2011**, *16*, 620–629. [CrossRef]
54. Chen, P.; Nakamura, H.; Asano, M. Saturation Flow Rate Analysis for Shared Left-Turn Lane at Signalized Intersections in Japan. *Procedia Soc. Behav. Sci.* **2011**, *16*, 548–559. [CrossRef]
55. Chandra, S.; Kumar, U. Effect of Lane Width on Capacity under Mixed Traffic Conditions in India. *J. Transp. Eng.* **2003**, *129*, 155–160. [CrossRef]
56. Patkar, M.; Dhamaniya, A. Effect of On-Street Width and Capacity of Urban Arterial Roads in India. 2019. Available online: https://www.istiee.unict.it/europeantransport/papers/N73/P01_73_2019.pdf (accessed on 11 January 2025).
57. *FHWA Road Diets (Roadway Reconfiguration)*; U.S. Department of Transportation Federal Highway Administration: Washington, DC, USA, 2010.
58. Gudz, E.M.; Fang, K.; Handy, S.L. When a Diet Prompts a Gain Impact of a Road Diet on Bicycling in Davis, California. *Transp. Res. Rec.* **2016**, *2587*, 61–67. [CrossRef]
59. Ntonifor, C. Valuation of the Impacts of Road Diet Implementation: Wilson Boulevard Road Diet, Arlington County Virginia. Master's Thesis, Morgan State University, Baltimore, MD, USA, 2017.
60. Anderson, G.; Searfoss, L. *Safer Streets, Stronger Economies*; Smart Growth America: Washington, DC, USA, 2015; p. 40.
61. Yang, W. Micromobility and Built Environment: Making It Accessible, Affordable, and Safe for Everyone. Ph.D. Thesis, University of Utah, Salt Lake City, UT, USA, 2023.
62. Liu, C.; Zhao, M.; Li, W.; Sharma, A. Multivariate Random Parameters Zero-Inflated Negative Binomial Regression for Analyzing Urban Midblock Crashes. *Anal. Methods Accid. Res.* **2018**, *17*, 32–46. [CrossRef]
63. Chen, T.; Sze, N.N.; Chen, S.; Labi, S. Urban Road Space Allocation Incorporating the Safety and Construction Cost Impacts of Lane and Footpath Widths. *J. Safety Res.* **2020**, *75*, 222–232. [CrossRef]
64. Hadi, M.A.; Aruldhas, J.; Chow, L.F.; Wattleworth, J.A. Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression. *Transp. Res. Rec.* **1995**, *1500*, 169–177.
65. Jones, B.; Janssen, L.; Mannering, F. Analysis of the Frequency and Duration of Freeway Accidents in Seattle. *Accid. Anal. Prev.* **1991**, *23*, 239–255. [CrossRef]
66. Lord, D.; Park, P.Y.J. Investigating the Effects of the Fixed and Varying Dispersion Parameters of Poisson-Gamma Models on Empirical Bayes Estimates. *Accid. Anal. Prev.* **2008**, *40*, 1441–1457. [CrossRef] [PubMed]
67. Poch, M.; Mannering, F. Negative Binomial Analysis of Intersection-Accident Frequencies. *J. Transp. Eng.* **1996**, *122*, 105–113. [CrossRef]
68. Shankar, V.; Mannering, F.; Barfield, W. Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies. *Accid. Anal. Prev.* **1995**, *27*, 371–389. [CrossRef] [PubMed]
69. Zhao, J.; Liu, Y.; Wang, T. Increasing Signalized Intersection Capacity with Unconventional Use of Special Width Approach Lanes. *Comput.-Aided Civ. Infrastruct. Eng.* **2016**, *31*, 794–810. [CrossRef]
70. Carson, J.; Mannering, F. The Effect of Ice Warning Signs on Ice-Accident Frequencies and Severities. *Accid. Anal. Prev.* **2001**, *33*, 99–109. [CrossRef]
71. Lee, J.; Mannering, F. Impact of Roadside Features on the Frequency and Severity of Run-off-Roadway Accidents: An Empirical Analysis. *Accid. Anal. Prev.* **2002**, *34*, 149–161. [CrossRef]
72. Anastasopoulos, P.C.; Mannering, F.L. A Note on Modeling Vehicle Accident Frequencies with Random-Parameters Count Models. *Accid. Anal. Prev.* **2009**, *41*, 153–159. [CrossRef]
73. Malyshkina, N.V.; Mannering, F.L. Zero-State Markov Switching Count-Data Models: An Empirical Assessment. *Accid. Anal. Prev.* **2010**, *42*, 122–130. [CrossRef]
74. Malyshkina, N.V.; Mannering, F.L. Empirical Assessment of the Impact of Highway Design Exceptions on the Frequency and Severity of Vehicle Accidents. *Accid. Anal. Prev.* **2010**, *42*, 131–139. [CrossRef]
75. McDowell, A. From the Help Desk: Hurdle Models. *Stata J. Promot. Commun. Stat. Stata* **2003**, *3*, 178–184. [CrossRef]
76. Yang, W.; Han, S. Direct and Indirect Effects of Road Design Attributes on Traffic Safety. *J. Safety Res.* **2025**, *93*. [CrossRef]
77. Gooch, J.P.; Gayah, V.V.; Donnell, E.T. Quantifying the Safety Effects of Horizontal Curves on Two-Way, Two-Lane Rural Roads. *Accid. Anal. Prev.* **2016**, *92*, 71–81. [CrossRef] [PubMed]

78. Watson, D.C.; Al-kaisy, A.; Anderson, N.D. Examining the Effect of Speed, Roadside Features, and Roadway Geometry on Crash Experience along a Rural Corridor. *J. Mod. Transp.* **2014**, *22*, 84–95. [CrossRef]
79. Wu, Y.; Nakamura, H.; Asano, M. A Comparative Study on Crash-Influencing Factors by Facility Types on Urban Expressway. *J. Mod. Transp.* **2013**, *21*, 224–235. [CrossRef]
80. Ewing, R.; Promy, N.S.; Choi, D.; Yang, W.; Tabassum, N.; Kaniewska, J.; Ameli, H.; Tuffour, J.P.; Kalantari, H.A.; Azin, B.; et al. *Transportation Benefits and Costs of Reducing Lane Widths on Urban and Rural Arterials*; University of Utah: Salt Lake City, UT, USA, 2024.
81. Hamidi, S.; Ewing, R. *A National Investigation on the Impacts of Lane Width on Traffic Safety: Narrowing Travel Lanes as an Opportunity to Promote Biking and Pedestrian Facilities Within the Existing Roadway Infrastructure*; Johns Hopkins: Baltimore, MD, USA, 2023.
82. Kim, J.; Ewing, R.; Yang, W.; Abdollahzadeh Kalantari, H. Short and Mid-Term Effect of the Streetcar on Vehicle-Vehicle (and Vehicle-Pedestrian) Crash Rate on the Adjacent Street. *Case Stud. Transp. Policy* **2024**, *17*, 101262. [CrossRef]
83. Younes, H.; Andrews, C.; Noland, R.B.; Xia, J.; Wen, S.; Zhang, W.; Metaxas, D.; Von Hagen, L.A.; Gong, J. The Traffic Calming Effect of Delineated Bicycle Lanes. *J. Urban Mobil.* **2024**, *5*, 100071. [CrossRef]