

Vulnerable Road User Safety Enhancements for Transportation Asset Management

Center for Transportation, Environment, and Community Health
Final Report



by
Carlos M. Chang, Edgar D. Rodriguez

January 31, 2019

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

1. Report No.		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Vulnerable Road User Safety Enhancements for Transportation Asset Management				5. Report Date January 31, 2019	
				6. Performing Organization Code	
7. Author (s) Carlos M. Chang and Edgar D. Rodriguez				8. Performing Organization Report No.	
9. Performing Organization Name and Address Department of Civil Engineering The University of Texas at El Paso 500 West University Ave. El Paso, Texas 79968				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. 69A3551747119	
12. Sponsoring Agency Name and Address US. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code US-DOT	
15. Supplementary Notes					
16. Abstract Safety of Vulnerable Road Users (VRU) is a problem of global magnitude since the proportion of fatalities represents more than half of the total deaths in traffic worldwide. VRUs are pedestrians, cyclists, and motorcyclists of all ages and abilities. Roadway assets play a significant role in traffic safety. Pavement markings, sidewalks, bikeways, medians, guardrails, and road lighting influence in the outcome of adverse traffic accidents. This research report describes a framework that explicitly incorporates VRU safety into Transportation Asset Management (TAM) practices. The framework should serve as a guideline for State Departments of Transportation (DOTs), Metropolitan Planning Organizations (MPOs), and local agencies. The framework includes a methodology to prioritize infrastructure projects using the Dynamic Bubble Up (DBU) technique for funding allocation and a Vulnerability Road User Safety Index (VRUSI). The TAM-VRU framework and methodology applies to all VRU groups, although VRUSI is developed for pedestrians due to the sustained uptrend of fatalities registered in the last decades. Safety indexes to assess specific risk factors of other VRU groups can also be incorporated in the overall framework.					
17. Key Words Vulnerable Road Users (VRU), Transportation Assess Management (TAM), Prioritization, Vulnerability Road User Safety Index (VRUSI), Pedestrian Safety, Dynamic Bubble Up (DBU)			18. Distribution Statement Public Access		
19. Security Classif (of this report) Unclassified		20. Security Classif (of this page) Unclassified		21. No of Pages 81	22. Price

TABLE OF CONTENTS

Chapter 1. Introduction.....	1
1.1 Introduction.....	1
1.2 Background.....	1
1.3 Motivation for this Research.....	2
1.4 Objective and Scope	2
1.5 Research Approach	2
1.6 Organization of the Final Report	4
Chapter 2. Transportation Asset Management and Safety Practices for Vulnerable Road Users	5
2.1 Transportation Asset Management (TAM).....	5
2.2 Vulnerable Road Users (VRU)	5
2.3 Vulnerable Road User’s Problem in the United States	6
2.4 Vulnerable Road User Safety Policy in the United States	7
2.5 International Vulnerable Road User Safety Policies	8
2.6 User Road Risks and Safety Exposure	10
2.7 Pedestrian Vulnerability.....	11
2.8 Vulnerability of Bicyclists	12
2.9 Vulnerability of Users with Disabilities	13
2.10 Vulnerability of Children.....	13
2.11 Vulnerability of Elderly Users	13
2.12 Vulnerability of Other Special Groups	13
Chapter 3. Identification of Factors Influencing Pedestrian Safety.....	15
3.1 Introduction.....	15
3.2 Driver and Vehicle Safety Risk Factors.....	15
3.3 Demographic, Cultural, and Social Safety Risk factors	15
3.4 Pedestrian Safety Risk Factors.....	16
3.5 Infrastructure Related Safety Risk Factors	16
3.5.1 Posted Speed	17
3.5.2 Crossing Distance	17
3.5.3 Presence of Medians or Midblock Cross Walks	17
3.5.4 Functional Classification	18
3.5.5 Intersections and Crosswalks.....	18
3.5.6 Land Use and Zoning.....	18
3.5.7 Traffic Control Signs	19
Chapter 4. Framework to Integrate Vulnerable Road Users into TAM	21
4.1 Introduction.....	21
4.2 Overview of the Framework to Integrate VRU into TAM	21
4.3 Safety Indexes for Pedestrians.....	22
4.4 Vulnerability Road User Safety Index (VRUSI)	26

4.5	Project Selection and Funding Allocation	27
4.6	Recommendations for VRU Safety	28
Chapter 5. Case Study		31
5.1	Introduction.....	31
5.2	Example on How to Calculate VRUSI	31
5.3	Project Selection and Funding Allocation	36
Chapter 6. Conclusions and Recommendations.....		39
6.1	Conclusions.....	39
6.2	Recommendations for Future Research.....	40
References.....		41
Appendix A.	Prospect Street Photos	45
Appendix B.	Yandell Drive Photos... ..	49
Appendix C.	Porfirio Diaz Street Photos.....	53
Appendix D.	Upson Drive Photos.....	57
Appendix E.	Lawton Drive Photos.....	61
Appendix F.	Safety Index Calculations.....	65

LIST OF FIGURES

Figure 1. Research Approach to Integrate VRU Safety in the TAM Process	3
Figure 2. Total Road Fatalities Comparison, US vs. Other Developed Countries	6
Figure 3. Example of Bicycle Network and Roadways Segregation and Connectivity	9
Figure 4. Vulnerable Road Users Exposed to Traffic in the Asia-Pacific Region	10
Figure 5. Examples of High and Low Walkability Neighborhoods with a Walkability Map for New York City	12
Figure 6. Factors Related to Pedestrian Risk Safety	15
Figure 7. Probability of Pedestrian Fatality and Speed	17
Figure 8. Influence of Zoning Areas on Pedestrian Risk	19
Figure 9. Framework to Integrate VRU in TAM.....	22
Figure 10. Scoring Matrices for PLOC Determination	23
Figure 11. Intersection Selected to be Evaluated in the Case Study	31
Figure 12. Distribution of Streets around Mundy Park	32
Figure 13. Data Collection Field Form for PLOC, PLTS, and Ped ISI calculation	33
Figure 14. Sidewalk Condition Rating Description.....	34

LIST OF TABLES

Table 1. Exposure and Risk 11
Table 2. Population in the US with Disabilities 13
Table 3. Physical Buffer Type 24
Table 4. Total Buffering Width..... 24
Table 5. General Land Use 24
Table 6. Collector and Local Unsignalized Intersection Crossing..... 24
Table 7. Arterial Unsignalized Intersection Crossing without a Median Refuge 25
Table 8. Arterial Unsignalized Intersection Crossing (1 to 2 lanes) with a Median Refuge..... 25
Table 9. Arterial Unsignalized Intersection Crossing (3 or more lanes) with a Median Refuge 25
Table 10. Adjustments for Crosswalks Enhancements 25
Table 11. Sidewalk Condition..... 26
Table 12. Countermeasures for Pedestrian Safety Improvement at Intersections..... 30
Table 13. Data Collected for Safety Index Calculation 35
Table 14. Data for the Project Selection and Funding Allocation 37
Table 15. Results for Intersections to be Improved Based on the VRUSI Ranking Criterion 37
Table 16. Results for Intersections to be Improved Based on the Cost/VRUSI Ranking Criterion.... 38

ACKNOWLEDGEMENT

We are thankful to El Paso Metropolitan Organization (ELP-MPO) for providing matching funds for the development of this research. We would also like to acknowledge the participation of students from the University of Texas at El Paso (UTEP): Marketa Vavrova, postdoctoral researcher; Johannes Makahaube, doctoral student; Raul Soto Armendariz, graduate research assistant; and undergraduate students: Marco A. Barraza, Marco Banda, and Alberto Ochoa.

CHAPTER 1

Introduction

1.1 Introduction

This Chapter describes the background of the problem and motivation for this study, explains the research objective and scope with an overview of the research approach and tasks conducted to integrate the safety needs of vulnerable road users into Transportation Asset Management (TAM). In the following Chapters, this final report presents a summary of road safety current practices and research efforts for pedestrians, bicyclists, and motorcyclists; explaining the particularities of vulnerable road users including children, seniors, and people with disabilities. It also identifies risk factors and needs of these vulnerable user groups as related to their mode of travel. As a result of this study, a methodology including safety measures and countermeasures is recommended for asset management practices to enhance safety for vulnerable road users.

1.2 Background

The transportation network in the United States is subject to a growing strain including safety. At present, safety is one of the most relevant challenges for policy makers coupled with a growing demand for mobility. The integration of different modes of transportation generates new issues in an environment where multimodal transportation becomes relevant (Milne et al, 2014). In this sense, better infrastructure should lead to improve the safety conditions for all users; particularly, to those who are subject to greater risks in traffic.

Statistics demonstrates that the safety of vulnerable road users is a problem of global magnitude. The proportion of fatalities involving cyclists, pedestrians and motorcyclists, represents more than half of the total deaths in traffic worldwide (World Health Organization, 2017). Road safety is with no doubt a major world health challenge accounting for almost 50 million injured individuals and 1.25 million fatalities every year (World Health Organization, World Bank, 2015). Pedestrian safety is a concerning issue due to its high percentage accounted in the total traffic deaths and because of the sustained uptrend shown in this decade. The share of pedestrian fatalities went up from 11% in 2007 to 16% in 2016, increasing one percent every two years in the United States (NHTSA, 2018). For example, according to the Active Transportation Annual Safety Report, in Washington the number of traffic fatalities involving people walking or biking has steadily increased from 60 in 2013 to 122 in 2017, an average of 94 fatalities per year over this five-year period (WSDOT, 2018).

Vulnerable Road Users (VRUs) are exposed to greater risks of bodily injury and can suffer serious physical harm or lose their lives in road crashes. The VRU group includes users of all ages and abilities, namely children, the elderly and people with disabilities (physically or mentally impaired). Pedestrians are even physically more vulnerable in traffic because they are not shielded by external protective elements such as airbags, bumpers, or metallic guards. The challenge is to incorporate the safety needs of all users into the asset management process.

It has been proven that roadway assets play a significant role in traffic safety. Pavement markings, sidewalks, bikeways, medians, guardrails, and road lighting to influence the outcome of adverse traffic accidents (Chang et al, 2016). TAM is a strategic and systematic decision-making process for managing transportation infrastructure. It includes the planning and programming of investments and expenditures throughout its lifecycle. It seeks to optimize the allocation of limited resources to improve the efficiency

and effectiveness of management decisions. This process involves three relevant aspects: system performance, technical requirements, and economic consequences.

1.3 Motivation for this Research

The motivation for this research arises from the need to incorporate vulnerable road user safety into TAM. In TAM, the inclusion of people needs is vital but not explicitly established in the decision-making process for VRU. TAM utilizes a number of methods to evaluate the impact of alternative funding scenarios, and the inclusion of VRU safety in the criteria for funding allocation is critical.

1.4 Objective and Scope

The objective of this research is to develop a methodology that explicitly incorporates VRU safety into TAM practices. TAM aims to achieve the required level of service of transportation infrastructure in the most cost-effective manner while providing safe transportation. It is critical to address the needs of all the users to foster transportation options that promote the well-being of the society. The methodology should serve as guidelines for State Departments of Transportation (DOTs), Metropolitan Planning Organizations (MPOs), and local agencies. The research objective applies to all VRU groups (e.g. children, elderly, the disabled, bicyclists, horseback riders), although the scope of the study is narrowed down to pedestrians due to the sustained uptrend of fatalities registered in the last decades.

1.5 Research Approach

The research approach was task-oriented and sought to identify road risk factors for pedestrians to develop a methodology to assess their effects on VRUs' safety. Figure 1 shows an overview of the research approach to integrate vulnerable road user safety into the TAM process. The research approach consisted of four tasks:

Task 1: Literature Review of VRU and TAM. This task included a review of the current safety practices and the identification of the most significant VRU risk factors for TAM decisions.

Task 2: Analyze Vulnerable Road Users Risk Factors. In this task, an analysis was performed to identify the infrastructure borne risk factors that influence pedestrian-vehicle crashes.

Task 3: Develop a Methodology to Consider VRUs in TAM Decisions. The methodology for VRU safety assessment for TAM was developed in this task. It includes the evaluation of infrastructure components from a VRU perspective in order to provide equal accessibility to the entire transportation system.

Task 4: Case study: The methodology developed in Task 3 was applied to a case study located at Mundy Park in El Paso, Texas.

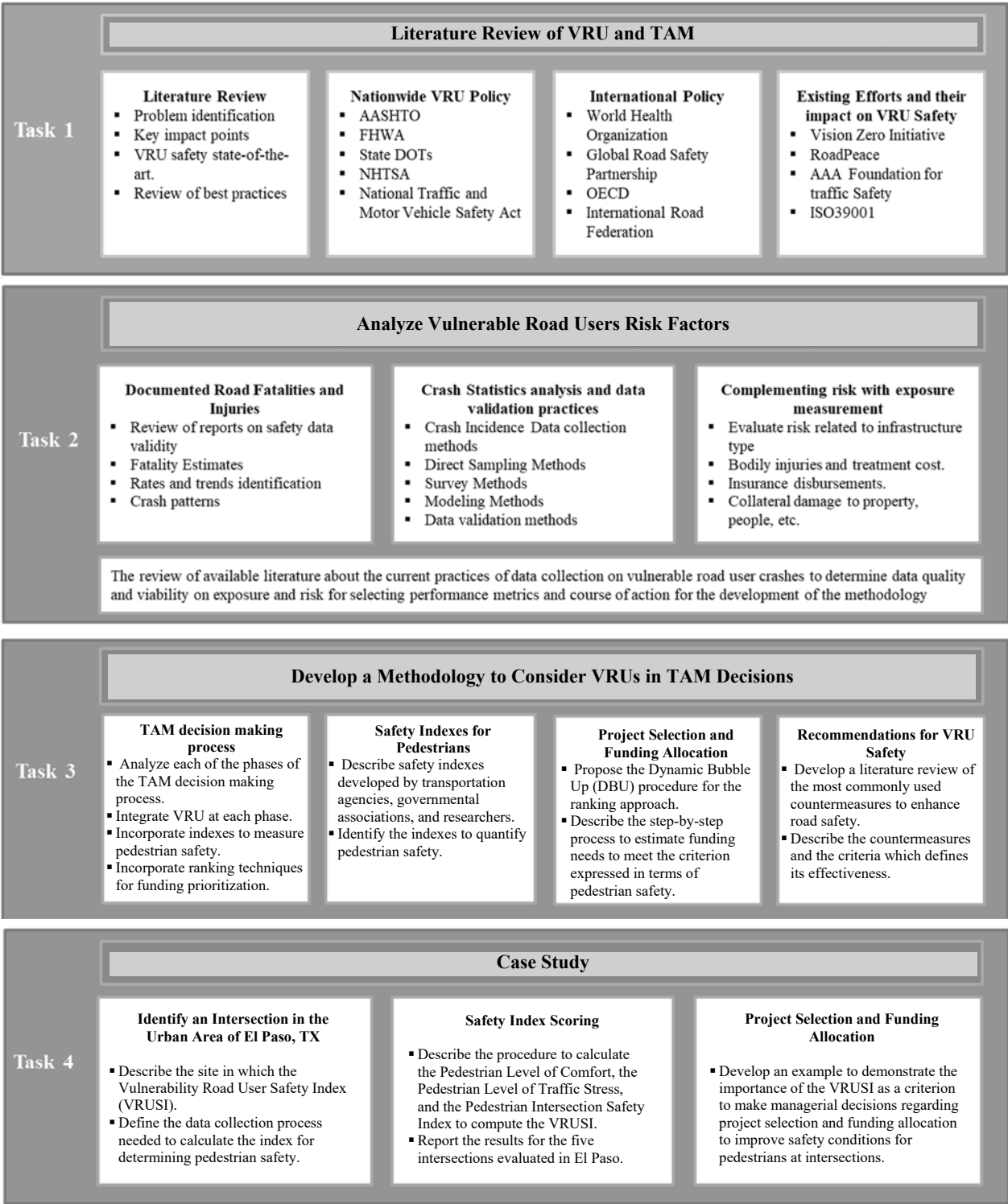


Figure 1. Research Approach to Integrate VRU Safety in the TAM Process.

1.6 Organization of the Final Report

This Final Report describes the state of the current practice for VRU safety and includes a comprehensive analysis of the risk safety factors related to infrastructure that affects pedestrians. A methodology is presented to integrate safety enhancements into TAM to reduce the VRU risk factors. The report is organized in six chapters:

Chapter 1 explains the problem and motivation for this research, objective and scope, and research approach to integrate the safety needs of VRUs into TAM.

Chapter 2 includes a description of Transportation Asset Management, vulnerability concepts and contributing factors, US and international road user safety policies as related to TAM practices, and a description of VRU risk factors.

Chapter 3 focuses on the identification of factors that influence pedestrian safety and morbidity; and concludes with the selection of infrastructure-borne factors.

Chapter 4 describes the framework to integrate Vulnerable Road Users into Transportation Asset Management. Safety indexes with the calculation procedures are explained in this Chapter. Recommendations for VRU's safety with countermeasure examples are also presented.

Chapter 5 presents a case study to demonstrate the applicability of the framework including the calculations of the Vulnerability Road User Safety Index. It also describes how to apply the results of the analysis for project selection and funding allocation in a pedestrian network.

Chapter 6 summarizes the conclusions of the study with recommendations for future research.

CHAPTER 2

Transportation Asset Management and Safety Practices for Vulnerable Road Users

2.1 Transportation Asset Management (TAM)

TAM practices respond to the growing need of agencies to better allocate limited resources despite the complexity of the decision-making process and the increasing needs to preserve the infrastructure transportation system. According to the United States Department of Transportation (USDOT), TAM “is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle” (FHWA, 2007a).

Transportation agencies adopt TAM to manage their assets with a business approach that follows a strategic view in compliance with the Moving Ahead for Progress in the 21st Century Act (MAP-21). MAP 21 compels transportation agencies to establish a performance-based methodology guided by a set of national goals: (1) safety, (2) asset condition, (3) reduction of traffic congestions, (4) reliability of transportation system, (5) freight movement for economic vitality, (6) environmental sustainability, and (7) reduced project delivery delays. In addition, MAP-21 aimed to transform the policies and the programmatic framework regulating transportation expenditures and program investments. After MAP-21, FastAct was signed in 2015 to cover the transportation funding bill for 2016-2020. FastAct is performance-based oriented and serves as an extension of previous funding programs for transport infrastructure in the United States. TAM seeks to improve the prioritization of capitals to provide a reliable, accurate and most cost-effective response. In order to be eligible for funding, transportation agencies must focus their measuring efforts on traffic safety as the number one goal in the national goals for infrastructure (USDOT, 2016).

2.2 Vulnerable Road Users (VRU)

Automobiles, freight (trailer hauling trucks), motorcyclists, bicyclists, and pedestrians compete for the use of limited space in the public transportation network. Factors like roadway’s geometric characteristics and constrained displacement space represent a challenge for TAM (Pan-American Health Organization, 2011). This situation increases the level of conflict among users, deriving in the spawn of risk factors, in particular for VRUs.

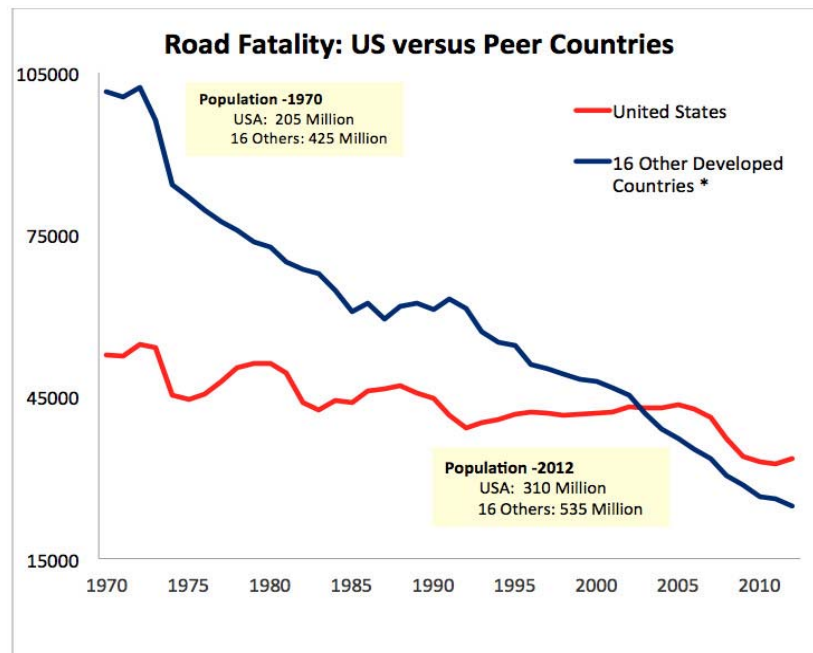
Road user’s vulnerability is a relative and dynamic concept; it encompasses all those users that are subject to external risk factors within the transportation network. Vulnerability can be defined as the diminished ability of a person or group of people to anticipate, cope and resist the harming effects of an external force or action (Blaikie et al, 2005). More specifically, road user’s vulnerability arises when humans move from one place to another to carry out their daily activities; and there are circumstances that influence user groups to use certain system component. Among the factors that influence the risk exposure is the rapid increase in motorization in the world. Pedestrians, bicyclists, moped riders, and motorcyclists endure a shortfall of shelter to their physical integrity when compared to other transportation modes. Those users have lesser protection to the effects of motorized traffic such as the lack of an external robust cover. Added to the previous factors, a number of research studies have demonstrated that risk exposure is related to demographics (e.g. age and gender), land planning, land use and road construction, and the increasing need to move as urban centers grow (Patiño, 2013).

2.3 Vulnerable Road User's Problem in the United States

The main problem of pedestrian safety in the United States is reflected in the high rate of pedestrian fatalities. The number of fatalities in different categories in the US increased 9% for pedestrian deaths from 2015 to 2016 of 492 from 5,495 to 5,987. This hike was also recorded in the number of bicyclists fatalities from 829 to 840, as well as in motorcyclists (+ 5.1%) and vehicle occupants (+ 4.7%) with a general increase of (+ 5.6%) from 2015 to 2016 (NHTSA, 2016). In 2016, total fatalities were about 38,000 motorcyclists, cyclists, pedestrians, and vehicle occupants. In 2018, pedestrian fatalities reach its highest level in the last 25 years, while the other groups' rate of road fatalities have been decreasing (GHSA, 2018).

According to The National Highway Traffic Safety Administration (NHTSA), VRU incident data shows that the vast majority of deaths related to traffic incidents with pedestrians occur in areas with the higher urban population concentration. In urban areas, the number of users is higher than rural areas, and the total adjusted accident ratio is also higher accounting for 75 % of total VRU fatalities (NHTSA 2017). Urban infrastructure conditions (e.g. crosswalks, sidewalks), and intricate intersections are factors that influence the higher crash rates.

This situation in the United States, regarding safety of VRUs, is even more challenging when compared to the rest of the world. In the United States, the configuration of the cities and distances for mobility present a unique pre-existing condition that it is very distinctive when compared to Europe, where the cities are denser, distances are shorter, and the cities have a very different demand for mobility. Figure 2 shows that decreasing fatalities in U.S. roads have lagged behind compared to other developed countries. The combination of the total population of the 16 developed countries sum up almost twice of America's. By simply analyzing the number of fatalities in contrast to the total population, it is concluded that there is a need to enhance the current TAM practices to explicitly integrate safety practices for VRUs (Garrick et al, 2016).



* Canada, Japan, Australia, New Zealand, Austria, Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Sweden, Switzerland, and the UK.

Figure 2. Total Road Fatalities Comparison, US vs. Other Developed Countries. (Garrick et al, 2016)

2.4 Vulnerable Road User Safety Policy in the United States

Safety is one of the top priorities for the USDOT, and the policy in the United States on VRU Safety has improved in recent years with the development of programs such as *USDOT Safer People, Safer Streets Initiative*, a road safety assessment endeavor performed in all 50 states since 2014 (USDOT, 2015).

NHTSA in conjunction with the Federal Highway Administration (FHWA), in turn, has exerted continuous efforts to improve the conditions of pedestrians in traffic with awareness programs. It is no surprise that transportation safety is at the forefront of the National Performance Goals, seeking to achieve measurable and significant reductions in the serious injuries and fatalities throughout the public transportation system. [23USC §150 (b)]. This strengthens the main objective of infrastructure management policies that is to enhance safety for all the users.

About two decades ago, the American Association of State Highway and Transportation Officials (AASHTO) started developing the Strategic Highway Safety Plan (SHSP) to offer transportation agencies nationwide with a comprehensive methodology to address road safety in 22 focused areas related to highway safety that includes pedestrians, older drivers, motorcycles, bicycles among many others. This plan presents a comprehensive outline of action items to implement each of the strategies described for the emphasis areas. Based on these efforts technical documents were developed under the SHSP. NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan consists of a series of 23 volumes focused on guiding transportation agencies to minimize injuries and fatalities in transportation systems. Each of the volumes describes the general problem at the national level and recommends strategic actions to address collisions with motorcycles that involve pedestrians, older drivers, utility poles, and bikers (NCHRP, 2003).

Safety Performance Management is the first part of the Transportation Performance Management (TMP) program (FHWA, 2017a). The Safety Performance Management Final Rule is aligned with the Highway Safety Improvement Program (HISP) by establishing five key performance measures that are re-evaluated every five years:

- I. Number of Fatalities
- II. Rate of Fatalities per 100 million Vehicle Miles Traveled (VMT)
- III. Number of Serious Injuries
- IV. Rate of Serious Injuries per 100 million VMT
- V. Number of Non-motorized Fatalities and Non-motorized Serious Injuries

The Safety Performance Management program also establishes the process for the DOTs and MPOs to report their safety objectives for traffic through a process established by the FHWA. By virtue of the new policies, agencies should transition into a performance-based management approach for road safety. FHWA developed a methodology for agencies to be accountable for safety using a wide array of data driven tools described as “Data Driven Safety Analysis, DDSA” (FHWA, 2017b). The focus of DDSA is on active models based on collected evidence about road incidents, providing state and local agencies with the tools to quantify accidents, similar way as it is used to measure environmental impacts, pavement service lives, and traffic operations. Traffic methods of crash analysis are usually based on numerical measures related to infrastructure safety performance. The difficulty is how to estimate correctly the project impacts for alternative planning options.

The Texas Public Work Department in the City of Austin, as part of its Pedestrian City Master Plan, developed a pedestrian infrastructure management system. The tool consists of a web-based management software with geo-spatial mapping capabilities (City of Austin, 2009). The tool allows Texas Public Work Department (TPWD), to make a network level assessment of pedestrian infrastructure in terms of condition, accessibility and ADA Compliance utilizing a GIS database. Data include curb ramps, network sidewalks

and driveways, government offices, parks, major employers, public facilities, bicycle lanes, rail stops, transit stops, religious institutions, core transit corridors, ADA Task Force Requests, among others. The system identifies the areas with an increase concentration of pedestrians such as stores, offices, parks; and in combination with demographic data from the census blocks. The information in this system is helpful to prioritize projects for funding allocation.

2.5 International Vulnerable Road User Safety Policies

Vulnerable Road User safety was established as a priority by the World Health Organization for Europe on resolution EUR/RC55/R9 almost 20 years ago (WHO Regional Office for Europe, 2005). The European Union (EU) Council recommends the prevention of injury and the promotion of safety, and the need to consider VRUs as a group of special attention for policymakers (European Commission 2015).

The United Nation General Assembly Resolution on improving global road safety recommended the implementation of road traffic injury prevention plans (Mohan et al, 2006). Concerns on road traffic increased fatalities are well founded. The World Health Organization reports traffic crashes in a number of countries demonstrating that road accidents have become a problem of major proportion that it is difficult to manage, affecting millions of families around the world. (Vargas, 2012). In 2013, the World Health Organization published a report to provide guidance to decision makers on how to develop situational assessments to implement effective pedestrian safety countermeasures (WHO, 2013). It is emphasized the importance of reducing exposure to live traffic, reduce vehicle speeds, improve visibility, raise awareness in users, work with manufacturers to improve vehicle design for pedestrian protection and provide care for injured pedestrians. In the following section, the most relevant international efforts with examples on how to address VRU safety are described.

Reducing VRU injuries are deemed as the single most relevant challenge of today's worldwide road safety, as they comprise the user group with the highest road fatality risk with around 612,500 total deaths in 2015 (49% of fatalities). Inherent increased VRU risk is caused by centered attention to faster travel modes, deficient planning, and omission of safety priorities. (World Health Organization, 2015). It is not surprising the fact that newly spawned initiatives on asset management policies focused on the mitigation of road safety risks due to a relevant growing trend of injuries and fatalities.

Vision Zero Initiative

A great example of safety policies is the Vision Zero Initiative program that emerged in Sweden in 1997, which later percolated unto other developed countries' policy priorities. Vision Zero is a voluntary commitment that organizations around the world are adopting to direct infrastructure policies towards total safety risk mitigation in public roads. The approach consists on the implementation of preventive measures to bring down to zero the number of fatalities with a strategy supported by a comprehensive road safety program. The strategy combines a series of actions including: law enforcement, promotion of a better culture of intermodality in transport infrastructure, improving the road condition, and strengthen agencies to improve their data collection practices (Hauer, E., 2010).

ISO 39001: Road Traffic Safety Management System Standards

ISO 39001 "Road Traffic Safety Management Systems" (RTS) establishes a global standard with the minimum RTS requirements to prevent serious injuries on the road. It can be used for certification, self-declaration, or simply as a guideline to plan, implement, and improve a dedicated road safety management system. (ISO, 2012). ISO39001 is well aligned with the best practices to achieve total road safety by reducing traffic fatalities, as it provides a highly adaptable framework. In its core, ISO 39001 is a management system standard that was developed following the same structure as ISO 9001, ISO45001 and ISO27001. (Hartzell, P. 2017)

ISO 39001 paves the way to actively manage road user risks to reduce fatalities, minimize lost productivity and advocates total commitment to social responsibility. The six-step process to adapt ISO39001 for transportation managing organization is based on the Plan, Do, Check and Act cyclic process (Hartzell, P. 2017). The first step is to identify the scope and decision-making context to adapt the standard to the needs of the organization, the second step is the necessity to assess leadership to adopt it, the third step is the thorough planning of the actions required to achieve road safety systems. The fourth step refers to the implementation actions of the standard, and the fifth step addresses monitoring and evaluation, followed in the sixth step by continual improvement of the process until the elimination of fatalities and serious injury (Hartzell, P. 2017).

Successful Multimodal Integration of Transport Systems

Amsterdam in the Netherlands is an excellent example of multimodal integration in transport systems. According to “Invest in Holland”, about 25% of all trips are done by bicyclists with only 185 fatalities in their 22,000 miles of bikeways (Pieters, J. 2016). Their approach to this successful integration of the bikeway lanes relies upon assertive safety policies that prioritize VRUs in spatial planning, enforce pro bicycle traffic laws, and foster this mode of transportation (McKibbin, D., 2014). Most bikeways are segregated from roadways reducing their bicyclist risk exposure significantly. This is a good example of roadway’s physical independency from the bikeway network. In addition to the roadway network separation, in the intersections, the bicyclist is protected with physical barriers. This practice achieves connectivity without compromising safety (Hembrow, D., 2012) Figure 3 shows how both systems operate in the same geographical area without a conflict. This type of configuration has been very beneficial for drivers, bicyclists, and pedestrians.



Figure 3. Example of Bicycle Network and Roadways Segregation and Connectivity (Hembrow, D., 2012)

Vulnerable Road Users in the Asian and Pacific Region

In the Asian and Pacific Region, there have been efforts to provide technical assistance to the decision makers to manage safety problems. The Asian Development Bank analyzed traffic accidents data to quantify the nature and scale of VRU incidents and summarize recommendations that are applicable to their infrastructure configuration especially for their mobility culture as shown in Figure 4. Due to the level of economic development in the Asian and Pacific region, with low car ownership ratios, walking and biking is part of their cultural and social customs that play a main role in their transportation mode share. Based on this context, the Asian Development Bank acknowledged the need to provide road safety guidelines for VRUs since they are subject to higher number of motorcycles and bicycles on busy roads, coupled with poor signal infrastructure (Asian Development Bank, 1998). Guidelines for the inclusion of “Safety Audit Considerations” include a feasibility study, visibility of signs and markings, landscape and environment assessment, speed enforcement laws near crossing locations, and overall more attention to VRU safety requirements on maintenance, rehabilitation, and new construction projects. They also encourage the improvement of VRU data collection methods over the last 20 years (Asian Development Bank, 1998).



Plate 1.1 (above): Pedestrians exposed to risk in the traffic stream.

Plate 1.2 (right): Vehicles in conflict in the People's Republic of China (PRC).



Plate 1.3 (below): Typical cycle-rickshaw in Bangladesh.



Figure 4. Vulnerable Road Users Exposed to Traffic in the Asia-Pacific Region
(Asian Development Bank, 1998)

2.6 User Road Risks and Safety Exposure

There are a number of methods to study the factors that contribute to VRU risk safety. Panel analysis methods such as the case-control study can be used to analyze pedestrian risk. Case-control studies follow observational methods to identify and relate accidents to a specific cause. This method of analysis seeks to compare results between two groups of the study universe; one group exposed to a certain risk factor, and another group that has not. The proportion of events in which the groups are exposed to the risk factor against to those in which they were not exposed is calculated. With this analysis, the association between the risk factor under study and the event outcome is studied (Gordis, 2014).

Based on an epidemiology study conducted by Gordis (2014), VRU risk on traffic depends on four primary factors. The first factor is exposure or the amount of movement of the different users in the transit system; the second factor is the probability that a crash will occur given the exposure; the third factor is the likelihood of an incident to produce an injury, and the fourth factor is the result or outcome of the injury. Some of the factors that influence the severity of the outcome include human errors and level of traffic, the amount of energy at the impact, the individual's tolerance to the impact; and the quality, availability of emergency services, and promptitude of the attention to the trauma. (Peden, 2004).

“The Vulnerable Road Users Traffic Risk and Exposure: California Department of Transportation’s Report” makes the distinction between user exposure and risk. For pedestrians, road exposure is defined as the amount of vulnerability that users pose to suffer a collision in traffic. The principle is based on the existence of multiple metrics to determine the magnitude of the exposure (Greene, 2010).

Federal, state and local agencies have developed specific methodologies to obtain pedestrian volume, although there is no consensus on which method of counting is the most appropriate to determine the exposure. The strategy depends on the characteristics of the study area, resources available for obtaining the data and specific purpose of the analysis. (Schneider et al, 2005). Table 1 shows the definition of risk as the probability of a crash per unit of exposure $P(c|x)$. Exposure is the amount of contact with the harmful event (x), therefore risk is the probability function of exposure (Greene, 2010).

Table 1. Exposure and Risk (Greene, 2010)

Concept	Definition	Symbol
Exposure	Contact or amount of contact with a potentially harmful situation (x)	(x)
Risk	Probability of Collision / Injury / Fatality (c) per unit of Exposure	P (c x)

In the science of epidemiology, exposure refers to the contact of an individual to a situation of danger, therefore it is mentioned that "Exposure can also be understood as a trial event in which a harmful outcome might occur" (Greene, 2010). On the other hand, risk is a concept that defines the probability of a negative event occurring given a series of trials (Greene, 2010). Besides, risk of an accident is defined in injury epidemiology as an unintended or unwanted event that causes damage, injury or other negative impact on an object or subject (e.g. a person or group of persons on the road) (Robertson 2015).

2.7 Pedestrian Vulnerability

In this research, pedestrians are defined as those users who travel on their own means (typically on foot) along public infrastructure. People who autonomously push or pull non-motorized wheeled devices and small-sized vehicle such as strollers, trolleys, load dolly's or suitcases are also considered pedestrians. People on wheel-chairs (motorized or non-motorized), segway users, hover boards riders, electric one wheelers and electric scooters are also considered in the pedestrian group.

Walking is the most versatile and energy efficient mode of transportation since pedestrians can move freely. Pedestrians require lesser area to freely transit and its level of service is easier to sustain when compared to other modes of transportation that require more complex infrastructure. Walking has been proven to possess many social, environmental and economic advantages on its own; however, it is a substantial challenge for planners as it requires the consideration of a number of factors. Some factors that influence walking are the presence of sidewalks, trails, footpaths or any other right of way components, traffic volume, road conditions, urban use, accessibility to buildings, and safety (Rundle, 2015). In some cities, factors such as the invasion of street vendor stalls, restaurant tables and chairs, narrow or shabby stools, building materials, tree roots, street furniture for advertising and signage also play a substantial role on pedestrian safety (Marquez, D., 2007).

Pedestrian vulnerability is related to the concept of walkability that measures how accessible and risky a public route is for walking (Forsyth, 2015). A new trend among many nations to promote multimodality, interconnectivity and transportation assets is measuring walkability. Recent efforts have been focused on improving urban infrastructure to enhance the quality of life of the community. In this matter, walkability is also a reflection of the extent of pedestrian safety as perceived by users. High walkability index zones include routes or pathways that are safer and less accident-prone paths for pedestrian mobility (R. Florida, 2014).

Figure 5 portrays a map of a Walkability Index Score in New York City. The Walkability Index Score is provided by Census Blocks by recording the walking path of a number of subjects in their daily routines by wearing accelerometers tracked by GPS signals. The method used to quantify the walkable area within residential zones was to delimit minimally convex polygons along GPS waypoints within 1 km of the walking paths (Rundle, 2015).

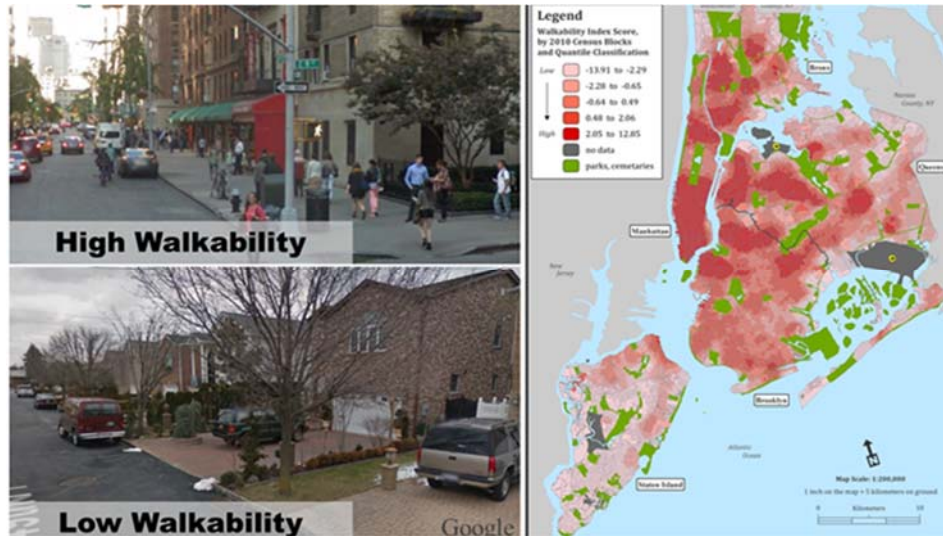


Figure 5. Examples of High and Low Walkability Neighborhoods with a Walkability Map for New York City. (Rundle, 2015)

One of the policy aspects gaining relevance is to reduce the impact of motorized vehicles on safety, health, and environment. Motor vehicle generates gas emissions with atmospheric polluting agents into the environment causing health related problems, and it is also a threat to VRU safety. Friendly environmental policies encourage bicycling and walking as non-motorized transport modes that contribute to avoid traffic jams, save fuel, improve the level of service, preserve air quality, and mitigate the strain on infrastructure demand. Therefore, they foster the development of healthy life styles by increasing physical activity, social integration, and community cohesion (Martinez, A., 2012).

2.8 Vulnerability of Bicyclists

A trend that has gained significant importance among the transportation management practice in recent years worldwide is the use of bicycles as a means of transport beyond recreational use. The increased use of bicycles as means of urban displacement is influenced by a number of factors related to the trip characteristics added to a paradigm shift in the way users, particularly younger generations, approach single occupancy vehicles for shorter distances. Biking is more affordable and allows greater mobility for short trips, and there are fewer traffic jams for cyclists. Cyclists are also aware that their embracement to biking has significant positive impacts on greenhouse gas emissions and other environmental benefits for global sustainability, while reducing the pressure on the demand for road infrastructure (e.g. highways, roadways, bridges).

Unfortunately, bicyclists are one of the most vulnerable road users in the transport system since they are exposed to crashes when they share the same road with motorized vehicles. Between 2010 and 2012, there was a consecutive increase of 16% in the number of deaths of bicycle users. In spite of the statistics, a report prepared for the Governor's Highway Safety Association mentions that the bicyclist community expressed their discontent with the fact that cyclists are classified as vulnerable road users, since it can be a psychological deterrent for promoting its adoption. They recommend more positive and cordial terms such as green, environmentally friendly or environmentally sound modes of transport (Williams, 2015).

2.9 Vulnerability of Users with Disabilities

According to the 2015 American Community Survey, there are 39,906,328 people with some kind of disability, about 12.6% of the total population in America as shown in Table 2 (United States Census Bureau, 2017). The Americans with Disabilities Act of 1990 (42 U.S.C. § 12101) defines Disability as "a physical or mental impairment that substantially limits a major life activity" (ADA, 1190 42 USC). The determination of whether a certain condition is considered a disability must be assessed on a case-by-case basis. Certain specific conditions might be excluded as disabilities, such as substance abuse and visual impairment that can be corrected with prescription lenses.

Table 2. Population in the US with Disabilities (United States Census Bureau, 2017).

Subject	United States		
	Total	With a disability	Percent with a disability
	Estimate	Estimate	Estimate
Total civilian noninstitutionalized population	316,450,569	39,906,328	12.6%

People with disabilities are vulnerable and subject to physical risk of severe bodily injuries on roads in two different roles: first as pedestrians when they are traveling in a non-autonomous mode (non-motorized), either in a wheelchair or some other vehicle or device through sidewalks, cycle paths, or any other route. They are subjected to higher risks of crashes than pedestrians or bicyclists due to their greater difficulty of performing sudden emergency movements such as drastic stops or evasion maneuvers when faced with a dangerous situation. Second, as occupants or riders of a motor vehicle in a collision and in this situation their vulnerability to external physical harm varies depending on their individual conditions. Any individual with physical, sensory or mental problems that affect their ability to move can also pose risk to others. They usually use certain aids to move around (crutches, canes, wheelchairs, etc.). The disabled road users are at greater risk in complex transit situations or in certain places where the infrastructure is not adapted for circulation. They also have a lower capacity to recover from serious injuries.

2.10 Vulnerability of Children

The vulnerability of children in traffic is mainly due to their lower ability to resist the effect of external hits or blows and lesser resiliency than adults in a collision with a vehicle, not only as pedestrians or bicyclists, but also as passengers in a motorized vehicle in a car crash. The particular physical risk for children derives from their low body mass, in addition to their body physiology that is still in development. On the other hand, the mitigation of children's vulnerability to traffic arises because they tend to recover rapidly from mild or even severe injuries derived from traffic accidents when compared to adults (UNICEF, 2017).

2.11 Vulnerability of Elderly Users

Elderly road users are particularly prone to suffer severe injuries in any transport mode. In general, the elderly tends to show a gradual decrease in their ability to deal with traffic situations that require the use of bodily reflexes, and therefore they are subject to greater risks of being involved in crashes. Physical fragility adds another edge to their vulnerability as users of any modes of the transport system (Cuevas, 2016).

2.12 Vulnerability of Other Special Groups

Other special vulnerable road user groups include all those who travel using non-motorized vehicles such as skateboards, skates, and other non-autonomous wheel-moving devices. The concept was separated from the pedestrian group in the definition provided in the Texas Transportation Code, Title 7. Vehicles and Traffic, Subtitle C. Rules of the Road, Chapter 541. Subchapter A. Persons and Governmental Authorities

defines a pedestrian as a “Person that travels on foot”. Following this definition, to preserve the distinction between pedestrians and other users moving on devices such as skates, roller blades or non-motorized scooters a new category was added. These groups are considered as pedestrians but move by means of skates, skateboards or other devices with integrated wheels. These transportation modes are faster although they require a certain degree of skill (e.g. teenagers performing maneuvers at considerable speeds who usually disregard safety provisions), which leads to high-risk situations for other road users (Cuevas, 2016). The following list shows examples of VRUs in this group:

- 1) Roller blade skaters
- 2) Hover board users
- 3) Segway users
- 4) Portable Electric Scooters
- 5) Electric Wheelchair Users

Roads are designed and built for cars, buses, trailers, motorcycles, and other motorized vehicles of greater size. Therefore, there is no consensus on where the users in roller skates, electric hover-boards, and segway users should run. Bikeways are built for bicycles and some devices like hover boards represent a hazard for pedestrians. The vulnerability of these users is related to a great extent to their own skills, efficiency of their braking systems, use of protection elements (e.g. helmet, elbow pads, knee pads), and travel speed. Some cities recommend to avoid the use of rollers, skates, and skateboards in areas with high pedestrian traffic flow (e.g. sidewalks in schools, public institutions) for safety reasons.

CHAPTER 3

Identification of Factors Influencing Pedestrian Safety

3.1 Introduction

There are a number of studies about the factors that influence pedestrian safety in traffic, and it is concluded that there is no single factor that causes pedestrian-vehicle crashes. It is rather the product or consequence of a combination of multiple factors that result in pedestrian injuries or fatalities. The extensive list of pedestrian safety risk factors can be grouped into five categories as shown in Figure 6. Driver's factors, demographic, cultural or social behaviors, pedestrian factors, and infrastructure related factors, and policies are associated with pedestrian risk of injuries and fatalities (Heinonen et al, 2007).

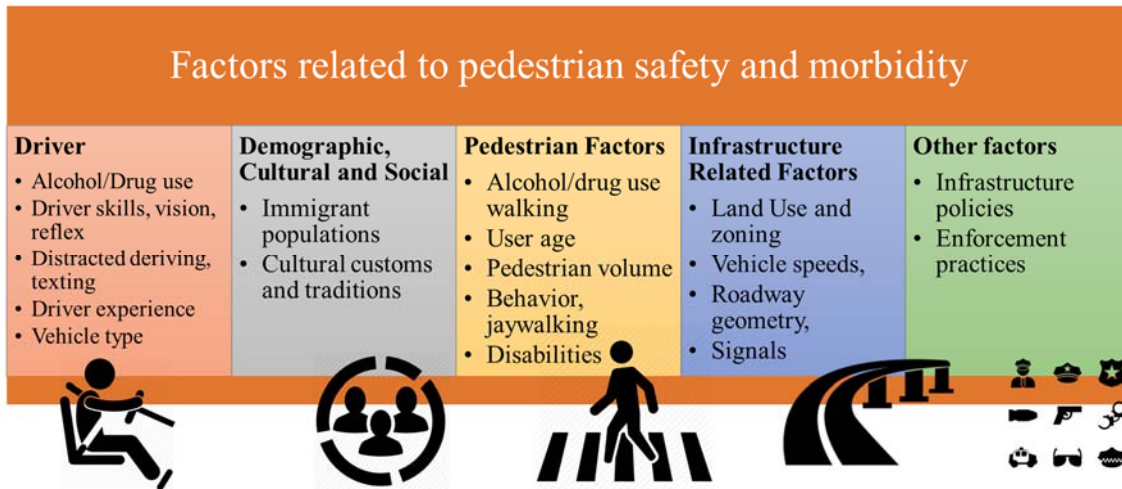


Figure 6. Factors Related to Pedestrian Risk Safety.

In the next sections, there are descriptions of each of the pedestrian risk safety categories.

3.2 Driver and Vehicle Safety Risk Factors

Among the factors that affect the occurrence and severity of crashes with pedestrians, the type of vehicle plays an important role. For example, in a collision of pickup trucks against pedestrians the risk of death is 3.4 times greater than those involving regular passenger vehicles (e.g. sedan). The reason relies upon the impact point of contact for a pickup, higher than the center of gravity of pedestrians, projecting pedestrians forward with greater possibility of even running over them (Roundsari et al, 2004). Other driver's factors that also exert influence on pedestrian safety include the use alcohol or drugs, amount of driving experience and skills, level of vision, reflex, and distracted driving among other factors related to drivers and vehicles.

3.3 Demographic, Cultural, and Social Safety Risk factors

There are cultural, social, and demographic factors that influence pedestrian exposure and injuries. Some studies conclude that there is a relationship between the population demographics and the rate of pedestrian injuries, level of schooling, pedestrian habits, customs and socioeconomic level of users. For example,

Zegeer observed that migration and population mobility play a relevant role in terms of pedestrian accidents. Groups of immigrants such as Hispanics and other ethnic groups are reported as being more prone to suffer injuries or fatalities in traffic. This is why the FHWA suggests a greater emphasis on the improvement of facilities in low income areas, and the installation of traffic safety messages in other languages while enhancing the ease of access to good transport infrastructure system (Zegeer, 2008).

3.4 Pedestrian Safety Risk Factors

Factors related to pedestrians also have an important influence in their own safety including the use of drugs and/or alcohol, usage patterns, and pedestrian volume behavioral patterns, jaywalking, age, disabilities, risk perception, among others. Alcohol use and other pedestrian behaviors have been found important contributors to their own risk, and it makes the agencies difficult to predict in order to implement countermeasures (Dultz, 2012).

The Texas Department of Transportation (TxDOT) considers crash contributing factors for different types of crashes (e.g. fatal, suspected serious, non-injury, etc.), and indicates statistics for rural, urban, and statewide areas in the Crash Contributing Factors document. Some of the factors are related to drivers being under the influence of alcohol or drugs (TxDOT, 2017). If these factors negatively affect drivers, those can also be considered as a negative influence to pedestrians and should be considered in a safety risk analysis.

3.5 Infrastructure Related Safety Risk Factors

The physical configuration of the transport infrastructure, climate, time of the day, visibility, regulations and legislation, enforcement and weather events are some of the external safety risk factors. These factors have an impact to the pedestrian safety conditions, but one of the main problems faced by agencies is the lack of systematic data collection methods to record volumes and usage patterns to measure the exposure of pedestrians in traffic. Counting pedestrian volumes at intersections and along the roadway is not a common practice. While it is true that some agencies have made efforts to develop useful methodologies to collect data on pedestrian volumes, there is no consensus on which the most effective method is, and there are no legislative requirements (Schneider et al, 2005). The lack of standardization in pedestrian volume data collection is because each management unit has its own geographical characteristics and infrastructure conditions (Greene et al, 2010). “The lack of pedestrian and bicycle volume data is a barrier to transportation agency efforts to plan more effective facilities and to improve safety for pedestrians and bicyclists” (Ryus et al., 2014). For this reason, the integration of pedestrian safety into TAM practices requires practical indicators based on relevant factors that affect VRUs’ safety. Infrastructure factors that have been identified as relevant for VRU’s safety include:

- 1) Posted speed
- 2) Crossing distance
- 3) Presence of medians or midblock cross walks
- 4) Functional classification
- 5) Intersections and crosswalks
- 6) Land use and zoning
- 7) Traffic control signs

It is recommended a TAM-VRU methodology with risk safety pedestrian indicators that require less labor-intensive data collection efforts. A discussion of the infrastructure factors related to pedestrian safety follows.

3.5.1 Posted Speed

A number of studies have concluded that speed is one of the most influential factors for occurrence and severity of pedestrian crashes. It is observed that the higher the posted speed, the greater the risk. For example, in Washington, 73% of pedestrian and bicyclist fatalities occurred on roads with posted speed limits of 30 mph or higher from 2013 to 2017, (WSDOT, 2018). Posted speeds can be used as a predictive variable for pedestrian safety risk. Negative binomial regressions have been used to analyze the correlation of speed to the probability and severity of pedestrian shock, finding that there is correlation between higher speeds and the reaction time for drivers to stop in front of pedestrians (Chimba et al, 2017). The conclusion is that higher posted speeds lead to increasing risk for VRU (Zegeer et al 2006), (Lee et al, 2006), Garder, (2004), (Sandt et al 2006).

The probability of pedestrian fatality against the vehicle's speed at impact can be calculated using Groeger's approach (Groeger, 2016). Groeger used data gathered from a study conducted by Tefft in 2011 (Tefft, 2011). Figure 7 shows that the probability of pedestrian fatality in an encounter with a vehicle behaves logarithmically. It portrays the estimated probability of pedestrian fatality according to vehicle speed for elder users (70 years old), all ages, and adults (30 years old). Fatality pedestrian risk has a slight increase for impacts at 30 mph, and the probability of death increases significantly above 50 mph.

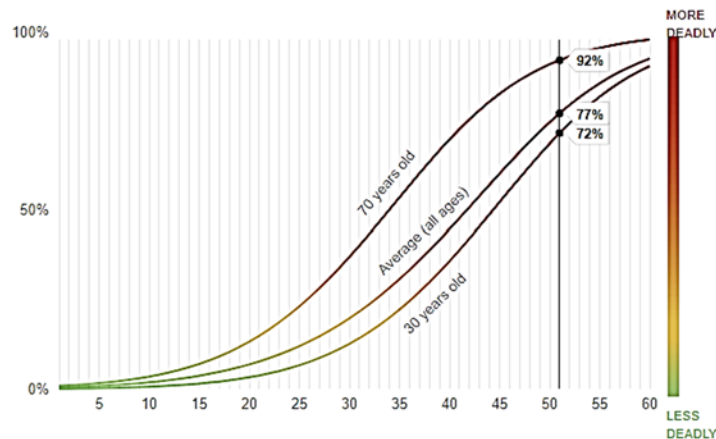


Figure 7. Probability of Pedestrian Fatality and Speed (Groeger, 2016).

3.5.2 Crossing Distance

Pedestrian exposure to automobiles is directly related to the perpendicular distance to walk when crossing a street or road, either at intersections, midblock crossings, or any other road sections. While it is true that pedestrians are exposed to the effects of traffic when walking along sidewalks without a physical barrier, direct exposure also occurs in cases when they are crossing the street. The effect of the crossing distance on the streets is another factor that has been analyzed in a number of studies. Schneider et al (2010) found that longer crossing distances could cause greater pedestrian crash incidences than those that are narrower. Other studies have found similar conclusions (Chimba et al, 2017), (Palamara et al, 2013), (Fitzpatrick et al, 2014), and (Sandt et al, 2006).

3.5.3 Presence of Medians or Midblock Cross Walks

Palamara concluded that median refuges effectively diminish pedestrian risk to traffic at crosswalks because they cut in half the amount of exposure of pedestrians (crossing distance) and provide shelter from incoming traffic (Palamara et al., 2013). Zegeer studied multilane pedestrian road crossings, and found lower crash risks in areas with presence of medians and concluded that medians reduce the frequency of pedestrian crashes (Zegeer et al., 2006). Schneider arrived at the conclusion that median existence significantly reduces pedestrian crash risk at crosswalks (Schneider et al., 2010). Lee found that the presence of medians is a

critical factor to reduce pedestrian crashes at crosswalks (Lee et al., 2006). Sandt discovered that the majority of pedestrian incidents occurred at undivided roads for midblock crossings (Sandt et al., 2006).

3.5.4 Functional Classification

Fitzpatrick analyzed pedestrian safety risk for different road functional classifications in Texas (Fitzpatrick et al., 2014). Pedestrian crashes were most frequent on local roads, and the majority of pedestrian fatalities occurred on highways. The North Carolina Bicycle and Pedestrian Crash Data Tool State Wide Data shows that more than half of all pedestrian crashes occurred on local roads (NCDOT, 2018). These results are tied to the posted speed; highways have a higher speed but experience fewer pedestrian exposure, the opposite occurs in local streets where the exposure tends to be higher and the speed is lower.

3.5.5 Intersections and Crosswalks

Monsere suggests that the most frequent areas for pedestrian crashes are within 50 ft. of roadway intersections (Monsere et al., 2017). Palamara, Schneider, and Garder had similar findings, concluding that areas around marked crosswalks are significantly more prone to pedestrian crashes than areas away from the vicinity of crosswalks and intersections. This factor is also related to exposure. The intersections are pedestrian hubs and, in most cases, they have designated crosswalks. (Palamara et al., 2013, Schneider et al., 2001, and Garder et al., 2004). Fitzpatrick identified that the majority of pedestrian crashes in Texas occurred around intersections, although the severity of injuries and fatalities was statistically higher in locations away from intersections. They found that 70% of severe crashes involving pedestrians and bicycles occurred at intersections (Fitzpatrick et al., 2014). Garder found that the presence of control devices at crosswalks reduce significantly the risk of pedestrian crashes (Garder, 2004).

3.5.6 Land Use and Zoning

Land use and zoning are utilized as a direct indicator of pedestrian exposure. Land use and city zoning allows identify areas of high concentration of pedestrians including commercial districts, residential areas, presence of schools, college campuses, stadiums, convention centers and other pedestrian proxies. The percentage of neighborhood commercial and residential areas are directly related to a higher occurrence of pedestrian crashes (Senserrick et al, 2014).

Wedagama studied the effect of land use on pedestrian fatalities. The influence of three age groups younger than 16 years old, 16 to 64, 64 and older, were compared to the spatial characteristics of urban land use in downtown Newcastle, UK. They found that 1% increase in retail land use raises pedestrian risk of accidents from 30% to 50% for adults (Wedagama et al, 2008).

Other studies have performed detailed analyses of crashes that involve pedestrians and the influence of infrastructure characteristics on the outcome of those accidents. They found that about 95% of pedestrian injuries and three quarters of fatalities occur in the vicinity of urban areas (Gitelman et al, 2010). Figure 8 illustrates the relationship between zoning areas and pedestrian risk. It is observed that areas with higher pedestrian activity have higher pedestrian crash occurrence. Other studies arrived at similar conclusions that single-family residential areas, urban residential-commercial area, commercial center area, and neighborhood service districts have increasing pedestrian crash occurrences (Loukaitou et al, 2007).

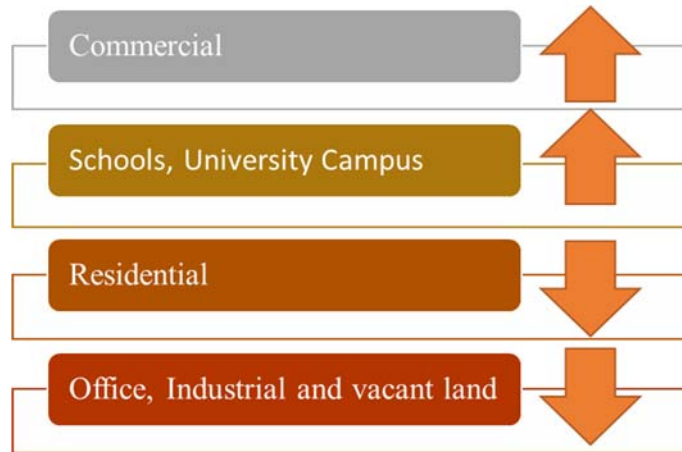


Figure 8. Influence of Zoning Areas on Pedestrian Risk.

3.5.7 Traffic Control Signs

The FHWA takes into account the type of traffic control in an intersection as a variable for a model to identify intersection crossings and intersection approach legs as the greatest priority for safety assessment. Traffic control signs, such as stop signs or pedestrian crossing signs, can improve VRU safety. The presence of signals are considered as a key safety factor because the traffic flow can be controlled to enhance pedestrian's safety (FHWA, 2007).

CHAPTER 4

Framework to Integrate Vulnerable Road Users into Transportation Asset Management

4.1 Introduction

The ultimate purpose of Transportation Asset Management (TAM) is to provide all road users with safe transportation options in the most cost-effective manner. In urban areas, these users include not only motorized vehicles, but also pedestrians, cyclists, gaining users, and users with disabilities. The reduction of pedestrian fatalities is a world widespread global challenge recognized by different national and international organizations. Road safety demands a set of specific actions, processes, plans and mechanisms, which are promoted and directed to assure the proper operation of transport infrastructure at the desired level of service. This Chapter describes a framework to incorporate vulnerable road users' safety into TAM practices including project enhancements and prioritization methods for funding allocation.

4.2 Overview of the Framework to Integrate VRU into TAM

The framework to integrate VRU into TAM is shown in Figure 9. It begins by establishing goals and policies to enhance pedestrian's safety. The transportation asset inventory is then revised to conduct a safety infrastructure assessment for pedestrians. In this research, the safety infrastructure assessment is focused on pedestrian intersections and considers three main aspects: traffic flow, geometry of the intersection, and condition of the infrastructure facility. Data are gathered from inventory records and field inspections. For example, traffic data include the average speed, presence of traffic signs, and annual daily traffic, among others. Geometrical data examples are the width of the street, number of through lanes, and physical buffer type; while condition infrastructure data refer to the physical condition of sidewalks based on visible distresses (e.g. cracking, faulting, raveling, and loose aggregate). Pedestrian safety indexes are determined with these data to identify safety risk areas in the transportation network in order to implement countermeasures to enhance pedestrian safety. If there are budget constraints, the pedestrian safety indexes are used for project prioritization and funding allocation. Once the safety countermeasures are implemented, the results in terms of pedestrian risk safety are monitored to make any necessary adjustments in the TAM process.

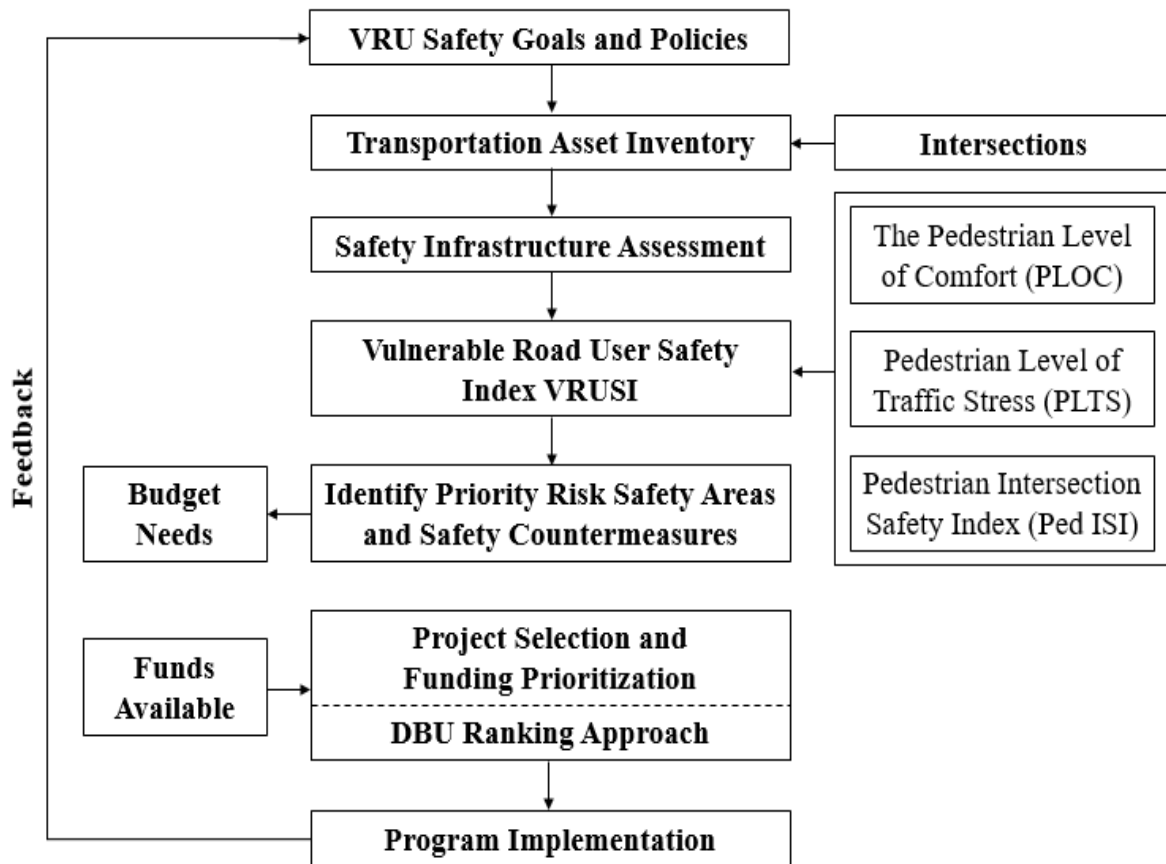


Figure 9. Framework to Integrate VRU into TAM.

4.3 Safety Indexes for Pedestrians

A number of safety indexes developed by transportation agencies, governmental associations, and researchers were reviewed for their application in the TAM-VRU framework. The most relevant pedestrian safety indexes are described in this section.

Pedestrian Level of Comfort (PLOC)

The Pedestrian Level of Comfort index (PLOC) was developed to identify corridors for pedestrian improvements. Data to calculate PLOC include roadway speed, number of lanes with the presence of sidewalk, bicycle lanes, parking, and planting buffers for each roadway segment. Intersections are classified by their crossing type (signalized, marked, unmarked), as well as the number of lanes and travel speed at the intersection (City of Encinitas, 2018). The walkway network can be analyzed using a combination of field survey assessments and geographic information systems (GIS) tools. Figure 10 shows three scoring matrices used to determine PLOC: missing sidewalk, sidewalks without road separation, and sidewalks with one separation. Based on the speed limit, a number from 1 to 4 is assigned, where 1 corresponds to the most suitable of all types of pedestrian facilities, and 4 to the less accessible.

Missing Sidewalks					Sidewalks Without Road Separation				Sidewalks With One Separation (On-street Parking, Bicycle Lanes, or Planting Buffer)		
Speed Limit	Number of Lanes				Speed Limit	Number of Lanes			Speed Limit	Number of Lanes	
	2	3 (2+1)	4-5 (4+1)	6+		2	3	4+		2	3+
< 25	2	2	3	4	< 25	1	1	2	< 25	1	2
30	2	3	4	4	30	1	2	2	30	1	2
> 35	4	4	4	4	35	2	3	3	35	2	3
					> 40	3	3	4	> 40	3	3

Figure 10. Scoring Matrices for PLOC Determination (City of Encinitas, 2018).

Therefore, PLOC categories are defined as follows:

- PLOC 1: Suitable for almost all pedestrians, including children trained to safely cross intersections.
- PLOC 2: Suitable for most adult pedestrians but demanding more attention that might be expected from children.
- PLOC 3: Suitable for older children with little or no parental supervision.
- PLOC 4: Mostly suitable for adults and children with parental supervision.

Pedestrian Level of Traffic Stress (PLTS)

Pedestrian Level of Traffic Stress (PLTS) rates the level of comfort of pedestrians crossing a roadway. PLTS is used to classify roadway segments based on the level of pressure or strain experienced by pedestrians and other sidewalk users, PLTS criteria is based on: sidewalk condition, physical buffer type, total buffering width, general land use, collector and local un-signalized intersection crossing, and arterial un-signalized intersection crossing with or without a median refuge. For each criterion, the information needed to determine PLTS includes sidewalk condition and width, buffer type and width, parking width, number of lanes and posted speed, functional class, roadway average daily traffic, and signalized general intersection features, among others (ODOT, 2018). Tables 3 through 11 shows the criteria used to determine PLTS values. The different PLTS values obtained have to be analyzed and a single overall PLTS value is determined. PLTS scores range from 1 to 4 (1 is the most comfortable and 4 is the least) with the following definitions:

- PLTS 1 indicates little to no traffic stress and it requires little attention to the traffic situation. This is suitable for all users including children 10 years or younger, groups of people and people using a wheeled mobility device. The facility is a sidewalk or shared-use path with a buffer between the pedestrian and motor vehicle facility. Pedestrians feel safe and comfortable on the pedestrian facility. Motor vehicles are far from either the pedestrian facility and/or traveling at low speed and volume. All users are willing to use this facility.
- PLTS 2 indicates little traffic stress but it requires more attention to the traffic situation for young children. This intersection is suitable for children over 10 years old, teens, and adults. All users should be able to use the facility but some factors may limit people using wheeled mobility devices. Sidewalk condition should be good with limited areas of fair condition. Roadways may have higher speeds and/or higher volumes. Most users are willing to use this facility.
- PLTS 3 indicates moderate stress and it is suitable for adults. An able-bodied adult would feel uncomfortable but safe using this facility. This includes higher speed roadways with smaller buffers. Small areas in the facility may be impassable for a person using wheeled mobility devices and/or requires the user to travel on the shoulder/bike lane/street. Some users are willing to use this facility.
- PLTS 4 indicates high traffic stress. Only able-bodied adults with limited route choices would use this facility. Traffic speeds are moderate to high with narrow or no pedestrian facilities. Typical locations include high speed, multilane roadways with narrow sidewalks and buffers. This also includes facilities with no sidewalks. Only the most confident or trip-purpose driven users will use this facility.

PLTS results can be shown on maps to visualize connectivity islands and high stress locations such as major road crossings. Such locations represent discontinuities to be improved to enhance the connectivity in the entire route.

Table 3. Physical Buffer Type (ODOT, 2018)

Buffer Type ¹	Physical Buffer Type			
	Prevailing or Posted Speed			
	≤25 MPH	30 MPH	35 MPH	≥40 MPH
No Buffer (curb tight)	PLTS 2	PLTS 3	PLTS 3	PLTS 4
Solid Surface	PLTS 2 ²	PLTS 2	PLTS 2	PLTS 2
Landscape	PLTS 1	PLTS 2	PLTS 2	PLTS 2
Landscape with trees	PLTS 1	PLTS 1	PLTS 1	PLTS 1
Vertical	PLTS 1	PLTS 1	PLTS 1	PLTS 1

¹Combined buffers: If two or more of the buffer conditions apply, use the most appropriate, typically the lower stress level.

²If stress furniture, street trees, lightning, planters, surface change, etc. are present then the PLTS can be lowered to PLTS 1.

Table 4. Total Buffering Width (ODOT, 2018).

Total Number of Travel Lanes (both directions)	Total Buffering Width (ft) ¹				
	<5	≥5 to <10	≥10 to <15	≥15 to <25	≥25
2	PLTS 2	PLTS 2	PLTS 1	PLTS 1	PLTS 1
3	PLTS 3	PLTS 2	PLTS 2	PLTS 1	PLTS 1
4 - 5	PLTS 4 ²	PLTS 3	PLTS 2	PLTS 1	PLTS 1
6	PLTS 4 ²	PLTS 4 ²	PLTS 3	PLTS 2	PLTS 2

¹Total Buffering Width is the summation of the width of buffer, width of parking, width of shoulder and width of the bike lane on the side same side of the roadway as the pedestrian facility being evaluated.

²Sections with a substantial physical barrier/tall railing between the travel lanes and the walkway (like might be found on a bridge) can be lowered to PLTS 3.

Table 5. General Land Use (ODOT, 2018).

PLTS	Overall Land Use
1	Residential, central business districts (CBD), neighborhood commercial, parks and other public facilities, governmental buildings/plazas, offices/office parks
2	Low density development, rural subdivisions, un-incorporated communities, strip commercial, mixed employment
3	Light industrial, big-box/auto-oriented commercial
4	Heavy industrial, intermodal facilities, freeway interchanges

Table 6. Collector and Local Unsignalized Intersection Crossing^{1,2,3,4} (ODOT, 2018).

Prevailing Speed or Speed Limit (mph)	No Median Refuge		Median Refuge Present
	Total Lanes Crossed		Maximum One Through/Turn Lane Crossed per Direction
	1 Lane	2 Lanes	
≤ 25	PLTS 1	PLTS 1	PLTS 1 ⁵
30	PLTS 1	PLTS 2	PLTS 1
35	PLTS 2	PLTS 2	PLTS 2
≥ 40	PLTS 3	PLTS 3	PLTS 3

¹For street being crossed. ²Minimum PLTS 3 when crossing lacks standard ramps.

³Use Table 8 or Table 9 for one-way streets, when ADT exceeds 5,000, or total number of lanes exceeds two.

⁴Street may be considered a one-lane road when no centerline is striped and when oncoming vehicles commonly yield to each other. ⁵Refuge should be at least 10 feet for PLTS 1, otherwise use PLTS 2 for refuges 6 to <10 feet.

Table 7. Arterial Unsignalized Intersection Crossing Without a Median Refuge^{1,2} (ODOT, 2018).

Prevailing Speed or Speed Limit (mph)	Total Lanes Crossed (Both Directions) ³					
	2 Lanes			3 Lanes		
	<5,000 vpd	5,000- 9,000 vpd ⁴	>9,000 vpd	<8,000 vpd	8,000- 12,000 vpd ⁴	>12,000 vpd
≤ 25	PLTS 2	PLTS 2	PLTS 3	PLTS 3	PLTS 3	PLTS 4
30	PLTS 2	PLTS 3	PLTS 3	PLTS 3	PLTS 3	PLTS 4
35	PLTS 3	PLTS 3	PLTS 4	PLTS 3	PLTS 4	PLTS 4
≥ 40	PLTS 3	PLTS 4	PLTS 4	PLTS 4	PLTS 4	PLTS 4

¹For street being crossed.²Minimum PLTS 3 when crossing lacks standard ramps.³For one-way streets, use Exhibit 14-10 and 14-24 (ODOT, 2018). Use PLTS 4 for crossings of more lanes.⁴Use these columns when ADT volumes are not available.**Table 8. Arterial Unsignalized Intersection Crossing (1 to 2 lanes) with Median Refuge^{1,2} (ODOT, 2018).**

Prevailing Speed or Speed Limit (mph)	Maximum Through Lanes Crossed per Direction			
	1 Lane	2 Lanes		
	Any	<5,000 vpd	5,000-9,000 vpd ⁴	>9,000 vpd
≤ 25	PLTS 1 ³	PLTS 1 ³	PLTS 2	PLTS 2
30	PLTS 2	PLTS 2	PLTS 2	PLTS 2
35	PLTS 2	PLTS 2	PLTS 2	PLTS 3
≥ 40	PLTS 3	PLTS 3	PLTS 3	PLTS 4

¹For street being crossed.²Minimum PLTS 3 when crossing lacks standard ramps.³Refuge should be at least 10 feet PLTS 1, otherwise use PLTS 2 for refuges 6 to <10 feet.⁴Use these columns when ADT volumes are not available.**Table 9. Arterial Unsignalized Intersection Crossing (≥3 lanes) with a Median Refuge^{1,2} (ODOT, 2018).**

Prevailing Speed or Speed Limit (mph)	Maximum Through Lanes Crossed per Direction			
	3 Lanes			4+ Lanes
	< 8,000 vpd	5,000-9,000 vpd ⁴	5,000-9,000 vpd ⁴	Any
≤ 25	PLTS 1 ³	PLTS 2	PLTS 3	PLTS 4
30	PLTS 2	PLTS 2	PLTS 3	PLTS 4
35	PLTS 2	PLTS 3	PLTS 4	PLTS 4
≥ 40	PLTS 3	PLTS 4	PLTS 4	PLTS 4

¹For street being crossed.²Minimum PLTS 3 when crossing lacks standard ramps.³Refuge should be at least 10 feet PLTS 1, otherwise use PLTS 2 for refuges 6 to <10 feet.⁴Use these columns when ADT volumes are not available.**Table 10. Adjustments for Crosswalks Enhancements (ODOT, 2018).**

Treatment	Deduction	Treatment	Deduction
Markings ¹	0.5	In-street signs	1.0
Roadside signage ¹	0.5	Curb extensions	0.5
Lighting	0.5	Raised crosswalk	1.0
PAB	1.0		

¹Not applicable for roadways with pedestrian median refuges as crosswalk marking and roadside signage assumed as part of the basic installation. PLTS can be lowered based on the deduction values to a maximum two level reduction or minimum PLTS 2.

Table 11. Sidewalk Condition^{1,3} (ODOT, 2018).

	Actual/Effective Sidewalk Width (ft) ²	Sidewalk Condition				
		Good	Fair	Poor	Very Poor	No sidewalk
Actual	<4	PLTS 4	PLTS 4	PLTS 4	PLTS 4	PLTS 4
	≥4 to <5	PLTS 3	PLTS 3	PLTS 3	PLTS 4	PLTS 4
	≥5	PLTS 2	PLTS 2	PLTS 3	PLTS 4	PLTS 4
Effective	≥6 ⁴	PLTS 1	PLTS 1	PLTS 2	PLTS 3	PLTS 4

¹Can include other facilities such as walkways and shared-use paths.

²Effective width is the available/useable area for the pedestrian. Does not include areas occupied by store fronts or curb side features.

³Consider increasing the PLTS one level (Max PLTS 4) for segments that do not have illumination. Darkness requires more awareness especially if sidewalk is in fair or worse condition.

⁴Effective width should be proportional to volume as higher volume sidewalks should be wider than the base six feet. Use a minimum PLTS 2 for higher volume sidewalks that are not proportional (include documentation).

Pedestrian Intersection Safety Index (Ped ISI)

The Pedestrian Intersection Safety Index (Ped ISI) was developed by the FHWA to identify intersection crossings in need of safety enhancements. Ped ISI is based on two measures: safety ratings from expert opinion, and observed pedestrians and motorist’s behaviors. The measures provided a multifaceted approach to determine the relative safety of a pedestrian crossing.

Sixty-eight pedestrian crossings at signalized and un-signalized intersections in Miami (FL), Philadelphia (PA), and San Jose (CA), were studied in order to develop the index. Ped ISI is calculated based on the type of traffic control for leg of crossing, number of through vehicle lanes on main street, eighty-fifth percentile traffic speed on main street, average daily traffic of main street, and predominant land use (FHWA, 2007b). The model is shown in Equation 1. The higher the value of Ped ISI, the greater the priority for an in-depth safety enhancement.

$$\text{Ped ISI} = 2.372 - 1.867*\text{SIGNAL} - 1.807*\text{STOP} + 0.335*\text{THRULNS} + 0.018*\text{SPEED} + 0.006*(\text{MAINADT}*\text{SIGNAL}) + 0.238*\text{COMM} \quad \text{Equation 1}$$

Where:

- Ped ISI : Safety index value (pedestrian).
- SIGNAL : Signal-controlled crossing. It is zero if there is no signal. It is one, if there is a signal.
- STOP : Stop sign controlled crossing. It is zero if there is no stop signal. It is one, if there is a stop signal.
- THRULNS : Number of through lanes on street being crossed (both directions)
- SPEED : Eighty-fifth percentile speed of street being crossed.
- MAINADT : Main street traffic volume, Annual Daily Traffic in thousands.
- COMM : Predominant land use on surrounding area is commercial development (i.e., retail, restaurants). It is 1 if the area is predominantly commercial, and 0 if not.

4.4 Vulnerability Road User Safety Index (VRUSI)

A Vulnerability Road User Safety Index (VRUSI) is proposed to assess the VRU safety conditions of road infrastructure. VRUSI combines three specific indexes: the Pedestrian Level of Comfort (PLOC), the Pedestrian Level of Traffic Stress (PLTS), and the Pedestrian Intersection Safety Index (Ped ISI). These three indexes are calculated independently, and VRUSI is obtained by adding the PLOC, PLTS, and Ped ISI as shown in Equation 2.

$$\text{VRUSI} = \text{PLOC} + \text{PLTS} + \text{Ped ISI} \quad \text{Equation 2}$$

Where:

VRUSI	: Vulnerability Road User Safety Index
PLOC	: Pedestrian Level of Comfort
PLTS	: Pedestrian Level of Traffic Stress
PED ISI	: Pedestrian Intersection Safety Index

VRUSI can be used at the strategic and network management level to identify high risk safety areas. The higher the VRUSI, the greater the priority for safety enhancement due to a lower level of comfort and higher traffic stress.

4.5 Project Selection and Funding Allocation

A ranking approach based on VRUSI is used for project prioritization and funding allocation. The Dynamic Bubble Up (DBU) technique is adopted for the ranking approach. DBU is typically applied in pavement management practices to determine the amount of funds required to achieve multiple objectives, and it follows a sequential year ranking approach (Chang, 2007).

At the strategic management level, the step-by-step process to estimate the funding needs to meet TAM-VRU objectives are as follows:

1. Conduct a pedestrian safety assessment of the current infrastructure facilities in the transportation network.
2. Calculate the VRUSI for the intersections under analysis.
3. Establish VRU strategic objectives using PLOC and PLTS. The desired target is to have all the intersections suitable for almost all pedestrians with little to no traffic stress, meaning that all users are willing to use this facility since they feel safe and comfortable. The countermeasures for each intersection are budgeted based on the cost estimates of the safety enhancements. The objective for the pedestrian network can be established in terms of an average VRUSI or percentage of the intersections that meet the target.
4. Rank the intersections from the highest to the lowest VRUSI to prioritize the projects for funding allocation.
5. Estimate the minimum amount of funds required to meet the objectives established in step 3 using the DBU technique. DBU consists of iterative calculations that starts from the top of the ranked list. For this calculation, the process assumes that k intersections are being funded and $N-k$ are not funded (k starts with one, and N is the total number of intersections in the dataset). If the value calculated for the intersection does not meet the objective, the next intersection is “bubbled up” (k increases) and the new value is calculated until the objective is met, or the last intersection in the dataset is reached ($k = N$).
6. Report the minimum amount of funds required to meet the objective.

More complex safety indexes could be used to apply the ranking approach if data are available and their models are calibrated to local conditions. This is the case of the Pedestrian Index of the Environment (PIE) and the Cost-effectiveness Index (CEI). PIE is based on a binomial logit model developed for Oregon and it is difficult to replicate in new scenarios. CEI predicts the number of crashes becoming a challenge to recalibrate their statistical models. PIE and CEI are considered too complex to use at the network

management level, and they are more suitable for project level analysis due the amount of data required for their calculations. Brief descriptions of PIE and CEI follows as a reference for project level applications.

The Pedestrian Index of the Environment (PIE)

The Pedestrian Index of Environment (PIE) is a component of a binary logistic walk trip mode split model to estimate the number of walk trips in a certain zone. There are few analytical models of pedestrian behavior that can predict traveler responses. In these models, regional household travel survey, pedestrian count data, and built environment attributes are used to incorporate walking activity into trip-based travel models. First, the spatial unit of analysis for trip generation from larger transportation analysis zones (TAZs) is transferred to 264 ft. by 264 ft. (6,400 m²) gridded pedestrian analysis zones (PAZs). Second, the total number of trips generated at these PAZs are calculated. Third, a binary logistic walk trip mode split model is utilized to predict the number of walk trips produced by each PAZs. Fourth, non-walk trips are then aggregated up to larger transportation analysis zones (TAZs) clustered by destination choice, mode choice, and traffic. Finally, destinations and routing of the PAZ pedestrian trips are chosen. The method is capable of improving travel models' sensitivity to evaluate walking influences using scenario analysis (Clifton et al., 2013).

PIE quantifies the influence of a built environment on the walking behavior in six dimensions: block size, people per acre, sidewalk density, transit access, and urban living infrastructure (e.g. shopping and service destinations used in daily life). Each dimension varies from 1 to 5. Different weights are given to the six dimensions, and PIE is equal to the weighted sum of each dimension and range from 20 to 100. The higher the value of PIE, the higher the walkability in the area. High values of PIE are in the neighborhood center, residential areas, and suburban downtowns; while low values of PIE to isolated areas dedicated to industry or rural areas.

Cost-effectiveness Index (CEI)

The cost-effectiveness index (CEI) was developed by the National Cooperative Highway Research Program (NCHRP) Project 17-73. CEI is calculated by dividing the project costs by the expected reduction in pedestrian crashes. The lower the value of CEI, the highest the cost-effectiveness. CEI requires the predicted number of crashes, countermeasure options, cost of the countermeasures, and the Crash Modification Factor (CMF). CMF is a numerical estimate of the expected reduction (or increase) in the number of crashes as a result of countermeasure. Predicted number of crashes are based on statistical models, developed for the City of Seattle, for pedestrians and motor vehicles crashes traveling straight at midblock locations. These models include traffic (average annual daily traffic) and pedestrian volume (AADP). CEI models also include roadway features site (e.g. median or crosswalk presence, average annual daily traffic), and social environment characteristics around the site (e.g. population and employment density, mode share, household density, commercial land uses, and distance to universities). The NCHRP report includes different values of CMFs depending on the type of countermeasure (e.g. high visibility crosswalk, road diet, longer pedestrian phase, and in-roadway yield to pedestrian sign) (NCHRP, 2018). VRUSI could also incorporate the likelihood of the pedestrians and bicyclists crashes in critical locations. An example of this approach is presented in the Star Rating and Investment Plan Implementation Support Guide. A Star Rating Score (SRS) is calculated based on the severity and likelihood of road crashes, operating speed, external flow influence, and median transverse ability. SRS can assess the road safety condition through a survey (iRAP, 2017).

4.6 Recommendations for VRU Safety

There are a number of recent DOT and FHWA documents with countermeasure recommendations to enhance road safety. In 2016, Caltrans, FHWA, and SafeTREC published the Local Roadway Safety manual with 85 countermeasures to address local roadway safety issues. This manual describes important safety activities that transportation agencies should conduct periodically to decrease the number and

severity of crashes within their jurisdictions. The countermeasures are organized in three groups: signalized intersection countermeasures, non-signalized intersection countermeasures, and roadway countermeasures. Crash reduction factors (CRF) are recommended for each countermeasure. The higher the CRF factor, the greater the expected reduction in crashes. Examples of the countermeasures and CRF values are shown as follows (Caltrans, FHWA, and SafeTREC, 2016).

Examples of signalized intersection countermeasures are (Total of 23):

- Add intersection lighting (CRF = 40%)
- Improve signal timing (CRF = 15%)
- Install pedestrian median on approaches (CRF = 35%)

Examples of non-signalized intersection countermeasures (Total of 20):

- Convert to all-way stop control (CRF = 50%)
- Install signals (CRF = 25%)
- Install pedestrian signal (CRF = 55%)
- Install pedestrian crossing at uncontrolled locations (CRF = 20%)

Examples of roadway countermeasures (Total of 42):

- Install median barrier (CRF = 25%)
- Install guardrail (CRF = 25%)
- Install impact attenuators (CRF = 25%)
- Install raised pedestrian crossing (CRF = 35%)

In 2017, The National Highway Traffic Safety Administration developed guidelines to assist State Highway Safety Offices in selecting effective, evidence-based countermeasures to address traffic safety problematic areas. Pedestrian safety countermeasures include pedestrian safety zones, reduction and enforcement of speed limits, conspicuity enhancement, driving training, pedestrian gap acceptance training, and university educational campaigns (NHTSA, 2017).

In 2018, FHWA published a list of 20 proven countermeasures and strategies to mitigate pedestrian and bicycle crashes in roadways departure and intersections. Some of the pedestrian safety countermeasures are: leading pedestrian interval, medians and pedestrian crossing islands in urban and suburban areas, pedestrian hybrid beacon, and walkways, among others. Each countermeasure includes safety benefits in terms of the expected percent reduction of pedestrian crashes. For example, pedestrian hybrid beacons are expected to reduce pedestrian crashes by 69% (FHWA, 2018). The NCHRP Project 17-73 expresses the level of effectiveness of a countermeasure using crash modification factors. These factors are related to the number of expected crashes after the implementation of the countermeasure (NCHRP, 2018). Table 12 shows countermeasure examples for safety improvements at intersections.

Table 12. Countermeasures for Pedestrian Safety Improvement at Intersections (NCHRP, 2018).

Countermeasures	Description	Criterion
All-way STOP control	Install STOP signs in intersections that are not signalized	One of the highest crash modification factors (6%-80%)
Pedestrian signals	Install pedestrian signals to warn motorists that pedestrians are in the crosswalk	One of the second highest crash modification factors (15%-69%)
Pedestrian crossing	Install marked crossing and pedestrian signal heads at the intersection	Crash modification factor of 25% applicable to multiphase traffic signals and double right or double left turns.
Leading pedestrian intervals	A leading pedestrian interval provides pedestrians the opportunity to enter an intersection 3 to 7 seconds before vehicles are given a green indication	Reduction of 60% in pedestrian-vehicle crashes at intersections
Enhanced signing and pavement markings at stop controlled intersections	Installing signs and pavement markings increase driver awareness of the closeness to a conflicting intersection	Reduction of 10% in injury and fatal crashes. Reduction of 15% in nighttime crashes
Speed limit signs	Install speed limit signs to control driving speeds of vehicles approaching at intersections	High effectiveness because lower maximum speed limits definitely reduce crashes
Reduction and enforcement of speed limits	Reducing motorist travel speeds to increase reaction time for drivers and pedestrians in order to avoid crashes	Reduced speed limits and enforcement can reduce vehicle speeds and all types of crashes and crash severity
High visibility crosswalk	The use of ladder or bar-pair pavement markings to increase the visibility of pedestrian crossings for both pedestrians and motorists.	High crash modification factor values.

CHAPTER 5

Case Study

5.1 Introduction

The framework to integrate VRU into TAM is demonstrated through a case study in the urban area of El Paso County, city of El Paso, State of Texas. The coordinates of the site, Mundy Park, are Latitude 31°45'52.26"N, Longitude 106°30'7.72"O. Figure 11 shows the location of the five streets and intersections located around Mundy Park.

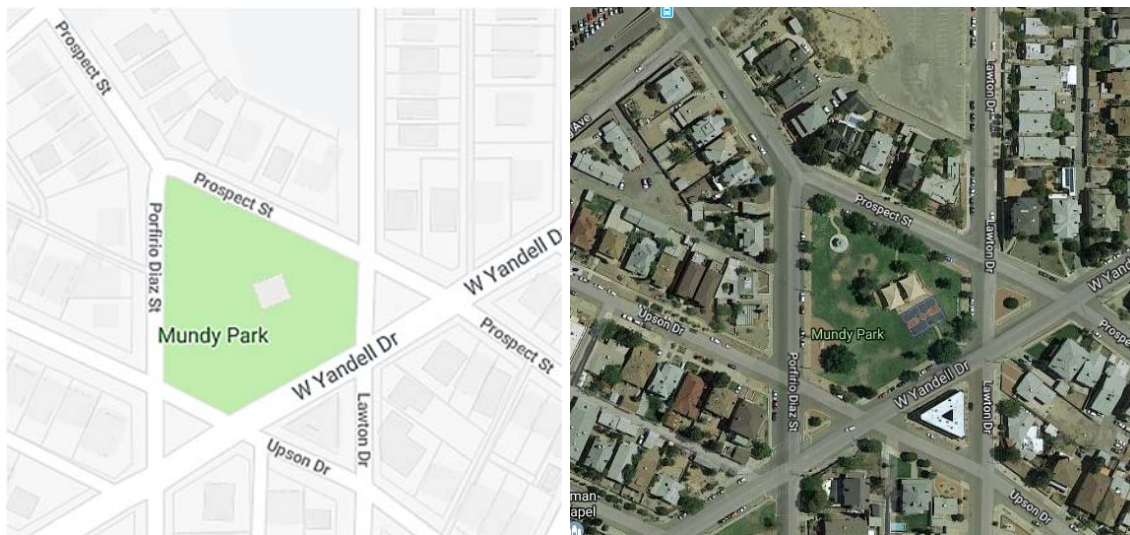


Figure 11. Mundy Park's Intersections.

The case study includes an example of the calculation of VRUSI at each intersection, and its application for project selection and funding allocation. VRUSI is used to assess their safety conditions, and it is obtained from the calculation of independent safety indexes including PLOC, PLTS, and Ped ISI.

5.2 Example on How to Calculate VRUSI

The intersections have five streets of interest: Prospect St., Yandel Dr., Porfirio Diaz St., Lawton Dr., and Upson Dr. A field inspection was performed on these streets to collect data to calculate VRUSIs. Figure 12 shows the location of each street around the park. Photos with more information about the streets are in Appendix A, B, C, D, and E for Prospect St., Yandell Dr., Porfirio Diaz St., Upson Dr., and Lawton Dr., respectively.








Field Study Legend	
	Prospect Street
	Yandell Drive
	Porfirio Diaz Street
	Upson Drive
	Lawton Drive

Figure 12. Distribution of Streets around Mundy Park.

Figure 13 shows the data collection field form that is organized in four parts: street geometry, land use, traffic characteristics, and sidewalk features.

Pedestrian Safety Score Card

Name of street: _____
To: _____ **From:** _____
Segment length _____ (ft)
Indicated data gathered in: [Field / Map]

A. Street Geometry

- Number of Lanes _____
- Number of through Vehicle Lanes on Main Street (total lanes in both directions) _____
- Outer Width of Lane _____ (ft)
- Is Median Refuge Present? Circle one option [Y / N]

B. Land Use

- Land Usage of Surrounding Area. (Check one that best fits to the location being analyzed)

The area is not predominantly commercial	<input type="checkbox"/>
The area is predominantly commercial	<input type="checkbox"/>

C. Traffic

- Street Speed Limit _____ (mph)
- Average Daily Traffic (ADT) of Main Street _____ (in thousands)
- Type of Traffic Control for Leg of Crossing (signal, stop sign, or neither)

Movements of vehicles and pedestrians at the crossing of interest are controlled by a traffic signal	<input type="checkbox"/>
Vehicle traffic on the leg with the crossing of interest must stop for a stop sign	<input type="checkbox"/>
Neither is present	<input type="checkbox"/>

D. Sidewalk

- Sidewalk Characteristics. (Check one that best fits to the location being analyzed)

Sidewalk is missing	<input type="checkbox"/>
Sidewalk is without road separation	<input type="checkbox"/>
Sidewalk has a road separation (e.g. on-street parking, bicycle lane, planting buffer)	<input type="checkbox"/>

- Sidewalk Width _____ (ft)
- If Buffer is present: Type and Width a) _____ (ft)
b) _____ (ft)
- If Sidewalk is present: (Circle best one option)

	Sidewalk Conditions		
Illumination	POOR	FAIR	GOOD
Cracking	NOT PRESENT	MINOR	MAJOR
Deterioration	NOT PRESENT	MINOR	MAJOR
Faulting	NOT PRESENT	MINOR	MAJOR
Patching/ Raveling	NOT PRESENT	MINOR	MAJOR

Figure 13. Data Collection Field Form for PLOC, PLTS, and Ped ISI Calculation.

Figure 14 shows the sidewalk rating criteria for good, fair, poor, or very poor condition.






Good	<ul style="list-style-type: none"> • No minor cracking • No patching or raveling and has a very smooth surface • No faulting • New construction 	
Fair	<ul style="list-style-type: none"> • Minor cracking (generally hairline) • Minor patching and possibly some minor raveling evident. Surface is generally smooth • Minor faulting (less than ¼") 	
Poor	<ul style="list-style-type: none"> • Minor cracking in several locations • Rough areas present but not extensive • Faulting may be present but less than ½" (No major faulting) 	
Very Poor	<ul style="list-style-type: none"> • Major cracking patterns • Rough conditions (major deterioration, raveling, loose aggregate, missing pavement, etc.) • Faulting greater than ½" 	
No sidewalk	<ul style="list-style-type: none"> • No solid and smooth surface is present on the side of the roadway. Pedestrians use the travel lane, paved shoulder, or soil shoulder to travel along the roadway. 	

Figure 14. Sidewalk Condition Rating Description.

The field evaluation includes 2-way street sections that are grouped on the main street and the beginning and ending streets that intersect them. Data was recorded from both directions and sides of each segment. The average daily traffic value was attained from the City of El Paso GIS traffic maps. Using data from the website, the ADT was approximated to 3,400. When scoring each individual segment, the side or direction of traffic that would result in the worst outcome was chosen. Table 13 shows a summary of the data for the VRUSI calculations and includes the following:

- Street/Sidewalk Geometry: number of lanes, outer lane width, width of buffer, and width of sidewalk.
- Land Use: if the area is predominantly commercial.
- Traffic: street speed limit, average daily traffic, and type of traffic control
- Sidewalk Characteristics: missing sidewalk, sidewalk without road separation, sidewalk with a road separation, sidewalk with a buffer, illumination, and distresses present on the sidewalk.
- Safety Index Scoring: Pedestrian Level of Comfort, Pedestrian Level of Traffic Stress, Pedestrian Intersection Safety Index, and Vulnerability Road User Safety Index. More details regarding the field data and calculations for PED ISI are found in Appendix F.

Table 13. Summary of Field Data and VRUS Calculation Results.

Street Analyzed	Prospect	Yandell	Porfirio Diaz	Lawton	Upson
From:	Porfirio Diaz	Prospect	Yandell	Yandell	Porfirio Diaz
To:	Yandell	Porfirio Diaz	Prospect	Prospect	Yandell
A. Street/Sidewalk Geometry					
Number of lanes	2	2	2	2	2
Outer lane width (ft)	11	17	22	14	24
Width of buffer if present (ft)	8 (parking) 5 (bike)	8	n/a	8	n/a
Width of sidewalk if present (ft)	4	6	7	0	0
B. Land Use					
Area predominantly commercial	No	No	No	No	No
C. Traffic					
Street speed limit (mph)	30	30	30	30	30
Average daily traffic (in thousands)	3.4	3.4	3.4	3.4	3.4
Type of traffic control	Stop Sign	Stop Sign	Stop Sign	Stop Sign	Stop Sign
D. Sidewalk Characteristics					
Sidewalk missing	No	No	No	Yes	Yes
Sidewalk is without road separation	No	No	Yes	No	Yes
Sidewalk has a road separation	Yes	Yes	No	Yes	No
If sidewalk has buffer what type	Parking and bike	On-street parking	n/a	On-street parking	n/a
If sidewalk present					
Illumination	Fair	Poor	Poor	Good	Good
Cracking	Minor	Minor	Not present	Not present	Not present
Deterioration	Not present	Minor	Not present	Not present	Not present
Faulting	Not present	Not present	Not present	Not present	Not present
Patching/Raveling	Not present	Not present	Not present	Not present	Not present
Sidewalk Condition	Fair	Fair	Good	n/a	n/a
E. Safety Index Scoring					
Pedestrian Level of Comfort (PLOC)	1	1	1	2	2
Pedestrian Level of Traffic Stress (PLTS)	3	2	3	4	4
Pedestrian Intersection Safety Index (Ped ISI)	1.78	1.78	1.78	1.78	1.78
VRUSI	5.78	4.78	5.78	7.78	7.78

All the five streets had two sides of pedestrian traffic except the two smaller segments Lawson Dr. and Upson Dr. The segments analyzed had several alike parameters (number of lanes, absence of commercial land use, posted speed limit, ADT, and governance of stop signs) that heavily factored into the scoring matrices and safety index calculations. As shown in Table 13, Prospect St., Yandell Dr., and Porfirio Diaz St. got PLOC values of 1, while Lawson Dr. and Upson Dr. got PLOC values of 2. Lawson Dr. and Upson Dr. only had one side of sidewalk along the inside of Mundy Park, and it was considered as a missing sidewalk. This changed the PLOC scoring for those segments.

Prospect St. and Porfirio Diaz St. got a PLTS value of 3, while Lawson Dr. and Upson Dr. got a PLTS value of 4. Yandell Dr. got a PLTS value of 2. The predominant criterion for the PLTS value on Prospect St. was set by the fair condition of the sidewalk. The predominant criterion for the PLTS values on Lawson Dr., and Upson Dr. was defined by the missing sidewalk on those streets. The predominant criteria for the PLTS values on Yandell Dr. was defined by the width of the physical buffer, the number of lanes, and the prevailing traffic speed. The predominant criterion for the PLTS value on Porfirio Diaz St. was the buffer type and the prevailing traffic speed. The PED ISI was 1.78 for all 5 segments. VRUSIs are also calculated for each street. The highest values for VRUSI (7.78) were found in Lawson Dr. and Upson Dr., indicating that those streets have lower levels of comfort and higher traffic stress. The second highest VRUSI values (5.78) were found in Prospect St. and Porfirio Diaz St. Finally, the lowest VRUSI values (4.78) was found in Yandell Dr.

A countermeasure to improve pedestrian safety on the intersections around Mundy Park is to build walkways on those streets with missing sidewalks. Other actions would be to repair the deterioration exhibited in some sidewalks (e.g. cracking) to improve its condition, and to add on-street parking, bicycle lanes, and/or planting buffer on those streets without road separation. In addition, safety enhancements could include: installing pedestrian signals to warn motorists that pedestrians are crossing on that area, installing speed limit signs to control traffic speed, and enhancing the streetlight in those areas with poor illumination.

5.3 Project Selection and Funding Allocation

Managerial decisions regarding project selection and funding allocation incorporate the VRUSI to improve safety conditions for pedestrians at intersections. Mock-up examples with ten intersections in a pedestrian network is used to illustrate the project selection and funding allocation process using a ranking approach with DBU. The costs associated with the safety enhancements are based on the document “Costs for Pedestrian and Bicyclists Infrastructure Improvements” (Bushell, M, et al., 2013).

Table 14 shows ten intersections in need of safety enhancements for pedestrians. VRUSIs are calculated for each intersection with the corresponding countermeasure costs. VRUSI is used to select the projects based on safety needs and costs. Safety needs are expressed by the VRUSI, while the cost is related to the proposed countermeasure to enhance safety. The ten sections have different VRUSIs and cost depending on the safety conditions. The higher the VRUSI, the lower the level of comfort, the higher the traffic stress, and the higher the priority for safety enhancements. The Cost/VRUSI ratio is also calculated for each intersection.

Table 14. Data for the Project Selection and Funding Allocation.

Intersection ID*	VRUSI before intervention	VRUSI after intervention	Cost**	Cost/VRUSI before intervention
1	3.78	2.90	\$2,200	582
2	4.78	4.00	\$1,950	408
3	5.10	1.80	\$8,250	1618
4	4.25	4.00	\$625	147
5	3.78	2.50	\$3,200	847
6	2.60	1.80	\$2,000	769
7	3.30	2.60	\$1,750	530
8	5.00	1.50	\$8,750	1750
9	4.88	2.88	\$5,000	1025
10	2.55	2.00	\$1,375	539
		Total	\$35,100	

*The ten intersections of the pedestrian network are mock-up examples.

**Costs are assumed based on “Costs for Pedestrian and Bicyclists Infrastructure Improvements” (Bushell, M, et al., 2013).

The average VRUSI for the intersections in the pedestrian network is 4.00. In this example, the target safety goal is setup as a VRUSI equal to 3. Two approaches are used for project selection and funding allocation. The first approach is based on the VRUSI and the second approach on the Cost/VRUSI ratio. The Dynamic Bubble Up technique is used for project selection in both ranking approaches. Tables 15 and 16 show the results for the VRUSI and the Cost/VRUSI ratio criteria respectively. As shown in Table 15, the intersections are ranked based on the VRUSIs before the intervention. The intersection with the highest VRUSI (Intersection 3) has the highest priority. Six intersections are selected for safety improvements to achieve the target value of 3.00 with total budget of \$26,775.

Table 15. Results for Intersections to be Improved Based on the VRUSI Ranking Criterion.

Intersection ID	VRUSI before intervention	VRUSI after intervention	Dynamic VRUSI Average	Selected (Y/N)	Cost
3	5.10	1.80	3.67	Y	\$8,250
8	5.00	1.50	3.32	Y	\$8,750
9	4.88	2.88	3.12	Y	\$5,000
2	4.78	4.00	3.04	Y	\$1,950
4	4.25	4.00	3.02	Y	\$625
1	3.78	2.90	2.93	Y	\$2,200
5	3.78	2.50	2.80	N	-
7	3.30	2.60	2.73	N	-
6	2.60	1.80	2.65	N	-
10	2.55	2.00	2.60	N	-
				Total	\$26,775

In Table 16, the intersections are ranked based on the Cost/VRUSI ratio. For this specific criterion, nine intersections are selected for improvement in order to achieve a target value of 3.00. The intersection with the lowest Cost/VRUSI (Intersection 4) has the highest priority. Nine intersections were selected with a total budget of \$26,350, which is lower than the budget estimated with the VRUSI criterion. The ranking approach based on the Cost/VRUSI is recommended due to the lower total cost to meet the network safety target.

Table 16. Results for Intersections to be Improved Based on the Cost/VRUSI Ranking Criterion.

Intersection ID	VRUSI before intervention	VRUSI after intervention	Cost/VRUSI before intervention	Dynamic VRUSI Average	Selected (Y/N)	Cost
4	4.25	4.00	147	3.98	Y	\$625
2	4.78	4.00	408	3.90	Y	\$1,950
7	3.30	2.60	530	3.83	Y	\$1,750
10	2.55	2.00	539	3.77	Y	\$1,375
1	3.78	2.90	582	3.69	Y	\$2,200
6	2.60	1.80	769	3.61	Y	\$2,000
5	3.78	2.50	847	3.48	Y	\$3,200
9	4.88	2.88	1025	3.28	Y	\$5,000
3	5.10	1.80	1618	2.95	Y	\$8,250
8	5.00	1.50	1750	2.60	N	-
Total						\$26,350

CHAPTER 6

Conclusions and Recommendations for Future Research

This research study developed a methodology that incorporates Vulnerable Road User (VRU) safety into the Transportation Asset Management (TAM) process to promote safe mobility to all the road users. The methodology includes the definition of the Vulnerability Road User Safety Index (VRUSI), which is proposed to identify high risk safety areas for pedestrians at the strategic and network management level. VRUSI is calculated based on measurable features including: street geometry, land use of the area, traffic, and sidewalks characteristics. Once VRUSI values are estimated on different intersections, managerial decisions regarding project selection and funding allocation are made based on the risk safety level and cost of the enhancements. The major conclusions and recommendations for future research are summarized as follows.

6.1 Conclusions

- a. A framework to integrate VRU into TAM is available for implementation as a result of this research study. The framework consists of the following major activities:
 - Establish goals and policies to enhance pedestrian's safety.
 - Review the transportation asset inventory.
 - Conduct a safety infrastructure assessment on high-risk areas for pedestrians considering traffic flow, geometry of the intersection, and condition of the infrastructure facility.
 - Gather data from inventory records and field inspections.
 - Determine pedestrian safety indexes to identify safety risk areas in the transportation network in order to recommend countermeasures and estimate budgets to enhance pedestrian safety.
 - Use pedestrian safety indexes for project selection and funding allocation.
 - Implement the safety countermeasures in the TAM program.
 - Monitor the results of the TAM program in terms of pedestrian risk safety.
 - Make any necessary adjustments in the TAM process to achieve the safety goals.

The methodology described in the TAM-VRU framework includes a safety index for pedestrians, however the overall framework can be applied to all vulnerable users with the appropriate safety indexes.

- b. A Vulnerability Road User Safety Index (VRUSI) is used in this methodology to identify high-risk safety areas. VRUSI combines three indexes: the Pedestrian Level of Comfort (PLOC), the Pedestrian Level of Traffic Stress (PLTS), and the Pedestrian Intersection Safety Index (Ped ISI). VRUSI can be used for project selection and funding allocation at the strategic and network management level. The higher the VRUSI; the lower the level of comfort, and the higher the traffic stress, therefore the greater the priority for safety enhancement.

- c. A case study was conducted for five intersections located around Mundy Park in El Paso County, City of El Paso, Texas. The streets geometry (e.g. number of lanes, outer width of lanes, number of through vehicle lanes), land use (e.g. predominantly commercial), traffic (e.g. street speed limit, average daily traffic), and sidewalks characteristics were evaluated to calculate their VRUSIs. It was found that two out of the five streets require pedestrian safety enhancements (e.g. build walkways, repairs, add buffers on those streets with road separation, installing pedestrian signals, installing speed limit signs, enhancing streetlights).
- d. VRUSI can be calculated for all the intersections in a pedestrian network to identify risk safety areas. Projects with safety enhancements can be prioritized using a ranking approach with the Dynamic Bubble Up Technique (DBU) for project selection. Two ranking criteria are proposed: VRUSI and Cost/VRUSI ratio. In general, the Cost/VRUSI ratio criterion is recommended because it considers the need for the safety enhancement as well as countermeasure costs. A low COST/VRUSI ratio represents a section with a high safety enhancement needs and a low cost.
- e. Departments of Transportation and Federal Highway Organizations have recommended specific countermeasures to address specific problems regarding the number and severity of fatalities involving pedestrians crossing at intersections. The effectiveness of the countermeasures is expressed by the reduction of the expected number of pedestrian crashes. Once the countermeasures are identified, the associated costs are estimated to formulate a budget for the pedestrian network. Examples of the most relevant countermeasures are:
 - To install pedestrian median on approaches
 - To install pedestrian crossing at uncontrolled locations
 - To install raised pedestrian crossing
 - To add intersection lighting

6.2 Recommendations for Future Research

- a. Future research can be conducted to combine the implementation of VRUSI with other infrastructure related indexes as criteria in the TAM decision-making process. For example, VRUSI and the Pavement Condition Index (PCI) can be used to establish target objectives in the TAM program. Hence, a multi-objective target analysis can be performed to achieve pedestrian's safety as well as pavement condition objectives established by the agencies.
- b. Research regarding the development and use of automated equipment for data collection is recommended for field data collection to save time. The use of unmanned aerial vehicles, commonly known as drones, could be an alternative to collect data required for the safety index calculations.
- c. A probabilistic approach for safety risk assessment is an alternative method that could be incorporated into the TAM-VRU framework. The implementation of the VRUSI can be expanded by including the "probability of a crash to occur given the exposure to potential crash events" which is the FHWA definition of risk in the "Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists" (Turner, S., et al., 2018).

REFERENCES

- Asian Development Bank. (1998). "Road Safety Guidelines for the Asian and Pacific Region Bank". ISBN 971-561-133-3 Asian Development Bank. Manila, Philippines.
- Blaikie, P., Cannon, T., Davis, I., and Wisner, B. (2005). "At Risk: Natural Hazards, People's Vulnerability, and Disasters". *Journal of Homeland Security and Emergency Management*, Volume 2, Issue 2.
- Bushell, M., Poole, B., Zegeer, C., and Rodriguez, D. (2013). "Costs for Pedestrian and Bicyclist Infrastructure Improvements". UNC Highway Safety Research Center, Prepared for the Federal Highway Administration and supported by the Robert Wood Johnson Foundation through its Active Living Research Program.
- Caltrans, FHWA, and SafeTREC. (2016). "Local Roadway Safety-Version 1.3". Manual for California's Local Road Owners.
- Garder (2004). "The impact of speed and other variables on pedestrian safety in Maine". *Accident Analysis and Prevention* 36: 533-542.
- Chang A., C. M. (2007). "Development of a Multi-Objective Strategic Management Approach to Improve Decisions for Pavement Management Practices in Local Agencies". Doctoral Thesis: Texas A&M University.
- Chang, C.M., M. Vavrova. (2016). "Vulnerable User Road Safety Enhancements for Transportation Asset Management." American Society of Civil Engineers. Reston, VA.
- City of Austin (2009). "Sidewalk Master Plan". City of Austin Public Works Department. City of Austin Transportation Department. MWM Design Group. HDR. Austin, Texas.
- City of Encinitas (2018). "Active Transportation Plan". Administrative Draft. California, 2018.
- Clifton, K., Singleton, P., Muhs, C., Schneider, R., and Lagerwey, P. (2013). "Improving the Representation of the Pedestrian Environment in Travel Demand Models, Phase I". Civil and Environmental Engineering Faculty Publications and Presentations.
- Cuevas C. (2016). "Análisis de la Siniestralidad de los Usuarios Vulnerables en Carreteras Federales." Instituto Mexicano del Transporte. Queretaro, Qro. Mexico.
- Dultz, Linda A., and Spiros G. Frangos. (2012) "The Impact of Alcohol in Pedestrian Trauma." *Trauma*, vol. 15, no. 1, Jan. 2013, pp. 64–75, DOI: 10.1177/1460408612464019.
- European commission. (2015). "Road safety in the European Union Trends, statistics and main challenges" DOI: 10.2832/404614. Brussels, Belgium.
- Federal Highway Administration FHWA (2007a). "Asset Management Overview". Federal Highway Administration. Retrieved: https://www.fhwa.dot.gov/asset/if08008/assetmgmt_overview.pdf.
- Federal Highway Administration FHWA (2007b). "Pedestrian and Bicyclist Intersection Safety Indices: User Guide". Report No. FHWA-HRT-06-130.
- Federal Highway Administration FHWA (2017a). "Pedestrian Intersection Safety Index. US Department of Transportation". Federal Highway Administration. Washington, DC.
- Federal Highway Administration FHWA (2017b) Data Driven Safety Analysis Using Evidence-Based Tools to Evaluate the Current and Future Safety Performance of Roadways. Washington DC.
- Federal Highway Administration FHWA (2018). Safety Performance Management. General Information. US Department of Transportation. Federal Highway Administration. Washington, DC.
- Fitzpatrick, K., Brewer, M., and Avelar, R. (2014). "Driver Yielding at Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid-Flashing Beacons in Texas". *Transportation Research Record: Journal of the Transportation Research Board*.
- Forsyth, Ann. (2015). "What is a walkable place? The walkability debate in urban design". *Urban Design International*. Harvard University, Cambridge, MA.

- Garrick N., C. Atkinson-Palombo, H. Ahangari. (2016). "Why America's roads are so much more dangerous than Europe's". Vox website.
Available: <https://www.vox.com/the-big-idea/2016/11/30/13784520/roads-deaths-increase-safety-traffic-us>. Accessed on September 19, 2017.
- Chimba. (2017). "Impact of Access Management Practices to Pedestrian Safety". Final Report. Transportation Research Center for Livable Communities. Report No. TRCLC 15-09.
- Gitelman V., D. Balasha, R. Carmel, L. Hendel, F. Pesahov. (2010). "Characterization of pedestrian accidents and an examination of infrastructure measures to improve pedestrian safety in Israel" Ran Naor Road Safety Research Center, Technion, Israel Institute of Technology, Haifa, Israel.
- Gordis, L. (2014). "Epidemiology". Fifth Edition. Elsevier Saunders. ISBN: 978-1-4557-3733-8. Philadelphia, PA.
- Governors Highway Safety Association GHSA (2018). "Pedestrian Traffic Fatalities by State". 2017 Preliminary Data. Washington, D.C.
- Greene, R., M. Chagas, D.R. Ragland. (2010). "Estimating Pedestrian Accident Exposure." California Department of Transportation (Caltrans). Safe Transportation Education and Research Center (SafeTREC). Berkeley, CA.
- Groeger, L. (2016). "Unsafe at Many Speeds". Last Day of Access: November 12, 2018. Article retrieved from ProPublica. <https://www.propublica.org/article/unsafe-at-many-speeds>
- Hartzell, P. (2017). "ISO 39001 and ISO 39002. Road traffic safety management system standards" Swedish Standards Institute, Stockholm, Sweden.
- Hauer, E. (2010). "Lessons Learned from Other Countries". White Papers for: Toward Zero Deaths: A National Strategy on Highway Safety. White Paper No. 9.
- Heinonen J., J.E. Eck (2007). "The Problem of Pedestrian Injuries and Fatalities". State University of New York at Albany. Retrieved from http://www.popcenter.org/problems/pedestrian_injuries/ Accessed no February 2018.
- Hembrow, D. (2012). "Unravelling of modes". A view from the cycle path.
Retrieved from: <http://www.aviewfromthecyclepath.com/2012/07/unravelling-of-modes.html>
- International Organization for Standardization. (2012). "ISO 39001:2012. Road traffic safety (RTS) management systems". Retrieved November 13, 2017.
- Lee, Hellinga, and Saccomanno. (2006). "Evaluation of variable speed limits to improve traffic safety". Transportation Research Part C: Emerging Technologies Volume 14, Issue 3, Pages 213-228.
- Loukaitou-Sideris, A., Liggett, R., and Sung, H. (2007). "Death on the Crosswalk: A Study of Pedestrian-Automobile Collisions in Los Angeles." Journal of Planning Education and Research, 26, pp. 338–351, SAGE Publications Inc., New Brunswick, NJ.
- Marquez, D. (2007). "Peatonabilidad, Accesibilidad o Caminabilidad y La Legislacion del Distrito Federal en Materia Urbana y Vialidad". Biblioteca Juridica Virtual del Instituto de Investigaciones Juridicas de la Universidad Nacional Autonoma de Mexico (UNAM).
- Martinez, A. (2012). "La Educacion Ambiental y la Formacion Profesional para el Empleo. La Integracion de la Sensibilizacion Ambiental". Tesis Doctoral, Universidad de Granada.
- McKibbin, D. (2014). "Why do people cycle & what benefits does cycling bring? Lessons from the Netherlands, Denmark and Germany". Research and Information Service Research Paper. Northern Ireland Assembly.
- Milne A., M. Melin, M. Milde, E. Bontrager, R. Buehler, T. Buskermolen, C. Cabansagan. (2014) "Bicycling and Walking in the United States". 2014 Benchmarking Report. Alliance for Biking and Walking. Washington D.C.
- Mohan, D. (2006). "Road Traffic Injury Prevention Training Manual." World Health Organization. Geneva, Switzerland.
- Monsere, C. (2017). "Safety Effectiveness of Pedestrian Crossing Treatment". Transportation Research and Education Center (TREC). Friday Seminar Series. Portland State University.
- National Cooperative Highway Research Program NCHRP (2003). "Guidance for implementation of the AASHTO strategic highway safety plan". Washington, D.C.: Transportation Research Board.

- National Cooperative Highway Research Program NCHRP (2018). "Pedestrian Safety Prediction Methodology". National Academies Press and the Transportation Research Board, Danvers, MA.
- National Highway Traffic Safety Administration (NHTSA) (2016), "Traffic Safety Facts 2015 Data: Bicyclists and Other Cyclists." National Highway Traffic Safety Administration, Washington, DC.
- National Highway Traffic Safety Administration (NHTSA) (2017). "Traffic Safety Facts 2015 Data: Pedestrians". National Highway Traffic Safety Administration, Washington, DC.
- National Highway Traffic Safety Administration NHTSA (2018), "Traffic Safety Facts 2016 Data: 2016 State Traffic Data." National Highway Traffic Safety Administration, Washington, DC.
- North Carolina Department of Transportation, NCDOT. (2018). "North Carolina Pedestrian and Bicycle Crash Data Tool". University of North Carolina Highway Safety Research Center (HSRC).
- Oregon Department of Transportation ODOT (2018). "Analysis Procedures Manual. Version 2". Oregon Department of Transportation, Transportation Development Division, Planning Section Transportation Planning Analysis Unit. Salem, Oregon
- Palamara and Broughton. (2013). "An investigation of pedestrian crashes at traffic intersections in the Perth Central Business District". Curtin-Monash Accident Research Centre, Faculty of Health Sciences Curtin University.
- Pan-American Health Organization (2011) "Seguridad Peatonal. Magnitud del Problema". Washington, DC.
- Patiño C. (2013) "Identificación de los Principales Factores de Riesgo en Usuarios Vulnerables no Motorizados en la Ciudad de Manizales y su Relación con la calidad de la Infraestructura Vial." Pontificia Universidad Javeriana. Facultad de ingeniería. Bogota, Colombia.
- Peden, M.M. (2004). "World report on road traffic injury prevention." World Health Organization. Geneva, Switzerland.
- Pieters J. (2016) "Some 185 Bikers Killed on Dutch Roads Last Year." Neatherland Times. December 20, 2016. Accessed <https://nltimes.nl/2016/12/20/185-bikers-killed-dutch-roads-last-year>
- Roundsari, B., Mock, C., Kaufman, R., Grossman, D., Henary, B., and Crandall, J. (2004). "Pedestrian crashes: higher injury severity and mortality rate for light truck vehicles compared with passenger vehicles". *Injury Prevention* 2004;10:154–158. doi: 10.1136/ip.2003.003814.
- Ryus, P, Ferguson, E., Laustsen, K., Schneider, R, Proulx, F., Hull, T, and Miranda-Moreno, L. (2014). "Guidebook on Pedestrian and Bicycle Volume Data Collection". National Cooperative Highway Research Program, NCHRP Report 797.
- Robertson, L. S. (2015) "Injury Epidemiology" Fourth Edition. Lulu Books. Morrisville, NC.
- Rundle A. G., D.M. Sheehan, J.W. Quinn, K. Bartley, D. Eisenhower, M.D. Bader, G.S. Lovasi, K.M. Neckerman. (2015) "Using GPS Data to Study Neighborhood Walkability and Physical Activity" *American Journal of Preventive Medicine*. Washington D.C.
- Sandt L., L. Thomas, K. Langford, D. Nabors (2006). "A Resident's Guide for Creating Safer Communities for Walking and Biking". Federal Highway Administration, FHWA. Washinton D.C.
- Schneider, R., Khattak, A., and Zegeer, C. (2001). "Method of improving pedestrian safety proactively with geographic information systems: example from a college campus", *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1773, pp. 97-107, 2001.
- Schneider, R., R. Patton, J. Toole and C. Raborn. (2005) "Pedestrian and Bicycle Data Collection in United States Communities: Quantifying Use, Surveying Users, and Documenting Facility Extent." FHWA, Office of Natural and Human Environment, U.S. Department of Transportation, Washington, D.C.
- Schneider, R, Diogenes, M., and Arnold, L. (2010). "Association between Roadway Intersection Characteristics and Pedestrian Crash Risk in Alameda County, California". Safe Transportation Research and Education Center.
- Senserrick, T., Boufous, S., Rome, L., Ivers, R., and Stevenson, M. (2014). "Detailed Analysis of Pedestrian Casualty Collisions in Victoria, Australia". *Journal of Traffic Injury Prevention*.
- Tefft, B. (2011). "Impact Speed and a Pedestrian's Risk of Severe Injury or Death". AAA Foundation for Traffic Safety, Washington DC.

- Texas Department of Transportation TxDOT (2017). “Texas Motor Vehicle Crash Statistics – 2017: Crash Contributing Factors”. Texas Department of Transportation, Austin, TX.
- The International Road Assessment Program iRAP (2017). “Star Rating and Investment Plan Implementation Support Guide”. © International Road Assessment Programme (iRAP), England.
- Turner, S., Sener, I., Martin, M., White, L.D., Das, S., Hampshire, R., Colety, M., Fitzpatrick, K., and Wijesundera, R. (2018). “Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists”. Federal Highway Administration (FHWA). Publication No. FHWA-SA-18-032.
- United Nations International Children’s Emergency Funds (UNICEF). (2017). “Have Them Home Safe”. <https://www.unicef.org/vietnam/press-releases/unicef-and-molisa-launch-nationwide-have-them-home-safe-campaign-call-helmet-wearing>
- United States Census Bureau. (2017). “Disability Characteristics 2015 American Community Survey 1-Year Estimates” Available. Washington D.C. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_15_1YR_S1810&prodType=table Accessed November 19, 2017
- United States Department of Transportation (USDOT). (2015). “Pedestrian and Bicyclist Road Safety Assessments”. Summary Report. U.S. DOT Pedestrian and Bicyclist Road Safety Assessments.
- United States Department of Transportation (USDOT). (2016). “Policy Priorities-Roadway Fatalities”. Retrieved from: <https://www.transportation.gov/transition/policy-priorities>.
- Vargas, D.J., (2012). “Accidentes de tránsito son una epidemia mundial, dice la OMS” Sura. Retrieved from <https://www.sura.com/blogs/autos/accidentes-transito-pandemia.aspx> Accessed September 3, 2017)
- Washington State Department of Transportation, WSDOT (2018). “People Power WSDOT on the Move to Improve Active Transportation”. Gray Notebook. Quarterly performance analysis of WSDOT’s multimodal systems and programs. Edition 69.
- Wedagama, D. P., Bird, R., & Dissanayake, D. (2008). “The Influence of Urban Land Use On Pedestrians Casualties”. IATSS Research, 73. DOI: 10.1016/s0386-1112(14)60201-6
- WHO Regional Office for Europe (2005). “Resolution EUR/RC55/R9 on prevention of injuries in the WHO European Region”. Copenhagen, WHO Regional Office for Europe.
- WHO Regional Office for Europe (2013). “Pedestrian Safety: A Road Safety Manual for Decision-makers and Practitioners”. WHO Library Cataloguing-in-Publication Data.
- Williams, A. (2015) “Bicyclist Safety”. Governors Highway Safety Association. Washington, D.C.
- World Health Organization (2015) “Global status report on road safety: time for action”. World Health Organization, Geneva, Switzerland. Retrieved from http://whqlibdoc.who.int/publications/2009/9789241563840_eng.pdf. Accessed on November 3, 2017
- Zegeer, Z., L. Sandt, M. Scully, M. Ronkin, M. Cynecki, and P. Lagerwey. (2008) “How to Develop a Pedestrian Safety Action Plan”. National Highway Traffic Safety Administration, NHTSA. Washington, D.C.

Appendix A

Prospect Street Photos



Figure A-1. Bike and on-street parking lanes in both directions of Prospect St.



Figure A-2. Sidewalk in general good condition on Prospect St.



Figure A-3. Localized minor cracking and raveling on the sidewalk of Prospect St.



Figure A-4. Symmetrical street geometry in both directions on Prospect St.



Fig A-5. Fair Illumination rating since lighting exists but is limited on Prospect St.



Figure A-6. Traffic control (Stop Sign) on Prospect St. as approaching Yandell Dr.

Appendix B

Yandell Drive Photos



Figure B-1. On-street parking buffer in both directions on Yandell Dr.



Figure B-2. Sidewalk in general good condition, Yandell Dr.



Figure B-3. Localized deteriorated sidewalk with cracks on Yandell Dr.



Figure B-4. One lane traffic in each direction on Yandell Dr.



Figure B-5. Poor illumination rating since no lighting existed on the outer sidewalk path.



Figure B-6. Traffic control (Stop Sign) governing Yandell Dr. approaching Porfirio Diaz.

Appendix C

Porfirio Diaz Street Photos



Figure C-1. Sidewalk without road separation on Porfirio Diaz St.



Figure C-2. Sidewalk in general good condition on Porfirio Diaz St.



Figure C-3. Sidewalk without road separation on a segment of Porfirio Diaz St.



Figure C-4. Street geometry with traffic lanes on Porfirio Diaz St.



Figure C-5. Poor Illumination Rating since there is no lighting on Porfirio Diaz St.



Figure C-6. Traffic control (Stop Sign) governing and parking buffer on Porfirio Diaz St. approaching Prospect St.

Appendix D

Upson Drive Photos



Figure D-1. Buffer or road separation missing on Upson Dr.



Figure D-2. Sidewalk missing on one side of Upson Dr.



Figure D-3. Street geometry and governing traffic control on Upson Dr.



Figure D-4. Good illumination with a light post on Upson Dr.

Appendix E

Lawton Drive Photos



Figure E-1. Bike and parking lanes in one direction on Lawton Dr.



Figure E-2. Street geometry and traffic lanes on Lawton Dr.



Figure E-3. Good illumination with a light post on Lawton Dr.



Figure E-4. Missing sidewalk and traffic control on Lawton Dr.

Appendix F
Safety Index Calculations

Table F-1. Safety Index Calculation Sheet, Prospect Street.

Street Analyzed:	Prospect
From:	Porfirio Diaz
To:	Yandell
Sidewalk features	
Sidewalk Missing	No
Sidewalk is without road separation	No
Sidewalk has a road separation	Yes
<i>If sidewalk has buffer what type:</i>	Multiple Buffers
<i>If sidewalk is present:</i>	
Illumination:	Fair
Cracking:	Minor
Deterioration:	n/a
Faulting:	n/a
Patching/Raveling:	n/a
<i>Sidewalk Condition:</i>	Fair
Traffic	
Street Speed Limit (mph):	30
Average Daily Traffic in (thousands):	3.4
Type of Traffic Control:	Stop Sign
Street/Sidewalk Geometry	
Number of lanes:	2
Outer lane width (ft):	11
<i>Width of buffer if present (ft):</i>	Parking 8, Bike 5
<i>Width of sidewalk if present (ft):</i>	4
Land use features	
Predominantly commercial area:	No
Safety Index Scoring	
PLOC	1.00
PED ISI	1.78
PLTS based on the Physical Buffer Type (Table 3)	2
PLTS based on the Total Buffering Width (Table 4)	1
PLTS based on the General Land Use (Table 5)	1
PLTS based on the Local Unsignalized Intersection Crossing (Table 6)	2
PLTS based on Sidewalk Condition (Table 11)	3
PLTS (most critical value)	3.00

Index calculations

$$PED\ ISI = 2.372 - 1.867 * SIGNAL - 1.807 * STOP + 0.335 * THRULNS + 0.018 * SPEED + 0.006 * (MAINADT * SIGNAL) + 0.238 * COMM$$

$$PED\ ISI = 2.372 - 1.867(0) - 1.807(1) + 0.335(2) + 0.018(30) + 0.006(3.4 * 0) + 0.238 * (0) = 1.78$$

Table F-2. Safety Index Calculation Sheet, Yandell Drive.

Street Analyzed:	Yandell
From:	Prospect
To:	Porfirio Diaz
Sidewalk features	
Sidewalk Missing	No
Sidewalk is without road separation	No
Aidewalk has a road separation	Yes
<i>If sidewalk has buffer what type:</i>	On-street Parking
<i>If sidewalk present:</i>	
Illumination:	Poor
Cracking:	Minor
Deterioration:	Minor
Faulting:	n/a
Patching/Raveling:	n/a
<i>Sidewalk Condition:</i>	Fair
Traffic	
Street Speed Limit (mph):	30
Average Daily Traffic:	3.4
Type of Traffic Control:	Stop Sign
Street/Sidewalk Geometry	
Number of lanes:	2
Outer lane width (ft):	17
<i>Width of buffer if present (ft):</i>	8
<i>Width of sidewalk if present (ft):</i>	6
Land use features	
Is area predominantly commercial:	No
Safety Index Scoring	
PLOC	1.00
PED ISI	1.78
PLTS based on the Physical Buffer Type (Table 3)	2
PLTS based on the Total Buffering Width (Table 4)	2
PLTS based on the General Land Use (Table 5)	1
PLTS based on the Local Unsignalized Intersection Crossing (Table 6)	2
PLTS based on Sidewalk Condition (Table 11)	1
PLTS (most critical value)	2.00

Index calculations

$$PED\ ISI = 2.372 - 1.867 * SIGNAL - 1.807 * STOP + 0.335 * THRU\ LNS + 0.018 * SPEED + 0.006 * (MAINADT * SIGNAL) + 0.238 * COMM$$

$$PED\ ISI = 2.372 - 1.867(0) - 1.807(1) + 0.335(2) + 0.018(30) + 0.006(3.4 * 0) + 0.238 * (0) = 1.78$$

Table F-3. Safety Index Calculation Sheet, Porfirio Diaz Street.

Street Analyzed:	Porfirio Diaz
From:	Yandell
To:	Prospect
Sidewalk features	
Sidewalk Missing	No
Sidewalk is without road separation	Yes
sidewalk has a road separation	No
<i>If sidewalk has buffer what type:</i>	n/a
<i>If sidewalk present:</i>	
Illumination:	Poor
Cracking:	n/a
Deterioration:	n/a
Faulting:	n/a
Patching/Raveling:	n/a
<i>Sidewalk Condition:</i>	Good
Traffic	
Street Speed Limit (mph):	30
Average Daily Traffic:	3.4
Type of Traffic Control:	Stop Sign
Street/Sidewalk Geometry	
Number of lanes:	2
Outer lane width (ft):	22
<i>Width of buffer if present (ft):</i>	0
<i>Width of sidewalk if present (ft):</i>	7
Land use features	
Is area predominantly commercial:	No
Safety Index Scoring	
PLOC	1.00
PED ISI	1.78
PLTS based on the Physical Buffer Type (Table 3)	3
PLTS based on the General Land Use (Table 5)	1
PLTS based on the Local Unsignalized Intersection Crossing (Table 6)	2
PLTS based on Sidewalk Condition (Table 11)	1
PLTS (most critical value)	3.00

Index calculations

$$PED\ ISI = 2.372 - 1.867 * SIGNAL - 1.807 * STOP + 0.335 * THRU LNS + 0.018 * SPEED + 0.006 * (MAINADT * SIGNAL) + 0.238 * COMM$$

$$PED\ ISI = 2.372 - 1.867(0) - 1.807(1) + 0.335(2) + 0.018(30) + 0.006(3.4 * 0) + 0.238 * (0) = 1.78$$

Table F-4. Safety Index Calculation Sheet, Lawton Drive.

Street Analyzed:	Lawton
From:	Yandell
To:	Prospect
Sidewalk features	
Sidewalk Missing	Yes
Sidewalk is without road separation	No
Sidewalk has a road separation	Yes
<i>If sidewalk has buffer what type:</i>	On-street parking
<i>If sidewalk present:</i>	
Illumination:	Good
Cracking:	Not present
Deterioration:	Not present
Faulting:	Not present
Patching/Raveling:	Not present
<i>Sidewalk Condition:</i>	n/a
Traffic	
Street Speed Limit (mph):	30
Average Daily Traffic:	3.4
Type of Traffic Control:	Stop Sign
Street/Sidewalk Geometry	
Number of lanes:	2
Outer lane width (ft):	14
<i>Width of buffer if present (ft):</i>	8
<i>Width of sidewalk if present (ft):</i>	14
Land use features	
Is area predominantly commercial:	No
Safety Index Scoring	
PLOC	2.00
PED ISI	1.78
PLTS based on the Physical Buffer Type (Table 3)	2
PLTS based on the Total Buffering Width (Table 4)	2
PLTS based on the General Land Use (Table 5)	1
PLTS based on the Local Unsignalized Intersection Crossing (Table 6)	2
PLTS based on Sidewalk Condition (Table 11)	4
PLTS (most critical value)	4.00

Index calculations

$$PED\ ISI = 2.372 - 1.867 * SIGNAL - 1.807 * STOP + 0.335 * THRULNS + 0.018 * SPEED + 0.006 * (MAINADT * SIGNAL) + 0.238 * COMM$$

$$PED\ ISI = 2.372 - 1.867(0) - 1.807(1) + 0.335(2) + 0.018(30) + 0.006(3.4 * 0) + 0.238 * (0) = 1.78$$

Table F-5. Safety Index Calculation Sheet, Upson Drive.

Street Analyzed:	Upson
From:	Porfirio Diaz
To:	Yandell
Sidewalk features	
Sidewalk Missing	Yes
Sidewalk is without road separation	Yes
sidewalk has a road separation	No
<i>If sidewalk has buffer what type:</i>	n/a
<i>If sidewalk present:</i>	
Illumination:	Good
Cracking:	Not present
Deterioration:	Not present
Faulting:	Not present
Patching/Raveling:	Not present
<i>Sidewalk Condition:</i>	n/a
Traffic	
Street Speed Limit (mph):	30
Average Daily Traffic:	3.4
Type of Traffic Control:	Stop Sign
Street/Sidewalk Geometry	
Number of lanes:	2
Outer lane width (ft):	24
<i>Width of buffer if present (ft):</i>	0
<i>Width of sidewalk if present (ft):</i>	12
Land use features	
Is area predominantly commercial:	No
Safety Index Scoring	
PLOC	2.00
PED ISI	1.78
PLTS based on the Physical Buffer Type (Table 3)	3
PLTS based on the General Land Use (Table 5)	1
PLTS based on the Local Unsignalized Intersection Crossing (Table 6)	2
PLTS based on Sidewalk Condition (Table 11)	4
PLTS (most critical value)	4.00

Index calculations

$$PED\ ISI = 2.372 - 1.867 * SIGNAL - 1.807 * STOP + 0.335 * THRULNS + 0.018 * SPEED + 0.006 * (MAINADT * SIGNAL) + 0.238 * COMM$$

$$PED\ ISI = 2.372 - 1.867(0) - 1.807(1) + 0.335(2) + 0.018(30) + 0.006(3.4 * 0) + 0.238 * (0) = 1.78$$

