In Search of Simultaneous Benefits of Infrastructure Provisions on Freight & Bicycle Movements
Final Report

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About the Western Transportation Institute

The Western Transportation Institute (WTI) was founded in 1994 by the Montana and California Departments of Transportation, in cooperation with Montana State University. WTI concentrates on rural transportation research; as stewards and champions of rural America, WTI also has a strong interest in sustainability. WTI research groups create solutions that work for clients, sponsors, and rural transportation research partners. WTI Research Centers include the Montana Local Technical Assistance Program, the National Center for Rural Road Safety, the Small Urban, Rural and Tribal Center on Mobility, the Federal-Public Lands Transportation Institute, and the West Region Transportation Workforce Center.

About the Small Urban, Rural and Tribal Center on Mobility

The mission of the Small Urban, Rural and Tribal Center on Mobility (SURTCOM) is to conduct research and provide leadership, education, workforce development and technology transfer in all transportation-related aspects of mobility for people and goods, focusing specifically on small urban, rural and tribal areas. Member institutions include the Western Transportation Institute at Montana State University, the Upper Great Plains Transportation Institute at North Dakota State University, and the Urban and Regional Planning program at Eastern Washington University.

Disclaimer

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1 Introduction

The United States has three million miles of rural roadways (U.S. Department of Transportation, Federal Highway Administration, 2000). Some bicyclists enjoy recreating on low-volume rural roadways because they are looking for long rides to physically challenge themselves. Some rural Americans commute to work by bicycle or travel by bike for other trips (e.g., to the grocery store), whether they are driven by environmental motivators (they do not want to further pollute the environment) or practical purposes (they have limited or no vehicles in their households but still need to make trips). Regardless of the reason, bicyclists can be found on rural roadways. While many riders may self-select onto lower-volume roadways and roadways where there are fewer large vehicles, the limited redundancy of some rural roadway networks may force bicyclists to travel on roadways with higher traffic volumes, with higher posted speed limits, and with large vehicles. With extensive miles in the rural context, the question then becomes: can providing additional pavement in the form of wide shoulders benefit both motorists, particularly those in large vehicles carrying freight, and bicyclists on roadways used by both, or should a separated facility, like a cycle highway, be considered instead? Thus, the purpose of this project is to consider whether wider road shoulders could benefit both freight and bicyclists traveling along rural roadways. Through a literature review focused on the crash experience of bicyclists, the impact of the road design on a bicyclist's crash experience, the impact of the vehicle type and vehicle technology on a bicyclist's crash experience, and policies impacting how and where a bicyclist may travel, recommendations and conclusions are made regarding if benefits can be had by both bicyclists and freight (a.k.a., large vehicles) within a corridor.

2 Literature Review

The literature review is divided into four sections: 1) bicycle, 2) roadway, 3) vehicle, and 4) policy, as these four components are at the heart of this analysis. First, the literature, both domestic and international, reviews the statistics of bicycle injury and fatal crashes identified by previous studies. The subsequent section presents and then summarizes the literature related to the roadway, with a focus on how widening the road shoulder may bring safety benefits to bicyclists and freight (e.g., large vehicles). Then after, a review is conducted of the influences of vehicle type on bicyclist crash type (e.g., injury or fatal crash) as well as the availability of vehicle technology to help mitigate crashes with bicyclists. Finally, a short discussion of policies is presented. Each section closes out with a summary of all the reviewed literature as well as findings based upon the review.

2.1 Bicycle

This section details literature about bicycle crash statistics, ordered chronologically.

Stutts and Hunter (Stutts & Hunter, 1999) analyzed data from eight hospital emergency departments that represented urban, suburban, and rural locations. They were attempting to better understand: 1) motor vehicle/non-roadway, 2) no motor vehicle/roadway, and 3) no motor vehicle/non-roadway crashes because the majority of studies analyzed motor vehicle/roadway crashes. The hospitals were in New York (urban), California (urban and suburban), and North Carolina (rural). A total of 2,558 bicyclists and pedestrians were treated between January 1, 1995, and May 1, 1996. Crashes involving two bicyclists, as well as bicyclist/pedestrian crashes, were removed from further analysis. Stutts and Hunter found that rural locations were associated with more severe crashes, and the crashes often involved a motor vehicle. Considering all the data, Stutts and Hunter concluded that "bicycle-motor vehicle events occurring on the roadway had by far the most serious consequences." Furthermore, "five of the six documented fatalities (those cases where the bicyclist was transported to the emergency department) also resulted from motor vehicle roadway collisions." For bicyclists hospitalized, Stutts and Hunter estimated that forty-three percent would have gone unreported in the traditional crash database (i.e., they were not motor vehicle/roadway crashes). For those treated in the emergency department and released, seventy-four percent were expected to have gone unreported. When considering the injury characteristics, Stutts and Hunter reported finding that heads and trunk areas were more likely to be injured, which they suggested were the result of higher speeds of both the bicyclist and motorist.

In the United States, bicyclists were twelve times more likely than vehicle occupants to die per kilometer traveled in 2001, alluding to the vulnerability of bicyclists traveling on a roadway (Pucher & Dijkstra, 2003).

Carter and Council (2006) analyzed North Carolina crash data from 1997 to 2002 to better understand: 1) the differences between urban and rural bicycle and pedestrian crashes, 2) the characteristics of bicycle and pedestrian crash types, and 3) bicycle and pedestrian crash locations on rural highways (Carter & Council, 2006). All crashes considered occurred on state-maintained roadways. Low-volume roadways were not part of the study, as information was not available for them in the Highway Safety Information System (HSIS) database. A total of 1,849 bicycle-vehicle crashes were identified, 956 (52%) of which occurred on rural roadways. The majority occurred during daylight. Two age groups (0-9 years old and 10-14 years old) were overrepresented when comparing rural to urban bicycle-vehicle crashes. The majority of bicyclists involved in the crashes in both contexts (rural and urban) were male. White bicyclists were overrepresented in rural crashes, whereas Black and Hispanic bicyclists were overrepresented in urban crashes. Most drivers involved in crashes with bicyclists in rural areas identified as White whereas Black drivers were overrepresented in urban areas. Estimated speeds of vehicles involved in rural bicycle/vehicle crashes were significantly higher than in urban crashes. The majority of rural crashes (80%) occurred on roadways that did not have paved shoulders; the unpaved shoulders ranged from 4 to 8 feet wide. Some crashes did occur on roadways with paved shoulders, which ranged from 8 to 16 feet. Crashes between bicyclists and vehicles in rural areas almost always occurred when both the motorist and bicyclist were traveling in the same direction. Most often, the bicyclist was traveling in the travel lane (74%) or bicycle lane/shoulder (10%). Rural bicyclist crashes were found to experience more disabling injuries and fatalities when compared with urban bicyclist crashes. Carter and Council summarized their findings for overrepresented bicycle crashes as found in Table 1. When considering potential countermeasures to address bicyclist crashes, Carter and Council suggested, "The addition of paved shoulders was recommended as a low-cost option for areas where adding sidewalks may be infeasible."

Table 1. Characteristics of Overrepresented Bicycle Crashes

Bicyclist Crashes	**Bicycle Turn/Merge into Path of Motorist, Midblock**	**Motorist Overtaking, Midblock**	**Bicyclist Failed to Yield, Midblock**	**Bicyclist Failed to Yield, Intersection**	
	Rural Two-Lane (R2L)	**R2L**	**R2L**	**R2L**	**Rural, multilane divided non-freeway**
Number of Crashes in Dataset	225	175	83	45	10
Bicyclist Age	Young bicyclists	Adult bicyclists	Young bicyclists	Young bicyclists	Young bicyclists
Bicyclist Injury		Fatalities	Type A Injuries*		
Estimated Speed of Vehicle	High speeds (55 mph or higher)		Mid-range speeds (25-45 mph)	Mid-range speeds (25-45 mph)	High speeds (55 mph or higher)
Bicyclist Position		In a travel lane			
Light Condition	Same direction as traffic				

Bicyclist Crashes	**Bicycle Turn/Merge into Path of Motorist, Midblock**	**Motorist Overtaking, Midblock**	**Bicyclist Failed to Yield, Midblock**	**Bicyclist Failed to Yield, Intersection**	
	Rural Two-Lane (R2L)	**R2L**	**R2L**	**R2L**	**Rural, multilane divided non-freeway**
Day of Week	Daylight	Dark, unlighted roads	Daylight	Daylight	Dark, unlighted roads
Time of Day		Morning and night			
Development	Farms/woods/ pastures	Farms/woods/ pastures	Residential	Residential	
Shoulder Type		Unpaved shoulder	Unpaved shoulder	Curb and gutter	Paved shoulders

*A Type A injury in North Carolina is defined as, "Injury obviously serious enough to prevent the person injured from performing his normal activities for at least one day beyond the day of the collision. Massive loss of blood, broken bone, unconsciousness of more than momentary duration are examples" (Federal Highway Administration (FHWA), n/d).

A 2010 summary of factors that led to bicycle and pedestrian crashes on rural highways was created from HSIS data from California, Illinois, Maine, Minnesota, North Carolina, Ohio, and Washington (Carter & Council, 2010). Carter and Council concluded that about twenty-five percent of fatal and injury bicycle and pedestrian crashes nationwide occurred on rural highways. They attributed higher vehicle speeds and the lack of sidewalks as contributing to these statistics. When comparing urban and rural crashes, crashes with vehicles traveling between 41 and 60 miles per hour (mph) contributed to 9 percent of the total crashes in an urban area and 47 percent of crashes in rural areas, in other words, more than five times higher in rural areas. Considering the percentage of crashes where speed limits were posted at 50 mph or faster, bicyclist crashes in rural areas were eighteen times more likely to occur on roadways with these posted speed limits as compared with urban areas. When considering the percentage of crashes that occurred on roadways with unpaved shoulders, rural areas were four times more likely to have crashes on such roadways when compared with urban areas. Overall, after their analysis, Carter and Council concluded that when comparing rural and urban crashes, rural crashes had higher fatality rates, higher vehicle speeds, less roadway lighting, were more likely to occur on roadways with unpaved shoulders, and were more likely to occur at non-intersection locations.

When one considers the interaction between bicyclists and motor vehicles, an important consideration is the vulnerability of a bicyclist compared to a motor vehicle occupant in a crash. To the authors' knowledge, no study exists, like it does for pedestrians, that relates the speed of a motor vehicle to injuries imparted to bicyclists. However, one can consider the results of a study conducted by Tefft (Tefft, 2013) on pedestrians, another vulnerable road user. Tefft examined pedestrian involved crash data from 1994 to 1998 and standardized the data to examine risk for pedestrians from 2007 to 2009. Tefft found that higher vehicle speeds increased the risk of crash involvement and injury or death for pedestrians. The average risk of *severe injury* (described as a rank of 4 or higher on the Abbreviated Injury Scale) to a pedestrian increased from ten percent at an impact speed of 17 mph to fifty percent at 33 mph. Risk of *death* was around fifty percent at an impact speed of 46.6 mph (Tefft, 2013).

Robartes and Chen (Robartes & Chen, 2017) investigated vehicle and bicycle crashes using 2010 to 2014 Virginia data to better understand what factors contributed to the crash severity level that a bicyclist experienced. While starting out with 3,679 possible crashes (including forty-nine that resulted in a fatality), after refining for those that were single vehicle-single bicycle crashes and then removing those crashes missing key variables, the final number of crashes analyzed was 2,435. No motor vehicle drivers died; all the fatalities represented in the data set were the result of a bicyclist dying. While the male/female ratio of vehicle drivers was almost evenly split, male vehicle drivers were vastly overrepresented in crashes that killed bicyclists, with a ratio of 15-5. Robartes and Chen used a multinomial logit model to analyze the data. Bicyclists under the influence were found to increase their likelihood of a fatal crash by 98.8% and increase their likelihood of a severe injury crash by 35.7%. However, these increases paled in comparison to the increases reported when a motor vehicle driver was operating under the influence, where a crash that killed a bicyclist was 502.4% more likely to occur and a crash that severely injured a bicyclist was 113.9% more likely to occur. Robartes and Chen noted that, a "driver's alcohol use has greater impact on cyclist injuries…." and "This result is intuitive considering the significant mass advantage of the automobile compared to the bike…" Robartes and Chen concluded that bicycling under the influence laws may need to be enacted in Virginia, as in 2017, "Virginia does not…have laws specifically prohibiting bicycling under the influence."

A meta-analysis study conducted by Høye (2018) examined 55 studies throughout the world from 1989 to 2017 on the effects of bicycle helmets on serious injuries. Bicycle helmets were found to reduce head injury by forty-eight percent, serious head injury by sixty percent, traumatic brain injury (TBI) by fifty-three percent, and the combination of fatalities or serious injuries by thirty-four percent (Høye, 2018). However, these injury reductions were found to be larger in single-bicycle crashes than in crashes with a vehicle, highlighting the importance of providing safe infrastructure or technology to prevent a crash between a bicycle and vehicle in the first place.

Lin and Fan (2019) employed a mixed logit model to describe the level of injury severity in bicycle-motor vehicle crashes for both urban and rural environments using data from North Carolina; crash data was drawn from 2007 to 2014 (Lin & Fan, 2019). Overall, Lin and Fan found there were more severe injury crashes and fatal injury crashes in the rural environment. Four factors were found to significantly impact the injury severity of crashes in the rural environment:

1) Bicyclists aged twenty-five to fifty-four years-old
2) Drivers younger than twenty-five
3) Vehicle speed
4) A divided road.

Considering bicyclist statistics, bicyclists younger than twenty-four were found to be less likely to have a fatal crash in both urban and rural areas. Drunk drivers involved in severe crashes in rural areas were associated with more than a 1275% increase in fatal injury crashes. When the vehicle speed ranged from thirty to sixty mph, an increase in the likelihood of a disabling injury for the bicyclist was found. At more than sixty mph, the probability of a bicyclist fatality increased by more than 2611%. Lin and Fan concluded: “installing completed bicycle facilities are critical for reducing severe injury in both urban and rural areas.”

The National Highway Traffic Safety Administration (NHTSA) summarizes statistics associated with bicyclists and other cyclists drawing from four databases: 1) Fatality Analysis Reporting System (FARS), 2) National Automotive Sampling System (NASS), 3) General Estimates System (GES), and 4) Crash Report Sampling System (CRSS) (National Highway Traffic Safety Administration (NHTSA), 2022). Data from 2020 were the most recently available data at the time of this report. NTHSA reported that there were 938 bicyclist fatalities that involved vehicles, accounting for 2.4 percent of all traffic fatalities that occurred in 2020 (a nine percent increase compared with 2019). (Note: To remain consistent with the descriptions used in the report, what NHTSA described as a “pedacyclist” will be termed a bicyclist.) The majority (79%) occurred in urban areas. Thirty-four percent of the fatal bicyclist crashes had alcohol involvement for either the bicyclist or vehicle driver; NHTSA combined these categories. Regarding injuries, an estimated 38,886 bicyclists were injured, which was a twenty-one percent decrease from the estimated number of injuries in 2019 (49,057). The bicyclist fatality and injury rate per 100,000 people was higher for males than females (seven times and four times, respectively). When comparing the average age of bicyclist fatalities between 2011 and 2020, the age increased from 43 to 48.

2.1.1 Bicycle – International Experience

Pattinson and Thompson (2014) considered how design (of intersections and vehicles), education, and enforcement could enable freight movement in urban areas while concurrently enabling bicycling (Pattinson & Thompson, 2014). While the focus was urban, and more specifically urban areas in Australia, some of the concepts may have relevance for rural areas as well. An important physical limitation that the article pointed out is that bicyclists cannot move sideways or backwards. It also highlighted how heterogeneous bicyclists are, ranging from fit and aggressive to cautious and less athletic.

Kullgren et al. (2017) analyzed bicycle and pedestrian crashes on rural roadways in Sweden to identify the causes of these crashes and consider the potential impact of mitigations, including alternative infrastructure and vehicle safety technologies (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017). Kullgren et al. noted that all bicycle crashes analyzed involved traditional bicycles, not e-bikes. E-bikes are expected to allow a bicyclist to travel at higher speeds and, consequently, the crash experience is expected to be different. From 2006 to 2015, seventy-six bicycle crashes on rural roadways were identified; the majority (fifty crashes or 66%) were between passenger vehicles and a bicycle. Bicyclists were most commonly hit when bicycling along the roadway. The majority of bicyclists were hit from the side (43%) followed by rear (37%), front (15%), and unknown (7%). Almost three quarters of the crashes (71%) were identified as occurring during daylight. Similarly, almost three quarters of the crashes (76%) were identified as occurring on dry roads. The estimated-time-to-collision for the majority of crashes (43%) was less than one second; this suggested that the “driver often kept too short [a] distance to the bicyclist." None of the bicyclist crashes occurred in a location where the bicyclist was separated from vehicles. Seventy-one percent of the bicyclists killed were not wearing a helmet.

2.1.2 Summary of Bicycle-Specific Literature

Table 2 summarizes some of the key points highlighted in the reviewed literature.

Table 2. Key Points of Bicyclist-Specific Literature.

Characteristic	**Source**
The consequences of vehicle-bicycle crashes were more serious when compared with bicycle-bicycle or bicycle-pedestrian crashes	(Stutts & Hunter, 1999)
Forty-three percent of bicyclists *admitted* to the hospital would *not* have been reported in the vehicle crash database	(Stutts & Hunter, 1999)
Seventy-four percent of bicyclists *treated and released* from the hospital would *not* have been reported in the vehicle crash database	(Stutts & Hunter, 1999)
Higher vehicle speeds, more common to rural areas, were described as explaining the greater crash severity found in rural bicycle/vehicle crashes	(Carter & Council, 2006); (Lin & Fan, 2019)
Most crashes (80%) in rural areas occurred where there were not paved shoulders	(Carter & Council, 2006)
Bicyclists cannot move sideways or backwards	(Pattinson & Thompson, 2014)
The bicyclist was the person who died in all the bicycle/vehicle fatal crashes, not a vehicle occupant	(Robartes & Chen, 2017)
Male drivers, when compared with female drivers, were overrepresented in crashes involving the death of a bicyclist	(Robartes & Chen, 2017)
While bicyclists under the influence were associated with more severe crashes for the bicyclist, the likelihood of a crash resulting in death or serious injury was significantly greater when the driver was operating under the influence	(Robartes & Chen, 2017); (Lin & Fan, 2019)
No crashes occurred between vehicle and bicyclist where they were separated	(Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017)

While adding a shoulder to a roadway will not completely eliminate crashes, as suggested by Carter and Council's findings, the data suggested that an average of 118 crashes could be eliminated on North Carolina roadways if shoulders were added ((956 rural bicycle crashes/6 years) * 0.74 (on roadways without shoulders) = 118 crashes). While not specific to freight, adding a shoulder also benefits those in vehicles as they are provided with a larger clear zone, which can help reduce the number of run-off-the-road crashes.

Carter and Council's (Carter & Council, 2006) data suggested that children were overrepresented in bicycle crashes. Also, the data always reported that the bicyclist was at fault (e.g., the bicyclist "failed"). It is unclear if this suggested that the cognitive development undergone by children was a challenge or if there was some possibility of a bias towards assigning fault to the child and/or bicyclist. If the former, in addition to providing infrastructure to support children's mobility, it alluded to a greater need for children's programs that teach the tools of how to bicycle safely.

The crash consequence of an inebriated driver in a vehicle was less impactful to the person operating the vehicle compared to the bicyclist on the road. Furthermore, it is unclear why NHTSA grouped vehicle drivers operating under the influence with bicyclists under the influence, as even Robartes and Chen (Robartes & Chen, 2017) reported more significant crash severity when the driver was the one under the influence. In addition, there is a need to better understand why bicyclists were operating under the influence. Before enacting laws, as suggested by Robartes and Chen (Robartes & Chen, 2017), policymakers should seek to influence and inform as compared to enacting a penalty. Regarding vehicle drivers, there still remains a significant need to address drivers operating under the influence.

2.2 Roadway

This section discusses roadway considerations, particularly, how roadway treatments (e.g., wider shoulders, bicycle lanes) influence the likelihood and severity of bicycle crashes. Hamann and Peek-Asa (Hamann & Peek-Asa, 2013) stated that "the United States has deficiencies in the physical traffic environment to accommodate bicyclists," further noting that the impacts of facilities in the rural environment on bicycle crashes was not well researched. This study added to that body of research, but also identified many more opportunities and needs for additional research to be conducted.

Almost thirty years ago, Kahn and Bacchus (Khan & Bacchus, 1995) discussed how the U.S. and Canada conceptualized accommodating bicycle travel along rural roadways. They offered the following reasons why paved shoulders provide benefits (rather than just wider unpaved shoulders):

1) "Road user safety improvement because of reduced 'run-off-road' and 'rollover' accidents;"
2) "Enabling the safe accommodation of bicycle travel;"
3) "Pedestrian safety;"
4) "Structural support of the travel lane, resulting in reduced pavement patching and maintenance cost;"
5) "Reduced shoulder maintenance cost;"
6) "Facilitate drainage of the roadway;"
7) "Use of shoulder as a traffic lane during rehabilitation work;"
8) "Enhanced snowplow operation;"
9) "Improved highway aesthetics;"
10) "Enabling the movement of agricultural equipment on shoulders;" and
11) "Providing a sense of [a] safe, open highway."

Kahn and Bacchus listed the following criteria for consideration when determining the width of shoulders for bicycle accommodation:

1) Adjacent travel lane width
2) Percentage of heavy vehicle traffic
3) Speed
4) Bicycle traffic volume
5) Overall width of the shoulder

Through surveying, Kahn and Bacchus found that a shoulder of 3 feet to 6 feet (0.91-m to 1.83-m) was typically provided to bicyclists. (The findings were typically presented in metric, so the values identified by Kahn and Bacchus are rounded.) However, they noted that the most common width was 3 feet with an approximately 1.5 feet (0.5-m) buffer, where pavement markings, signs, and rumble strips were provided. (This means that about a 1.5 feet of the shoulder was allocated to the bicyclist.) For low-speed roadways, they reported 5 feet (1.5-m) shoulders, where rumble strips took up about 1.5 feet (0.5-m). When considering safety, Kahn and Bacchus suggested that two concerns were: 1) motorists seeing bicyclists, and 2) the speed differential between vehicles and bicyclists. Kahn and Bacchus also calculated the probability of a crash between a vehicle and bicyclist using some example values. Ultimately, they conclude, "0.0016 accidents per year per direction/0.5 km are expected to result if bicycles share the roadway with motor vehicles." They suggested that by adding a paved shoulder, the number of crashes would be "negligible."

Tilahun et al. (Tilahun, Levinson, & Krizek, 2007) conducted a novel experiment to compare individual preferences for five different facility types (1) off-road facility, (2) bike-lane no on-street parking facility, (3) bike-lane with parking facility, (4) no bike-lane no parking facility, and (5) no bike-lane with parking facility) using a methodology called adaptive stated preference (ASP). Participants were recruited from the University of Minnesota employee listserv, excluding students and faculty. Each participant was presented with nine different options that paired two facilities, each with a ten second video clip of facilities found in St. Paul, Minnesota as viewed from the bicyclists' perspective; 167 people participated and provided complete information. They were given $15 for their time. Ultimately, with numerous models (e.g., generalized linear mixed model) and statistical approaches (e.g., non-parametric bootstrap) applied, Tilahun et al. reported that participants would be willing to travel an extra 16.41 minutes to use a bike-lane improvement, travel an extra 9.27 minutes to use a facility without parked vehicles, and travel an extra 5.13 minutes to use an off-road facility. Therefore, they concluded that a designated bike lane held the most significant valuation by participants. They evaluated and did not find a difference between study participants who were bicyclists as compared with those who were not. They also did not find a statistically significant difference when comparing gender (male versus female), although indications were that female participants (representing 65.5% of the sample) reported a preference for "better quality facilities" (e.g., the off-road facility).

In 2012, Abdel-Rahim and Sonnen analyzed cross-section, traffic, and crash data for two-lane rural roadways to estimate crash modification factors (CMFs) for lane width and shoulder width based on Idaho data (Abdel-Rahim & Sonnen, 2012). They identified the five benefits of shoulders as:

1) A recovery area for drivers;
2) Space for drivers to maneuver to avoid crashes;

3) A place for law enforcement to pull vehicles over;
4) Space for disabled vehicles; and
5) Space for bicyclists and pedestrians.

Only total, single vehicle, and multi-vehicle crashes were considered, as Abdel-Rahim and Sonnen reported that there were not enough run-off-road, opposite direction, and sideswipe crashes to develop CMFs. They also briefly reported on the safety of bicyclists and pedestrians on Idaho roadways. While Abdel-Rahim and Sonnen reported that a literature review was part of the project, they did not include any analysis of previous studies related to bicycle and pedestrian crash experiences in the rural context. The data consisted of 127 roadway segments from forty-eight different highways in Idaho. The segments ranged in length from five to eight miles; a total of 923 miles of roadway segments were represented in the data. Crash data from 1993 through 2010 was used, constituting 7,977 crashes. (While a table detailing the various categories suggested that five bicycle and pedestrian crashes were in the database, the figure showing shoulder width by number of crashes suggested about eighty total crashes.) Roadway segments had lane widths from ten to twelve feet and shoulders ranging in width from zero to more than eight feet. Abdel-Rahim and Sonnen found that for various categories of vehicle crashes (all crashes, single-vehicle, multiple-vehicle) as well as pedestrian and bicycle crashes, a shoulder width of less than three feet would increase the probability of crash occurrence (the number is greater than one for less than three feet, as shown in Table 3). For vehicles, any shoulder width greater than three feet was associated with a decrease in the probability of a crash.

Table 3. CMFs for Shoulder Widths in Idaho

Highway	Crash Type	Shoulder Width (ft)								
		0	1	2	3	4	5	6	7	8
All Highways	All Crashes	1.16	1.13	1.03	1.00	0.97	0.95	0.93	0.91	0.87
	Single-Vehicle Crashes	1.17	1.07	1.02	1.00	0.95	0.93	0.91	0.92	0.90
	Multiple-Vehicle Crashes	1.15	1.18	1.03	1.00	0.97	0.95	0.94	0.89	0.83
Low-Volume Highways	All Crashes	1.13	1.11	1.03	1.00	0.98	0.94	0.93	0.90	0.88
	Single-Vehicle Crashes	1.14	1.09	1.03	1.00	0.94	0.94	0.90	0.92	0.91
	Multiple-Vehicle Crashes	1.11	1.13	1.02	1.00	0.97	0.93	0.94	0.88	0.84

From a pedestrian and bicycle perspective, Abdel-Rahim and Sonnen recommended a shoulder width of four to six feet, as it was found that shoulder widths greater than eight feet were again associated with an increase in the probability of a crash. Essentially, the relationship between crash probability and shoulder width was u-shaped, where very narrow shoulders and very wide shoulders were associated with more crashes. Abdel-Rahim and Sonnen's recommendation for roadways with shoulders four feet wide or less would restrict bicyclists and pedestrians from using them. They also reported that most pedestrians were hit from either in front or behind as they were walking or running along the roadway while most bicyclists were hit when a vehicle was overtaking them. Abdel-Rahim and Sonnen also indicated that the bicyclists involved in the crashes were young (eighteen years old or younger), older (sixty-five years old or older) or had "consumed alcohol."

A 2012 periodical article highlighted the conflicting levels of comfort of bicyclists in relationship to the roadway cross-section (Brogdon, 2012). In Georgia, U.S. 17 and U.S. 82 were state designated bike routes. The article reported on the death of two bicyclists riding along U.S. 17 who were "following all of the laws" (e.g., "obeying traffic signals, wearing reflective clothing and helmets and by having proper lighting for riding at night") with a third bicyclist severely injured and, as a result, flown to a hospital for treatment. The article described the Sidney Lanier Bridge, which was part of U.S. 17, as having a wide lane that bicyclists and runners can use. In 2023, the bridge appeared as shown in Figure 1.

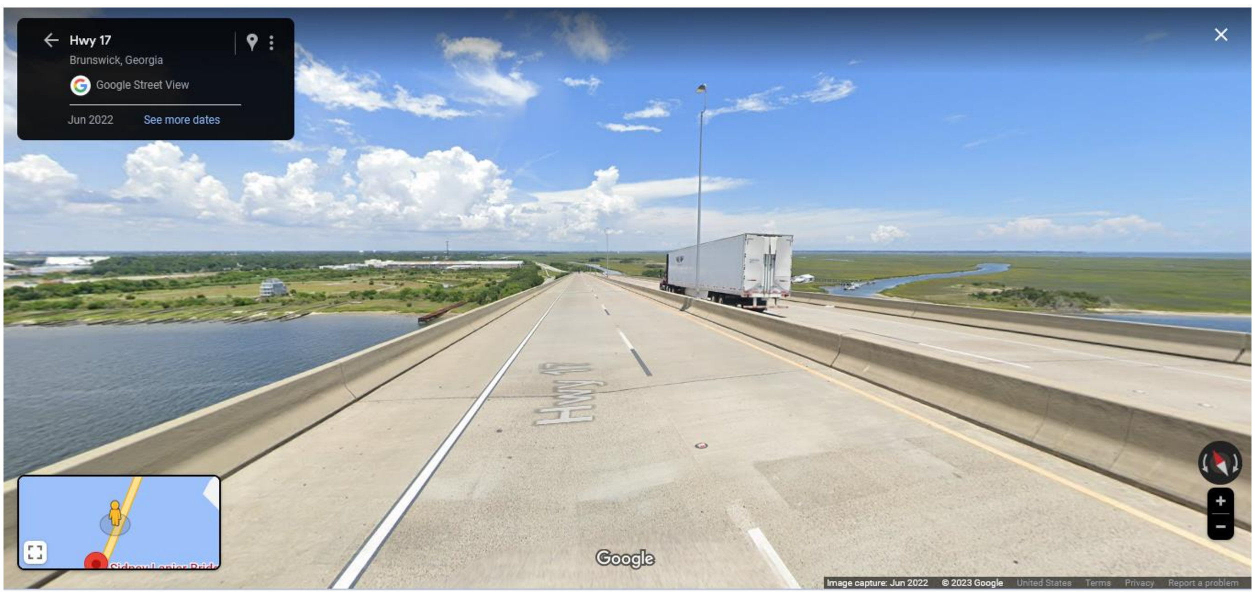

Figure 1: U.S. 17 with Shoulders and Large Vehicle (Google, 2022)

The article also suggested that a community could just "put down some paint" and add "three extra feet of pavement" to accommodate bicyclists. Yet a mayor, who indicated that he had previously bicycled, noted that he was not comfortable biking on U.S. 17; instead, he reported that the community in which he was serving as mayor was actively working on providing multi-use trails. A final quote summarized the tug between providing for vehicles and bicyclists: "When a bike and a car are competing for space, the bike is always going to lose, unfortunately."

Love et al. (Love, et al., 2012) evaluated motorist compliance with the three-foot law using data captured from Baltimore, Maryland. While this is an urban example, the methods could be employed in a study in the rural context, and, therefore, provides a good case study. Baltimore had implemented a Maryland state law that required a motorist keep at least three feet between their vehicle and a bicyclist when passing. Five bicyclists (four males and one female) collected 10.8 hours of data, which recorded

586 vehicles passing on thirty-four bicycle commuting trips in September and October of 2011. The roadways that the bicyclists traveled on had one of three treatments: no bicycle provisions, shared lane markings (a.k.a. sharrows), and bicycle lanes. Lane width was found to be an influential factor in the distance that motor vehicles put between themselves and bicycles when passing, with wider lanes associated with greater passing distances. Bicycle infrastructure (none, shared lane markings, bicycle lanes) was also found to be an influential factor in the distance that motor vehicles put between themselves and bicycles, with no passes closer than three feet on streets with bicycle lanes. Love et al. did note that the roadways considered in the study had speeds at or below thirty-five mph, and they cited another study that suggested that motorists tended to stay within their lanes when speeds were greater than forty-miles mph. Therefore, it is unclear if these results would hold true on high speed, rural roadways. Love et al. also reported that the lowest percentage of passes (3%) by motorists three feet or closer was associated with the one female bicyclist participating in the study. Because only one female bicyclist participated, the researchers did not indicate it to be a definitive conclusion but suggested that there might be an influence.

Hamann and Peek-Asa (2013) randomly selected 147 bicycle crash sites and 147 non-crash sites to analyze the impact of bicycle-specific roadway facilities on the frequency and severity of bicycle crashes in Iowa (Hamann & Peek-Asa, 2013). The types of bicycle infrastructure that were analyzed included bicycle lanes, shared lane markers, and signs. Crash data from 2007 through 2010 was used; Hamann and Peek-Asa controlled for bicycle volume, motor vehicle volume, street width, the presence of sidewalks, and traffic controls. Control sites were found to have more on-road facilities and on-road facilities combined with signage compared to bicycle crash sites. Control sites also had lower motor vehicle volumes. When the on-road facility (bicycle lanes and a shared lane arrow treatment were combined for this category) was implemented in cooperation with bicycle-specific signage, Hamann and Peek-Asas reported a crash risk reduction of sixty percent. While less of a reduction, Hamann and Peek-Asa found a thirty-eight percent crash reduction with bicycle-specific signage. They also found an increase in crash risk with an increase in motor vehicle volumes and curb-to-curb width of the roadway (i.e., a wider roadway).

DiGioia et al. (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017) evaluated the safety impacts of various bicycle infrastructure, grouped as bicycle corridor treatments (bike lanes, buffered bike lanes, colored bike lanes, bicycle boulevards, cycle tracks, multi-use trails, shared lane marking, wide shoulder, wide curb lane) and bicycle intersection treatments (bike box, two-stage turn queue box, raised bicycle crossing, neighborhood traffic circle, roundabout). The majority of the infrastructure (e.g., buffered bike lanes, colored bike lanes, bicycle boulevards, cycle tracks, bike box, two-stage turn queue box, raised bicycle crossing, and neighborhood traffic circle) discussed were rarely seen in the rural context, particularly along the roads that connect the rural communities that were the focus of this study; however, with the inclusion of wide shoulders, the DiGioia et al. evaluation held some interest for the study at hand. In fact, DiGioia et al. specifically noted that wide shoulders were most often seen on rural roadways. They suggested that the "treatment extends the service life of the road, provides temporary storage space for disabled vehicles, and provides space for bicycles to operate with some separation from higher speed traffic." DiGioia et al. described the safety infrastructure as addressing at least one of five potential objectives, two of which are relevant to the study at hand: 1) increasing the separation between vehicles and bicyclists in both time and space, and 2) reducing vehicle speeds. However, while DiGioia et al. suggested that separation between the two user types was desirable, they also highlighted the findings of at least one study that suggested that offering a reduction in visual complexity in conjunction with increased separation may result in drivers feeling safe traveling at faster speeds, which could have significant consequences if a bicyclist is struck. Their findings implied that multi-use pathways were associated with a higher crash rate for bicyclists; however, the results were not statistically significant. DiGioia et al. suggested that this result may be indicative of the multitude of users of such facilities, including those walking their dogs, as the dogs may move in front of the bicycle unexpectedly, resulting in the bicyclist being thrown from the bike. DiGioia et al. also found that more pavement width was associated with a "slight" positive safety impact on bicyclists. Furthermore, since more crashes and conflicts between bicyclists and vehicles occurred at intersections and driveways, DiGioia et al. recommended supporting access management. DiGioia et al. also noted that when safety was improved for bicyclists, more bicyclists rode.

Hardy and Hunter (2017) discussed a framework developed by the Florida Department of Transportation's District 7 to provide better guidance for balancing the needs of livability with goods movement (Hardy & Hunter, 2017). Overall, the emphasis was more on the urban context. The document suggested that narrower roadways constrained motor vehicles to slower speeds. Four area types were defined: community-orientated, diverse activity area, freight-orientated, and low activity. The first two were more commonly associated with livable communities and the latter more commonly associated with the movement of goods. However, for the diverse activity area, freight and livability were identified as being in conflict. The document further indicated the existence of limited research regarding the implications of narrower lanes and road diets on freight movement, which suggested that slower speeds, which were associated with these geometric design treatments, often resulted in fewer crashes, which also benefited freight. It did, however, acknowledge that narrower widths reduced the physical separation between freight and vulnerable road users (bicycles and pedestrians). The lack of research also carried into the lack of guidance found in design manuals, where "professional judgement" was the default. The article noted that, "The idea of context-sensitive design is to develop a roadway that not only respects current conditions but, more importantly, also helps to achieve the desired future context, a concept particularly important in areas that are being urbanized." Another interesting assertion was that "not all streets need to provide the same quality of service to all users." They also noted that travel lanes may be narrowed in a "community-orientated area to increase bicycle lane or sidewalk width." Furthermore, the article acknowledged that, while it was desirable to have design speed, the speed limit, target speed, and operating speed all to be the same, "Operating speed typically exceeds design speed when few natural [(e.g., trees)] or built environmental variables (e.g., horizontal or vertical curves, side friction from driveways or intersections) exist, so that that roadway is comfortable for travel well above the design speed."

The Adventure Cycling Association (ACA) described themselves as a "passionate group of bicycle travelers…dedicated to making the renewal and accomplishment we feel while touring attainable for everyone" (Adventure Cycling Association, n.d.). At one point in time, ACA identified their route selection philosophy as preferring rural back roads to "more highly engineered roads," even if the engineered roads had wide shoulders (Adventure Cycling Association). The ACA also noted a preference for "advocating that bicyclists and motorists share the roads" (Adventure Cycling Association). Another criterion of interest was that ACA preferred roads with "fewer than 1,000 vehicles per 24 hours" (Adventure Cycling Association). The ACA also noted a preference for two lane roadways that had two to four-foot paved shoulders (Adventure Cycling Association), although it was unclear if this was in comparison to roadways that had no shoulders or roadways with wide shoulders.

2.2.1 Roadway – International Experience

While growing, the body of research on the impact of roadway cross-sections on bicyclist safety, particularly in the rural context, is limited. Therefore, the following examples from abroad are offered.

Laird et al. (2013) conducted a willingness-to-pay (WTP) analysis using data from three areas of rural Ireland: Passage West, Greystones, and Tullamore (Laird, Page, & Shen, 2013). Passage West was described as "constructed on a dismantled railway line parallel to the rural main road," which sounds similar to rail-to-trail projects within the United States. The Greystones facility was described as a facility separated from the road by a grass strip. This example sounds similar to some multiuse trails in the U.S. that are minimally separated from the vehicular roadway. In Tullamore, bicyclists shared the roadway with vehicles, which is similar to most rural roadways in the U.S. The paper defined journey ambience as "a user cost/benefit and is a measure of the improved environment and reduction in feelings of danger that cycle or walking facilities provide." The paper suggested that its value included presenting "new evidence on the value of cycleways and footpaths on rural roads." The authors employed intercept and household surveys; however, only household surveys were used to obtain input for Tullamore because the location was "too unsafe for intercept surveys." The surveys focused on obtaining three pieces of input: 1) use of dedicated walking and bicycling facilities, 2) change in amount of walking and bicycling if a facility was available, and 3) contingent valuation questions to provide information for the WTP analysis. Six hundred and seven surveys were collected; 554 surveys were ultimately used after missing data and outliers were removed. The collected data identified four times the number of households that reported walking when compared with bicycling. Half of the cycling trips and two thirds of the walking trips reportedly occurred during the summer. The majority of trips were made for health and recreational purposes (51% to 59% for Greystones and Passage West), while significantly fewer were made for commuting purposes (9% to 18%). Their findings suggested that facilities "increase exercise levels and therefore indirectly give health benefits." In addition, they found that health/recreational purpose trips were longer than those made for other reasons. From their WTP analysis, while not all roadways were identified as having benefits exceeding the cost of providing walking and bicycling facilities, about three quarters of roadways that had upgrades planned were identified as representing "good value for money." Consequently, Laird et al. concluded that their "findings challenge the often pre-conceived idea amongst highway design engineers that there is little value in including facilities for pedestrian and cyclists particularly in rural areas."

Pattison and Thompson (Pattinson & Thompson, 2014), previously highlighted, discussed roadway modifications that had been employed in Europe and Japan, which included separated facilities for trucks and bikes.

Kullgren et al.'s (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017) analysis of the Swedish crash experience concluded that the intervention identified as having the greatest potential to reduce bicycle crashes was to build separate paths, with more than fifty percent of the crashes being eliminated with such a provision. Compare this with the expected reduction for pathways (a.k.a. wider shoulders) along the existing roadway, where only a one to five percent reduction was anticipated. Rumblestrips were identified as having a similarly low percentage of bicycle crash reduction. While Kullgren et al. conceded that in the short term, building separated paths would be difficult, they recommended creating a prioritization plan.

Liu et al. (Liu, te Brommelstroet, Krishnamurthy, & Wesemael, 2019) interviewed eleven individuals from five European countries (Belgium, Denmark, Germany, Netherlands, and United Kingdom) that were developing “cycle highway” networks. Some of their main takeaways included, “you should definitely try to have the cycle highways away from the car traffic with the noise,” and those from Belgium and the Netherlands encouraged designing facilities that allow bicyclists to travel side-by-side because their culture views bicycling as a social experience. At least one interviewee emphasized the need to not treat the facilities as an afterthought, where “Oh yeah, we just need to do something. Let’s put a little bit of [a] wide lane in or bit of paint for them.”

2.2.2 Roadway Summary

Table 4 summarizes some of the key points highlighted in the reviewed literature related to roadway design.

Table 4. Key Roadway Considerations

Characteristic	Source
“On high-speed roads with a substantial amount of heavy vehicle traffic, a cyclist’s balance may be adversely affected by the air displacement caused by heavy vehicles traveling at or above the posted maximum speed.”	(Khan & Bacchus, 1995)
Paved shoulders provide several benefits including: 1) a recovery area for drivers, 2) space for drivers to maneuver to avoid crashes, 3) a place for law enforcement to pull vehicles over, 4) space for disabled vehicles, and 5) space for bicyclists and pedestrians.	(Abdel-Rahim & Sonnen, 2012)
Abdel-Rahim and Sonnen recommended a shoulder width of four to six feet, as it was found that shoulder widths greater than eight feet were associated with an increase in the probability of a crash.	(Abdel-Rahim & Sonnen, 2012)
On-road facilities, including bicycle lanes or sharrows, in combination with bicycle-specific signage reduced crash risk by sixty percent. Bicycle-specific signage alone could reduce crash risk by thirty-eight percent.	(Hamann & Peek-Asa, 2013)
The ACA reported preferring rural back roads with lower traffic volumes and two to four-foot paved shoulders for their bicycle routes.	(Adventure Cycling Association, n.d.)

Kahn and Bacchus (Khan & Bacchus, 1995) identified eleven benefits of providing a paved shoulder on a roadway; however, only two out of the eleven benefits were related to bicyclists and pedestrians. Similarly, Abdel-Rahim and Sonnen (Abdel-Rahim & Sonnen, 2012) identified five benefits of shoulders, only one of which was for bicyclists and pedestrians, and it was merely the provision of space. DiGioia et al., like Kahn and Bacchus and Abdel-Rahim and Sonnen, also only identify one benefit of wide shoulders for bicyclists and pedestrians. This suggests that wider, paved shoulders primarily benefit motorists.

Kahn and Bacchus (Khan & Bacchus, 1995) reported concern that motorists may not see bicyclists. This is even more problematic for large vehicles, which have more “blind spots,” and suggests that facilities that intermingle bicyclists and large vehicles are not desirable. Furthermore, Kahn and Bacchus’s view that the number of crashes that occurred between motorists and bicyclists was “negligible” seems to overlook the crash statistics discussed in the preceding section, where it was the bicyclist that died in every bicyclist/motor vehicle fatal crash. Considering that the report was completed in 1995, it highlights views that align with crash acceptance as compared with the more contemporary efforts at crash elimination, which are more common with Towards Zero Deaths initiatives.

Hardy and Hunter (Hardy & Hunter, 2017) suggested that the lack of side friction from driveways or intersections would result in roadway operating speeds that were higher than the posted speed limit. So, considering whether wide shoulders can benefit both freight and bicyclists, it seems that Hardy and Hunter suggested such a provision would result in freight traveling at higher speeds. With speed identified as a significant factor in crash severity from the preceding section, one may conclude that increasing the shoulder width would not result in concurrent benefits to both users.

Kahn and Bacchus’ (Khan & Bacchus, 1995) analysis suggested that crash occurrence was not an “if” but, rather, a “when.” Furthermore, if the crash occurred between a large vehicle and bicyclist, it could be assumed to be fatal for the bicyclist. This would suggest that providing wider shoulders would not benefit bicyclists, as at some point, a bicyclist could be expected to die. In contrast, with wider shoulders, large vehicles would likely travel faster (benefit = shorter travel time) and if they were to leave the travel lane, would be more likely to recover and therefore less likely to crash. It seems that freight (e.g., large vehicles) would be the only beneficiaries if shoulders were added to a corridor where bicyclists and freight were encouraged to travel. To truly benefit bicyclists, providing wider shoulders (at least three feet beyond rumble strips designed to accommodate bicyclists) on roadways where freight vehicles are prohibited seems to bring the most safety benefits.

Hardy and Hunter (Hardy & Hunter, 2017) highlighted the importance of considering the future context of a design implemented in the present, particularly in urban areas. However, considering how infrastructure may look in the future is equally important in the rural context, where, once implemented, designs typically do not change for extended periods of time. A unique example is the sidewalks and curbs constructed and date stamped by the Civil Conservation Corps (CCC) that can still be found in rural communities more than eighty years later (see Figure 39 in *Case Studies of Communities of Less Than 10,000 People with Bicycle & Pedestrian Infrastructure* (Villwock-Witte & Clouser, Case Studies of Communities of Less Than 10,000 People with Bicycle & Pedestrian Infrastructure, 2022)).

An insightful study would be to conduct research similar to Tilahun et al. (Tilahun, Levinson, & Krizek, 2007), but draw from bicycle facilities found in the rural context.

2.3 Vehicle

This section discusses vehicle size and whether technology is present (and if so, the type) on a vehicle to assist with the detection or avoidance of a collision with a bicyclist.

2.3.1 Vehicle Size

Several of the studies identified in previous sections also provided information relevant to vehicle size ((Adventure Cycling Association), (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017), (Love, et al., 2012), (Brogdon, 2012), (Robartes & Chen, 2017), (Lin & Fan, 2019), (National Highway Traffic Safety Administration (NHTSA), 2022), (Khan & Bacchus, 1995)). When discussing how they selected routes, the ACA noted a preference to, "Whenever possible, we try to avoid roads which carry a high number of trucks and commercial traffic" (Adventure Cycling Association); a specific threshold regarding what constitutes a "high number" was not provided. DiGioia et al. (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017) acknowledged a shortcoming of their study in that it did not describe safety impacts to bicyclists as a result of the presence of heavy-duty trucks. Love et al. did not find vehicle type to be influential, although the majority of their sample was made up of personal vehicles (passes by a personal vehicle = 521; commercial vehicle = 25; taxi = 23; bus = 15; police vehicle = 2). In the periodical article, an interviewee described eighteen-wheelers traveling at fifty mph past them on a bicycle as a "harrowing experience" (Brogdon, 2012). Furthermore, the experience of riding with a large vehicle was described as "an 80,000-pound metal dragon [that] goes screaming by…" (Brogdon, 2012). Most of the vehicles involved in crashes with bicyclists in the study by Carter and Council (Carter & Council, 2006) were reported to be passenger cars and pickup trucks. Even though passenger cars were overrepresented in the sample (61%) within Robartes and Chen's study (Robartes & Chen, 2017), vans, sport utility vehicles (SUVs), and light duty trucks (which were grouped by Robartes and Chen because of the smaller sample size) were found to increase fatal crashes by 50.6% and severe injury crashes by 21.1%. Robartes and Chen (Robartes & Chen, 2017) noted that because vans, SUVs and light duty trucks were "heavier," they "exert more force on an unprotected bicyclist." Lin and Fan (Lin & Fan, 2019) reported that, in rural areas, pick-up trucks were associated with an increase in the likelihood of possible injury (59.91%) and disabling injury (96.37%). Based on NHTSA summary statistics (National Highway Traffic Safety Administration (NHTSA), 2022), when considering vehicle type, "light" trucks were overrepresented when considering bicyclist fatalities; the front of the "light" truck hit the bicyclist in most of the crashes. The largest percentage of right-side bicyclist fatalities involved large trucks (thirteen percent) (National Highway Traffic Safety Administration (NHTSA), 2022). Khan and Bacchus (Khan & Bacchus, 1995) also detailed the impact of various vehicle speeds as well as vehicle types on the lateral force felt by bicyclists as the motorists passed them. Of particular note, "On high-speed roads with a substantial amount of heavy vehicle traffic, a cyclist's balance may be adversely affected by the air displacement caused by heavy vehicles traveling at or above posted maximum speed" (Khan & Bacchus, 1995). Khan and Bacchus went further, saying that the impact of this force, along with winds, could result in a bicyclist losing their balance (Khan & Bacchus, 1995).

The presence of larger vehicles seems to put bicyclists at particular risk for injury or death. An Insurance Institute for Highway Safety (IIHS) study of seventy-one single-vehicle crashes from the Vulnerable Road User Injury Prevention Alliance crash database found that bicyclist injuries from crashes with SUVs were more severe than those from smaller passenger cars (Monfort & Mueller, 2023). A study of Illinois crash and hospital records from 2016 to 2018 found that larger vehicles were more likely to result in a fatality in a crash with a bicyclists or pedestrian. Pickup trucks were involved in 5.6 percent of bicycle/pedestrian crashes but involved in 12.6 percent of fatalities (Edwards & Leonard, 2022). SUVs were involved in 14.7 percent of bicycle/pedestrian crashes but involved 25.4 percent of fatalities

(Edwards & Leonard, 2022). Additionally, this study found that hospital charges were the highest among bicyclists and pedestrians struck by large vehicles (Edwards & Leonard, 2022).

A dissertation by Chowdhury (Chowdhury, 2018) was reviewed as the analysis was conducted on crashes from Alaska, a very rural state, and some of the identified results suggested that trucks played a role in the crash injury. However, a review of the methods brings the results into question. For example, the author eliminated property damage only crashes in the analysis, and grouped fatal crashes into injury crashes, stating that they wanted to focus on injuries. Furthermore, the author did not indicate why they chose to group September through December together to form a "winter" variable. They did not suggest that an analysis of the data would imply that such a grouping was made (even if the variable label was a less than desirable choice). Similarly, they grouped time of day into three categories: 6-12pm, 12-8pm, and 8-6am without explanation. They also grouped ages into three categories: 0-12, 21-50, and 51 or above. There was no explanation as to why these groupings were made. Vehicle type was identified as "light truck," "trucks," and "trailers," yet the author ultimately seemed to suggest that they defined "trucks" as consisting of "light trucks" and "trailers." It is unclear how many trailers were grouped into this category and why they were added to the "trucks" category. As a consequence, the results of Chowdhury were not considered further.

To combat the overrepresentation of large vehicle/bicycle fatalities compared with large vehicle/bicycle crashes, the San Francisco Municipal Transportation Agency (SFMTA) developed curriculum along with a video to train large vehicle drivers on how to safely operate around bicyclists (U.S. Department of Transportation, Federal Highway Administration, 2017). The project was reported to be successful - the video was streamed more than 6,400 times and there was an increase in commercial drivers' awareness of their responsibility to operate safely around bicyclists.

2.3.2 Vehicle Technology

Advanced driver assistance technologies like blind spot warnings, forward collision warnings, and automatic emergency braking are expected to reduce crashes with bicyclists and pedestrians; however, these technologies are not standard equipment on vehicles, so the presence of these technologies within vehicles can vary from location to location. A study of 2014 to 2020 crashes from police-reported crash databases in sixteen U.S. states was used to examine whether the automated emergency braking (AEB) technology in Subarus, called EyeSight, was effective at reducing bicycle-involved crashes (Cicchino, 2023). EyeSight was associated with a nine percent overall reduction in bicycle crash rates; however, the technology was more effective at reducing crashes with a parallel configuration rather than those with a perpendicular configuration (Cicchino, 2023).

2.3.3 Vehicle – International Experience

While growing, the body of research available in the U.S. on the impact of vehicle size and vehicle technologies, particularly in the rural context, is limited. Therefore, the following examples from abroad are offered.

Kullgren et al.'s (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017) analysis described previously suggested that four of the bicyclist crashes could not have been prevented. Two were single bicycle crashes, where the rider was traveling downhill on a narrow road. The other two involved large vehicles: the first was hit from behind by a truck and the second was hit by a wheel loader.

Lateral protective devices (LPDs) are used by trucks to prevent vulnerable road users (e.g., bicyclists, pedestrians, and motorcyclists) from being run over by a large truck in side-impact crashes. A study completed in the United Kingdom found that LPDs can reduce bicyclist fatalities by sixty-one percent (Epstein, Peirce, Breck, Cooper, & Segev, 2014). While LPDs have been required by the European Union and Japan since the 1980s, there has been growing interest in the United States (Epstein, Peirce, Breck, Cooper, & Segev, 2014).

Pattinson and Thomson (Pattinson & Thompson, 2014), discussed in earlier sections, noted that due to the many blind spots present in large vehicles, bicyclists may not be seen by truck drivers. The speed at which a bicyclist is traveling may also be underestimated and lead truck drivers to overestimate how quickly a bicyclist can stop. Some suggested truck modifications made in the article were to increase the driver's visibility area by lowering the cabins and installing under-run protection on the truck. Other ideas included providing more mirrors (including smart mirrors that show a symbol when an object is in the blind spot) or cameras. The article highlighted the vehicle-to-vehicle (V2V) systems, but noted that protecting vulnerable road users, like pedestrians and bicyclists, was not identified as a clear priority for initiatives like V2V. An interesting quote they featured within stated, "The conflict between a truck and a cyclist or pedestrian may not be the most common situation encountered, but it is the most dangerous." Vehicles weighing more than twelve tons were reported as being required to have speed limiters, which they noted may hold less importance on urban roads but may be more applicable on rural roads. The article also suggested that lane departure warnings, sold on trucks in Europe and "Freightliner Trucks" in North America, can assist in ensuring separation between bicyclists and trucks. Another point made in the article was the "emotional trauma" that a serious crash may cause a driver; Pattison and Thompson noted that they may cause some drivers to stop working. They also suggested that while traffic engineers were well versed in designing roadways for vehicles, they knew "very little" about bicyclists. The article also suggested that the logistics industry should "consider the extent to which best practice for providing for cyclists was compatible with best practice for truck operations." From an educational perspective, the article suggested retraining and on-going training for truck drivers that focuses on bicyclist awareness; the Netherlands was identified as a location already following this approach. Share the Road Cycling Coalition was identified as an educational effort in the United States.

Kullgren et al.'s (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017) analysis concluded that twelve percent of the bicyclist crashes occurred where vehicle safety technologies may not have detected the bicyclist (i.e. heavy rain/snow, fog or blinding sunlight). Autonomous Emergency Braking (AEB) and Autonomous Emergency Steering (AES) were suggested as holding promise for detecting bicyclists. Other technologies were identified (vulnerable road user detection for large goods vehicle (LGVs), heavy goods vehicles (HGVs) and buses; lane departure warning (LDW)/lane keeping assist (LKA) for LGVs and buses; side radar for buses and HGVs; and alcohol interlock systems for passenger cars and LGVs), but the implementation rate was not available to consider their impacts.

2.3.4 Vehicle Summary

Table 5 summarizes some of the key points highlighted in the literature reviewed related to the vehicle.

Table 5. Key Vehicle Considerations

	Characteristic	Source
Vehicle Size	Any vehicle larger than a passenger car (e.g., as "small" as a pick-up truck) was found to be associated with more severe crash injuries for a bicyclist.	(Robartes & Chen, 2017); (Lin & Fan, 2019); (National Highway Traffic Safety Administration (NHTSA), 2022); (Edwards & Leonard, 2022) (Monfort & Mueller, 2023)
	Half of crashes described as impossible to prevent involved a large vehicle.	(Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017)
Vehicle Technology	Automatic emergency braking helps to reduce the crash rates between bicycles and vehicles.	(Cicchino, 2023)
	LPDs can reduce bicyclist fatalities by sixty-one percent.	(Epstein, Peirce, Breck, Cooper, & Segev, 2014)
	Twelve percent of bicyclist crashes occurred where vehicle safety technologies may not have detected the bicyclist (i.e., heavy rain/snow, fog or blinding sunlight).	(Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017)

Carter and Council's (Carter & Council, 2006) findings suggest that the majority of bicycle crashes are with passenger vehicles and pick-up trucks. Lin and Fan (Lin & Fan, 2019) further added to this finding by showing that possible injury and disabling injury increases when a pick-up truck strikes a bicyclist. Freight vehicles were not identified as contributing to crashes in either study. However, no information was provided regarding the representation of freight (e.g., large vehicles). Therefore, rather than concluding it is safer for a bicyclist to share roadways with freight, it could instead suggest that bicyclists are already self-selecting roadways where freight is less likely to be present.

Kullgren et al. (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017) concluded that the majority of crashes are preventable, except those that involve large vehicles. One may infer then that collisions between large vehicles and a bicyclist should be avoided. Instead of providing a wider shoulder, perhaps roadways with a certain percentage of large vehicles should be required to include a separate path.

Pick-up trucks and similar vehicles (e.g., vans) were overrepresented in crash statistics. Considering that the size of the front of light trucks is increasing with every new vehicle year, the expectation is that the experience for the bicyclist will become more and more dire.

Large trucks were overrepresented in right-side bicyclist fatalities, suggesting that these vehicle types have a difficult time seeing bicyclists.

2.4 Policy

This section highlights relevant policies that were identified in the reviewed literature.

In a preceding section, the study by Kahn and Bacchus (Khan & Bacchus, 1995) was highlighted. As part of their study, they surveyed Canadian provinces and U.S. states for information about their policies for accommodating bicyclists on rural roadways. Kansas was identified as having the policy of not encouraging the "mixing of high and low speed traffic," which implies that motorists and bicyclists should not be using the same corridor. They then clarified that "paved shoulders are not designed for bicycles."

While their focus was on more urban environments, Pucher and Dijkstra's (Pucher & Dijkstra, 2003) reported policies from the Netherlands and Germany could largely be applied to rural American environments as well:

1) "Better facilities for walking and cycling;"
2) "Urban design sensitive to the needs of non[-]motorists;"
3) "Traffic calming in residential neighborhoods;"
4) "Restrictions on motor vehicle use in cities;"
5) "Rigorous traffic education of both motorists and non[-]motorists;" and
6) "Strict enforcement of traffic regulations protecting pedestrians and bicyclists."

Pucher and Dijkstra spoke to the political challenges in the U.S., where raising taxes on automobile ownership and charging for parking (where Pucher and Dijkstra suggest more than ninety-five percent of all parking is free) are still barriers. Using data collected from the Netherlands, Germany, and the U.S., Pucher and Dijkstra showed a decline in the bicycle and pedestrian fatalities in all countries; the Netherlands showed the greatest decline, followed by Germany. The U.S., while showing a general decline in fatalities, is on a different trajectory than the other two countries. Pucher and Dijkstra suggested this was the result of the decrease in children bicycling. They noted that the bicycling networks in Netherlands and Germany had been developed to not just connect recreational attractions but everyday destinations (e.g., grocery stores) as well. Furthermore, Pucher and Dijkstra highlighted that both urban and rural areas had connected networks, not disjointed ones like those found in the U.S. Highways, roads and rivers are obstacles in the U.S., because providing bicycle and pedestrian connections tends to be the exception rather than the rule; this is the opposite case in the Netherlands and Germany. Finally, Pucher and Dijkstra spoke to the cultural differences regarding licensing and how motorists behave around pedestrians and bicyclists. Training to drive a vehicle is expensive, thorough, and extensive in the Netherlands and Germany. Even if the pedestrian and bicyclist is in the wrong, the burden of a crash is almost always placed on the motorist, with the entirety of fault placed on the motorist if a child or elder is involved. Pucher and Dijkstra suggested that public campaigns, to convince Americans that walking and biking will directly benefit them, are needed. They suggested emphasizing the direct impact to American's, their families, and their friends.

3 Conclusions, Recommendations, & Future Research

This section details the conclusions, recommendations, and recommended future research as a result of the study.

3.1 Conclusions

The premise of this study was that providing wider shoulders on roadways in rural areas would benefit both the heavy vehicles and bicyclists traveling along these corridors. However, as suggested by the reviewed literature, when a crash occurs between a large vehicle and bicyclist, it often results in the fatality of the bicyclist. Therefore, the authors do not believe that simply widening shoulders will bring benefits to both freight and bicyclists. Instead, according to at least two sources that identified benefits associated with widening shoulders, the only benefit identified for the bicyclist seems to be that some space is provided, in part, for them.

While the Swedish example highlights that almost three quarters of the bicyclist fatalities in that country were not wearing a helmet, there is no understanding of whether the bicyclist would have the same quality of life if they survived the crash. While helmets have been shown to reduce fatalities and serious injuries, it seems that preventing a crash, such as by providing separated infrastructure or vehicle safety technologies would be preferable to merely focusing on survival after the crash.

Higher speeds have been found to correlate with more severe injury and a greater likelihood of mortality for the bicyclist ((Carter & Council, 2010); (Lin & Fan, 2019)).

Helmets were identified as a way to reduce crash severity. However, as identified by Høye (Høye, 2018), helmets are more effective at addressing the crash severity when a motor vehicle is not involved in the crash.

The outcome and recommendations of at least one study (Lin & Fan, 2019) suggested the need for facilities that provide safety and comfort for a broader cross-section of bicyclists, rather than providing merely a widened, paved surface, which has been likened to an “afterthought” by at least one author.

A large number of crashes occurred during daylight, as suggested by at least two studies ((Carter & Council, 2006) and (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017)), indicating that merely providing lighting will not address crash causal between a bicyclist and motor vehicle.

Women are able to bicycle, and women are interested in bicycling. Therefore, it is telling that the majority of bicycle and vehicle collisions are between males, as suggested by the overrepresentation of male drivers in crashes involving a bicyclist fatality, as well as data that suggest that more male bicyclists are involved in crashes (Carter & Council, 2006). This implies that the current design of infrastructure in rural areas is not conducive to supporting women’s interest in bicycling. Consequently, rather than continuing to use the same old designs, it is time to consider new alternatives. For example, rather than simply widening the shoulders on either side of the travel lane, why not instead use the space to add an exclusive bicycle highway offset from the primary vehicular roadway? Agencies that consider this alternative also need to understand the relationship between the use of such a facility and the ability to feel safe using it, including ensuring that maintenance is done on such facilities.

Reviewing prior studies, based on the information provided, it would appear that the vast majority did not include metrics that measured the level of use of the corridors by freight (e.g., large vehicles).

Without comprehensively including a discussion on the influence of freight in every study, it is difficult to compare studies.

In some cases, it is hard to identify the influence from the roadway cross-section versus the vehicle size, because several of the described studies did not consider or report on traffic volumes, number of large vehicles, or roadway cross sections. Therefore, in some cases where there were no pick-up trucks or other large vehicles, bicyclists may have already been self-selecting off of roadways that were infrequently, if ever, traveled by large vehicles.

As highlighted by Kullgren et al. (Kullgren, Rizzi, Stigson, Ydenius, & Strandroth, 2017), much of the current understanding of crash experience, regardless of context (urban or rural), is with traditional bicycles. With e-bicycles becoming increasingly popular, particularly because they allow users to travel further and faster, the crash experience has the potential to change. Their ability to go further and faster may make them even more popular for rural riders, because they can ferry users across the longer distances more common to rural areas. This potential increase in e-bicycles may further exacerbate the need to consider infrastructure provisions to improve safety for bicyclists.

3.2 Recommendations

What can be done? At least one study highlighted the overrepresentation of male drivers as contributing to the death of a bicyclist when a bicycle/vehicle crash occurred. Therefore, assuming that this trend holds true across the U.S., it would be of value to develop educational materials that specifically target male drivers. Prior to developing such materials, it would be beneficial to understand if this experience is consistent across the U.S. Once that understanding is established, then one needs to determine if male drivers of all ages are represented, and the other socioeconomic and demographic identifiers that may relate to a group that should be targeted for such educational products. A recently completed study in cooperation with the Montana Department of Transportation (MDT) examined the effectiveness of displaying traffic safety videos at driver's license stations, including a video that highlighted the rules for both bicyclists and motorists (Villwock-Witte, et al., 2023). The included video did not convey a rural context (e.g., it had green painted bike lanes which are rarely found in rural areas). The style of the video was informative. Survey respondents reported that they would be safer drivers, but they did not suggest that they would change their behavior. The study did conclude that videos that engaged a viewer's emotional response or empathy and videos that were shocking seemed to improve a viewer's recall of the material (Villwock-Witte, et al., 2023). Therefore, creating videos that engage the viewer's empathy in the rural context is one strategy that may benefit educational campaigns.

While NHTSA combined bicyclist and motor vehicles operating under the influence, Robartes and Chen's (Robartes & Chen, 2017) analysis showed significantly greater mortality outcomes for a bicyclist when the motor vehicle driver was the intoxicated party. The authors therefore recommend that these two categories are not grouped in the analysis.

Regardless of how you look at it, if a roadway does not have a shoulder, or if it is unpaved, it is not good for bicycle travel. Identifying a rural bicycle network with lower speeds and with shoulders four to six feet in width should be provided as the bare minimum of such a network, as suggested by Carter and Council (Carter & Council, 2006). The network should not be prioritized for freight, as freight's fundamental objective of getting goods from one place to another as efficiently and safely as possible contradicts the need for lower speeds in the presence of bicyclists.

Hamann and Peek-Asa (Hamann & Peek-Asa, 2013) identified the need for more rural-specific bicyclist research. This synthesis of available resources adds a small contribution. However, more notable are the following research ideas that could be pursued as a result of this synthesis.

3.3 Future Research

The following are future research studies that are suggested as a result of this literature review synthesis. There remain many opportunities to improve the safety of bicyclists operating in the rural context.

Evaluating Vehicle Passing Distance (VPD) in the Rural Context Love et al. (Love, et al., 2012) conducted a novel study, albeit in the urban context (Baltimore, Maryland), which allowed them to understand how infrastructure (among other variables) may influence vehicle passing distance. With speeds often higher and vehicle types potentially larger in the rural context, there would be value in better understanding how various rural infrastructure (e.g., bike lane, no shoulder, narrow shoulder, wide shoulder) as well as speed and vehicle type may influence the space that motorists provide between themselves and a bicyclist. Rural bicyclists across the U.S. could be invited to participate, potentially leveraging members of the League of American Bicyclists as well as members of other bicycling advocacy groups (e.g., BikeMN) to recruit bicyclists. This would allow a variety of demographics, infrastructure provisions, and states to be included in such a study.

Evaluating Shoulder Width Impacts on the Safety of Bicyclists To better understand the influence of wider shoulders on the safety of bicyclists and freight, if a state department of transportation (or ideally multiple agencies) was planning to widen shoulders throughout their state, the roadways could be segmented based on roadway characteristics. Then vehicle (including freight percentages) and bicycle counts could be conducted. On-site, long-term data collection of bicycle and concurrent vehicle counts would be needed for each segment (noting that the volumes are contemporary and may not necessarily relate to crash experience directly). Ideally, data from rural roadway segments from five state departments of transportation, that represent roughly five regions, would be collected for analysis. The crash statistics before and after the shoulder width was added (and the amount of added width) could then be analyzed to estimate the safety benefit (if there was one) to both bicyclists and freight. The intent of the project would be to create a passive experiment where the bicyclist and/or freight would not necessarily be encouraged to use or not to use the facilities before and after the shoulders were widened.

Wide Shoulder or Separated Facility in the Rural Context: Influences on Who and How Many Bicyclists Use Such Facilities In order to truly understand the trade-offs between adding a wider shoulder as compared with adding a parallel separated facility, a before and after study should be conducted. Where right-of-way (ROW) is available, a separated facility should be added parallel to some rural roadways. Where ROW is not available, a wider shoulder should be added. Extensive vehicle and bicyclist volume counts (including an analysis of the use by different axel types) should be conducted throughout the project period, including before any changes are made. A roadway that has not had changes should also be integrated into the analysis. Demographics of bicyclist users should also be captured over time (e.g., children, women, men).

Preferences for Rural Bicycling Infrastructure Using Adaptive Stated Preference Tilahun et al. (Tilahun, Levinson, & Krizek, 2007) used a novel approach to evaluate the preference of bicyclists and non-bicyclists for various infrastructure that may support bicycling as a mode of travel. This approach could be used to evaluate preferences for rural bicycling infrastructure. Videos from an area that had no shoulders, narrow shoulders, wide shoulders, and a separated multi-use pathways could be presented to participants.

Operating Under the Influence, Bicycles and Motor Vehicles: Uncovering the Details Studies have suggested that more severe crashes occur when the bicyclist and/or motor vehicle driver are operating under the influence ((Robartes & Chen, 2017); (Lin & Fan, 2019)). Data has even been presented as combined motor vehicle driver and bicyclist operating under the influence percentages, although the outcome of a motor vehicle driver operating under the influence is often more impactful than a bicyclist operating under the influence because the mass of the vehicle they are operating is significantly different (bike = 19 lbs, motor vehicle average weight 3,000 lbs). Moreover, while this data has been reported, few details have been provided then after. For example, is the bicyclist operating under the influence after a night of revelry? Or has the bicyclist had their driver's license revoked (and potentially vehicle impounded) and they are now commuting to work via bicycle with on-going substance abuse issues? If it is the latter, it suggests that instead of enacting bicycling under the influence laws, as suggested by Robartes & Chen (Robartes & Chen, 2017), social interventions are needed instead. Therefore, in order to effectively address the issue, additional research is needed in this area. This research could include an in-depth examination of crash data involving bicyclists under the influence of drugs and/or alcohol to determine if there are trends in these crashes. For example, when are these crashes occurring, where are these crashes occurring, and who is involved?

Examining the Effectiveness of Traffic Safety Videos on Bicyclist Safety Pucher and Dijkstra (2003) noted the need for public campaigns to emphasize the impact of bicycle crashes on Americans (Pucher & Dijkstra, 2003). Recent work found that traffic safety videos, in particular videos that are shocking or engage a viewer's empathy, can have an impact on traffic safety culture (Villwock-Witte, et al., 2023). Future research could include developing traffic safety campaigns related to bicycle safety, which is either shocking or engages a viewer's emotions. A multi-year study (e.g., five years) could examine the effectiveness of said traffic safety campaigns on improving bicyclist safety, as changes to culture require longer-term monitoring and evaluation.

The Psychological Implications of Bicyclists and Pedestrians Being Struck by a Vehicle Thinking about friends, family, and co-workers, are you aware of anyone that was hit by a vehicle while riding a bike or walking? If so, what are the implications of this knowledge? Is it more likely for a person with this knowledge to avoid walking or bicycling outside? The proposed research study would seek to identify how many people who currently walk and/or ride outside, as compared with those who choose not to walk and/or ride outside, may have had their choice influenced by actual or even potentially perceived safety.

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