Meeting Performance Priorities in the U.S. Through Geometric Design

United States Country Report for the 6th International Symposium on Highway Geometric Design Featuring the 6th Urban Street Symposium

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ABSTRACT

Transportation agencies in the United States (U.S.) are challenged to achieve results with fewer resources. Meanwhile, technologies, analysis tools, and new approaches are being implemented to achieve transportation for the future. As a result, agencies strive to be strategic in their allocation of resources by linking design decisions to explicit performance outcomes. Updates to the American Association of State Highway and Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets are changing the fundamentals and approach to design. Wider and more routine use of the methodologies of the AASHTO Highway Safety Manual (HSM) to predict the safety performance of geometric design choices provides experience and a new understanding of the challenges faced in safety prediction. Better use of three-dimensional modelling in design is also providing opportunities to visualize and evaluate design choices.

Transportation professionals across the U.S. are focusing on the roadway user and how people of various ages and abilities utilize the transportation network. While the Nation experienced decreasing fatalities and serious injuries in most categories of road transportation, there have been meaningful increases in pedestrian and bicyclist fatalities. There is heightened awareness of this situation and designers are placing greater emphasis on designing for the needs and safety of non-motorized users of the highways. Many efforts to deploy innovative approaches to design for vulnerable users have been accelerated and offer tremendous promise to reverse crash trends. These approaches improve safety by removing conflicts at intersections, providing more space for non-motorized transportation, and enhancing the friction of roadway surfaces. Meanwhile, U.S. agencies and the automotive industry seek ways to utilize vehicle communication and automation technologies to significantly reduce crashes and explore how those technologies will affect geometric and infrastructure design decisions in the future.

TRENDS IN GEOMETRIC DESIGN

Transportation professionals, and agencies responsible for managing the highway-related infrastructure needs across the United States (U.S.), are responding to an increasingly difficult operating environment by applying innovative data-driven methods to implement cost-effective solutions that promote safety, mobility, and economic growth. Transportation professionals responsible for the geometric design work products at the project level seek project-level investment choices while considering competing system level priorities.

The 2012 Moving Ahead for Progress in the 21st Century (MAP-21) Act [1] transportation legislation set forth significant changes in the management and planning of federally-funded highway programs by establishing a framework for a streamlined and performance-based surface transportation program. MAP-21 established seven performance management goal areas addressing:

- Safety;
- Infrastructure Condition;
- Congestion Reduction;
- System Reliability;
- Freight Movement and Economic Vitality;
- Environmental Sustainability; and
- Reduced Project Delivery Delays.

The 2015 Fixing America's Surface Transportation (FAST) Act [2] continues to emphasize these performance management goal areas and State and regional planning organizations continue to implement changes to their planning processes to measure the programs' effectiveness against these goals and targets.

Planning processes have become more data-driven and transportation professionals are exploring more effective ways to address system needs. As a result, geometric design programs are evolving toward a performance-driven mindset to maximize cost-effectiveness and achieve project centered goals while being mindful of the limited financial resources available toward system-level needs and priorities.

EVOLVING FRAMEWORK FOR GEOMETRIC DESIGN

The AASHTO released the 7th edition of *A Policy on Geometric Design of Highways and Streets*, commonly called the "Green Book", in late 2018. Chapter 1 of the Green Book was largely rewritten to describe a new framework for geometric design. The practice of geometric design in the U.S. continues to advance toward a more flexible approach that evaluates the past and expected future performance of the roadway, better incorporates in the decision-making the context of the project, the varied needs of all modes of transportation, and other factors.

This new framework was developed in response to a resolution that was unanimously adopted by the AASHTO Standing Committee on Highways in 2016 which recognized increases in non-motorized traffic demand and crash frequency [3]. The resolution directed the AASHTO Committee on Design to develop guidance to be included in the Green Book and other publications that furthers the development of a multimodal transportation system utilizing flexible design practices that are research-based and peer-reviewed. The shift toward performance-based design is possible due to extensive research over the last 25 years into the relationship between design features and actual performance outcomes, including traffic operations, crash frequency, and crash severity. This research informed publications such as the AASHTO HSM and the TRB Highway Capacity Manual [4], and tools developed by the Federal Highway Administration (FHWA), such as the Interactive Highway Safety Design Model (IHSDM) [5].

The 2018 Green Book expands beyond simply urban and rural classifications to adopt five context classifications: urban core, urban, suburban, rural town, and rural. Design guidance for each context was incorporated to the extent possible within this limited update, with more comprehensive guidance on contextual design anticipated in the next edition. The 2018 Green Book recognizes that the functional and context classification for the roadway is not a sufficient basis for design. Therefore, it also includes:

- a modal classification system;
- a project-type classification used to choose the appropriate design approach for each project;
- a flexible design approach needed to find the appropriate balance to meet the needs of all users and modes; and
- a performance-based approach to geometric design.

This flexible approach recognizes that the best use of limited funding available on any one project is essential to improving the overall performance of the transportation network. Since not all aspects of performance are quantifiable, we will need to continue considering both quantitative and qualitative measures.

Beyond the application of performance-based design approaches, dimensional design criteria have also been subject to adjustment with the findings of applied research. The new edition of the Green Book features updated design criteria reflecting the known safety effects of roadway features; the human factors, vehicle characteristics; the contemporary vehicle fleet; and a greater understanding of the physics of vehicular operation. Various innovative intersection and interchange forms were added as well.

The evolution toward a performance-based, flexible and multimodal design approach is expected to continue throughout the development of the 8th edition of the Green Book and be fully integrated in that publication. The next edition may also include a *Safe System* [6] approach to design that is gaining popularity internationally. Members of AASHTO are evaluating the deliverables from a recent research project and developing a vision for the 8th Edition [7]. Since some decisions made early in the planning process determine what options and alternatives are available during the design phase, application of a performance-based design approach will be necessary in the earliest stages of project decision-making. This shift into the planning arena will challenge the existing compartmentalized nature of project development in many transportation agencies.

UNITED STATES HIGHWAY AND TRAVEL PERFORMANCE CHARACTERISTICS

Today, road building consists primarily of widening projects that increase lane-miles, upgrades or additions to local street networks to serve new commercial and residential developments, and rehabilitation and maintenance projects to maintain the serviceability of existing highways. Local roads are by far the most extensive proportion of the road network, amounting to 2.9 million miles (69.1 percent of total centerline-miles) in 2016 (Figure 1). However, Interstate highways, which accounted for about 48,000 miles (1.2 percent of total system-miles) handled most of the traffic volume (25.4 percent) in 2016 [8].

Highway Infrastructure and Usage	2000	2010	2016
Public road and street mileage by functional type (miles)	**3,936,222**	**4,067,076**	**4,140,108**
Interstate	46,427	46,900	48,192
Other freeways and expressways	9,140	14,619	18,633
Other principal arterial	152,233	157,194	155,865
Minor arterial	227,364	242,815	246,193
Collectors	793,124	799,226	812,261
Local	2,707,934	2,806,322	2,858,964
Total lane-miles	**8,224,245**	**8,581,158**	**8,711,076**
Total bridges	**587,135**	**604,460**	**614,386**
Total registered vehicles	**225,821,241**	**250,070,048**	**268,799,083**
Vehicle-miles of travel (millions)	**2,746,925**	**2,967,266**	**3,174,408**

Table 1. Public Roads, Streets, and Bridges: 2000, 2010, and 2016 [8]

Safety remains a top priority in the United States (U.S.) with 36,560 motor vehicle fatalities reported in 2018 (Figure 1). This value represents a 2.4-percent decrease from 2017 reported fatalities despite increasing travel volumes. However, non-motorized fatalities continue to increase year after year, with a reported 6,283 pedestrian fatalities and 857 bicyclist fatalities in 2018.

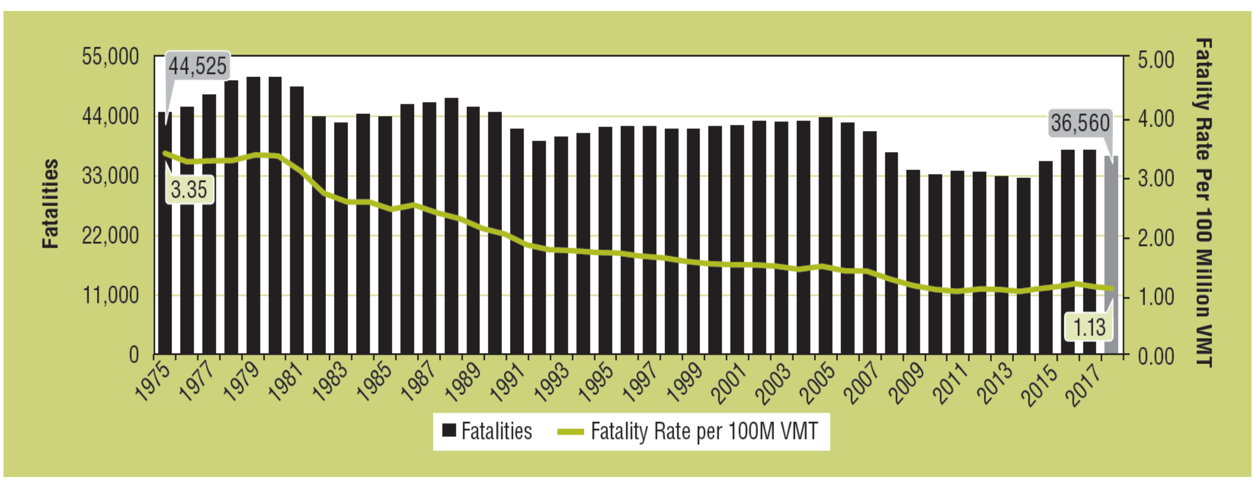

Figure 1. Fatalities and Fatality Rate per 100 Million Vehicle Miles Traveled, 1975-2018 [9]

IMPROVING DESIGN AND ENGINEERING FOR ALL USERS

In 2010, the United States Department of Transportation (USDOT) Secretary Ray LaHood announced a new policy on accommodating pedestrians and bicyclists in our transportation networks, which included considering pedestrians and bicyclists as being equal with other modes and providing facilities that serve users of all ages and abilities [10]. In the decade since, there has been a flood of new guidance to help practitioners who are changing their focus from motor vehicle to multimodal forms of travel.

The Federal Highway Administration (FHWA) issued a memorandum in 2013 emphasizing the flexibility inherent in the American Association of State Highway Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* and acknowledged other resources available to improve street design for pedestrians and bicyclists [11]. The FHWA also compiled information on innovative traffic control devices specific to bicyclist facilities that are either the subject of an interim approval or experimentation in accordance with procedures contained in the Manual on Uniform Traffic Control Devices (MUTCD) [12]. In the absence of a design guide for what were then known as *cycle tracks*, the FHWA released the *Separated Bike Lane Planning and Design Guide* [13]. This was shortly followed by the Massachusetts Department of Transportation's similarly titled guide [14], which provided more design details and was the first US publication to address the design of protected intersections.

While the frequency of pedestrian and bicyclist fatalities may be low when compared to the frequency of motor vehicle fatalities, pedestrians and bicyclists are overrepresented and are certainly the most vulnerable users [15]. One way in which States are trying to improve safety for pedestrians is by engaging in the *Every Day Counts* program [16] for rapid deployment of the following countermeasures:

- Rectangular rapid flashing beacons (RRFBs) are active (user-actuated) or passive (automated detection) amber light-emitting diodes (LED) that use an irregular flash pattern at mid-block or uncontrolled crossing locations. They significantly increase driver yielding behavior.
- Leading pedestrian intervals (LPI) at signalized intersections allow pedestrians to walk, usually 3 to 4 seconds, before vehicles get a green signal to turn left or right. The LPI increases visibility, reduces conflicts, and improves yielding.
- Crosswalk visibility enhancements, such as crosswalk lighting and enhanced signage and markings, help drivers detect pedestrians–particularly at night.
- Raised crosswalks can serve as a traffic calming measure and reduce vehicle speeds.
- Pedestrian crossing/refuge islands allow pedestrians a safer place to stop at the midpoint of the roadway before crossing the remaining distance. This is particularly helpful for pedestrians with limited mobility.
- Pedestrian hybrid beacons (PHB) provide positive stop control for higher-speed, multilane roadways with high vehicular volumes. The PHB is an intermediate option between a flashing beacon and a full pedestrian signal.
- Road Diets can reduce vehicle speeds and the number of lanes pedestrians cross, and they can create space to add new pedestrian facilities such as pedestrian crossing/refuge islands [17].

Some cities across the U.S. have robust bicycle networks in place, but many are just beginning to add segments of bikeways to selected corridors, or they are struggling with adapting their facilities to a higher comfort design that will be useful and safe for all ages, genders and abilities. The FHWA has released a *Guidebook for Measuring Multimodal Network Connectivity* [18] that highlights case studies from several locations where they are seeking ways to identify and implement improvements for key segments of their networks. Most recently the FHWA has also released a *Bikeway Selection Guide* [19] to aid practitioners in choosing a bikeway form that is suitable for the project context and those who will be using the facility. Additionally, the National Association of City Transportation Officials (NACTO) released a supplement to their *Urban Bikeway Design Guide* entitled "Don't Give Up at the Intersections" [20], which is the first national publication to provide details for protected intersections. Work has been ongoing on the 5th addition of AASHTO's *Guide for the Development of Bicycle Facilities* which we expect to incorporate many of these approaches for safer, more comfortable bikeways. Many other related FHWA publications and research products are posted to their web site [21].

An emerging issue in many urban areas across the country has been the deployment of micromobility devices, particularly shared dockless bikes and scooters. Communities are struggling with how to capture data on trips and crashes, classifying devices, and where devices may be used. Additionally, some cities are developing policies on where the devices can be parked, distribution of devices, enforcement for users and for vendors, and equity for all populations. Evaluations are being made of sustainability when considering the life of devices and the traffic generated to maintain the system. Several research studies are ongoing and initial information is being captured on the Pedestrian and Bicycle Information Center web site [22].

DESIGNING FOR PEDESTRIANS WITH DISABILITIES

The Americans with Disabilities Act of 1990, a Federal law referred to as the ADA, requires public entities, such as state and local governments, to operate services, programs, and activities, including pedestrian facilities in public street rights-of-way, such that, when viewed in their entirety, they are readily accessible to and usable by individuals with disabilities. The ADA requires that a public entity's newly constructed facilities be made accessible to and usable by individuals with disabilities to the extent that it is not structurally impracticable to do so. The ADA also requires that, when an existing facility is altered, the altered facility be made accessible to and usable by individuals with disabilities to the maximum extent feasible. Section 504 of the Rehabilitation Act of 1973, generally referred to as Section 504, includes similar requirements for entities that receive Federal financial assistance.

Figure 2. Man with visual impairment navigates on a shared street with aid of a long white cane.

The 2010 Standards for Accessible Design, adopted by the U.S. Department of Justice (USDOJ), address some aspects of rights-of-way projects, particularly the requirement to provide curb ramps at the intersection of newly constructed or altered roads and sidewalks. However, these DOJ standards, and the 2006 Standards adopted by the U.S. Department of Transportation (USDOT), have limited applicability in the public right of way.

In 2011, the U.S. Access Board published a Notice of Proposed Rulemaking (NPRM) in the Federal Register to invite comment on the Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (PROWAG) [23]. The intent of this effort was to provide comprehensive accessibility guidelines for pedestrian facilities in the public right-of-way that would ultimately be adopted as enforceable standards by USDOT and USDOJ. The Access Board published a Supplemental Notice of Proposed Rulemaking (SNPRM) in 2013 [24] to add draft guidelines for shared use paths, i.e. paths serving a transportation purpose and used by pedestrians, bicyclists, and sometimes others. The proposed PROWAG, including the shared use path provisions, have not been finalized or adopted as of this writing and are not requirements.

The proposed PROWAG includes the following guidance:

- Sidewalks should be at least 4-feet wide (1.2 m.), exclusive of curb.
- The longitudinal grade of the sidewalk should not exceed the grade of the adjacent roadway.

- Wherever pedestrian-activated signals are installed, the pushbuttons should be properly located, include locator tones, and communicate the walk signal in audible and vibrotactile formats.
- The cross slope of crosswalks at intersections should not exceed 2% unless the crossing is signalized or uncontrolled, since in those cases traffic may at times proceed through the intersection without slowing.
- Curb ramps and blended transitions should have detectable warning surfaces to effectively communicate the boundary between the sidewalk and street to pedestrians with vision disabilities.
- When on-street parking is marked or metered, a portion of the parking spaces should be accessible.

While the PROWAG has now been under development for 20 years, research into accessibility issues has continued, especially with respect to better provisions for pedestrians with vision disabilities. In 2017, the FHWA published *Accessible Shared Streets: Notable Practices and Considerations for Accommodating Pedestrians with Vision Disabilities* [25]. Based on field observations at several early shared street installations in the U.S., this document summarizes the challenges faced by pedestrians with vision disabilities in these open environments, the effectiveness of treatments that were used on these projects, and the need for further research. A major research effort is now underway in the U.S. to develop a guide to tactile wayfinding in transportation settings for travelers who have vision disabilities [26]. The researchers will conduct human factors testing to determine the detectability, discriminability, and usability of various tactile walking surface indicators to provide wayfinding information in the public right-of-way and in transit stations. The anticipated completion date for this effort is September 2021.

The USDOJ Standards, PROWAG, SNPRM and ongoing research provide a useful framework to help public entities meet their obligations to make their programs, services, and activities in the public rights-of-way readily accessible to and usable by individuals with disabilities.

SAFETY PERFORMANCE ANALYSIS

The 1st Edition of the AASHTO HSM was published by the American Association of State Highway Transportation Officials (AASHTO) in 2010, consisting of three volumes containing:

- Part A (Introduction, Human Factors, and Fundamentals);
- Part B (Roadway Safety Management Process);
- Part C (Predictive Method); and
- Part D (Crash Modification Factors).

A Supplement to the 1st Edition HSM was published in 2014, adding crash prediction methods for freeway segments and ramps/interchange components to Part C. In the years since, efforts have been focused on implementation of HSM methods as well as working towards an expanded 2nd Edition of the HSM (HSM2) [27].

Transportation agencies are applying HSM analytical procedures to planning, programming, environment, design, operations, and maintenance activities. Designers are applying the HSM to support alternative analyses, design exceptions, and performance-based project decisions. Transportation agencies are investing considerable resources toward developing staff competency and professional capabilities as they work to integrate the HSM into policies and programs.

For transportation agencies to more fully utilize HSM methods and other quantitative safety analysis tools, there is a need to develop more robust data systems. For example, the FHWA Model Inventory of Roadway Elements (MIRE) [28] contains a recommended catalogue of roadway inventory and traffic elements critical to safety management.

The HSM has fostered significant advances in analytical methods in highway safety and this evolution continues; with increased knowledge, safety performance functions and crash modification factors are being developed on an ongoing basis. Users and researchers now have gained experience with the HSM and have outlined priorities for enhancements to HSM chapters, procedures, and models. The proposed Second Edition will synthesize and incorporate relevant ongoing and completed research, related documents, and user feedback to expand the scope and quality of the HSM to increase application and improve the usability [29].

PERFORMANCE BASED PRACTICAL DESIGN

The FHWA launched an effort in 2015 to promote a concept called Performance Based Practical Design (PBPD) [30] which was developed in response to the increasing use and popularity of the Practical Design (PD) concept by state agencies. The goal of a PD program can be characterized as a renewed focus on scoping and designing projects to stay within the core purpose and need and reducing the net-cost of all projects. The FHWA's goal in developing a PBPD concept was to improve the state-developed concept of PD by encouraging transportation professionals to increase the use of performance analysis information to make more informed decisions while utilizing flexibility that exists in current design guidance and regulations. After interviewing several states about how their PD programs are structured and implemented, the FHWA focused PBPD on developing/improving the capability of applying data-driven tools and methods to help inform project decisions.

Under the PBPD philosophy, the FHWA encourages design engineers to consider how a project investment decision may compliment an agency's system objectives, and when appropriate, scrutinize a design choice regarding the project purpose and need. Where possible, the FHWA encourages designers to consider whether it is appropriate to make a design choice that improves performance over existing conditions while not meeting full design standards. The use of data-driven tools can help quantify how this choice may be a more cost-effective choice for a given project, while being consciously aware of how project decisions can compete with meeting system-wide performance objectives for all users and modes of travel. By meeting a project's purpose and need and making improvements to the existing conditions while preserving precious funds for needs found elsewhere in the system, an agency should be able to accelerate performance improvements of the system. Several state agencies have adopted a PBPD philosophy into their design programs and increased the use of data-driven tools in design decision making.

HIGHER DESIGN SPEEDS

Mainly in the western U.S., there is growing interest and consideration for using high design speeds on rural and/or toll facilities (80 mph [130 kph] and above). The Texas Department of Transportation (TxDOT) was one of the first states to embark on design considerations for high-speed corridors and other states have followed. Most state and national roadway design guidance does not provide for design speeds above 80 mph [130 km/h], so roadway designers have been struggling to identify appropriate design values for these special high-speed facilities.

The TxDOT sponsored initial research and a report titled *Criteria for High Design Speed Facilities* [31] expanded upon existing design guidance and identified new criteria for design speeds up to 100 mph [160 km/h]. The report presented the issues and concerns, along with generating potential values for design speeds of 85 mph [140 km/h] to 100 mph [160 km/h] for certain design criteria, ramp design elements, and roadside items.

The 7th Edition of the AASHTO Policy on Geometric Design for Streets and Highways added values for stopping sight distance, decision sight distance and superelevation runoff for a design speed of 85 mph, while in other cases providing the designer with information on how to calculate needed values for higher design speeds. Several state transportation agencies are further developing guidelines and considerations for higher speed design criteria.

MANAGED LANES

Transportation agencies are faced with growing challenges of congestion and a limited ability to expand freeway capacity due to construction costs, right-of-way constraints, and environmental and societal impacts. Transportation officials are taking advantage of opportunities to address mobility needs and provide travel options through a combination of limited capacity expansion coupled with operational strategies that seek to manage travel demand and improve transit and other forms of ridesharing. Managed lanes are one approach that combines these elements to make more effective and efficient use of a freeway facility. More information on managed lanes is available at https://ops.fhwa.dot.gov/freewaymgmt/managed_lanes.htm.

The distinction between managed lanes and other traditional forms of freeway lane management is the operating philosophy of "active management." Under this philosophy, the operating agency can proactively manage demand and available capacity on the facility. The agency defines from the outset the operating objectives for the managed lanes and the kinds of actions that will be taken once pre-defined performance thresholds are met. Actions may include: modifying vehicle occupancy requirements, making certain vehicle types permitted or not permitted to use the managed lanes, or adjusting the times that the managed lanes are in operation. [32]

Managed lanes encompass a range of strategies and techniques to more efficiently utilize limited freeway capacity. These strategies and techniques may be implemented using a fixed; i.e., time of day, scheme or dynamically where the managed lane approach varies as traffic and other conditions change. The managed-lane strategy most commonly used in the U.S. is high-occupancy-vehicle (HOV) lanes, where priority is given to vehicles with two or more occupants. Several previously implemented HOV lanes have since evolved into high-occupancy-toll (HOT) lanes, where drivers can pay a toll to use the HOT lane when they don’t meet the vehicle occupancy requirements to use the lane for free. Prices are set to keeping the lane flowing reliability and maximizing the movement of people, while also providing a benefit of travel time and trip reliability to drivers who pay the toll. Presently there are more than 150 HOV or HOT facilities in the U.S.

Where congestion is high and space for the addition of lanes is limited, part-time shoulder use (PTSU) is another managed-lane strategy that is becoming more commonly considered in the U.S. With PTSU, the existing shoulder is used as another travel lane, either for set time periods when congestion is usually high, or dynamically in response to existing or predicted traffic conditions. Often PTSU deployments are combined with Active Traffic Management strategies which allow operators to immediately open or close lanes, change speed limits, or adjust ramp metering rates. These complementary strategies support traffic incident management and maintenance activities on facilities with PTSU. Research is currently underway to investigate and develop crash prediction models for both freeways with managed lanes as well as freeways with PTSU. [33]

INNOVATIVE INTERSECTION AND INTERCHANGE GEOMETRICS

The dual challenges of improving safety for all users and reducing congestion is particularly problematic at intersections. Transportation professionals in the U.S. have expanded the utilization of innovative intersection designs to better meet the increasingly complex safety and mobility needs and do so within the practical constraints and limited resources available. Examples of innovative intersections and interchanges promoted by the Every Day Counts program [34] and gaining popularity in the U.S. include the roundabout, restricted crossing U-turn (RCUT), median U-turn (MUT), displaced left-turn (DLT), and the diverging diamond interchange (DDI).

The safety benefits of innovative intersection designs come from reducing the number and severity of intersection conflict points. In comparison to conventional intersections, designs such as the RCUT and MUT reduce the total number of conflict points and particularly the more severe crossing conflicts. By reducing the number and severity of conflict points, innovative intersections greatly reduce the risk of severe injury. Many innovative intersection designs are also demonstrating advantages for pedestrians and bicyclists. Several U.S. transportation agencies have implemented Intersection Control Evaluation (ICE) policies and procedures to evaluate and screen an expanded array of intersection choices with specific goals for implementing safer and more operationally efficient choices for a variety of user groups. The FHWA supports and encourages the advancement of ICE as a data-driven, performance-based framework and approach to objectively screen alternatives and identify an optimal geometric and control solution for an intersection.

With approximately one-fourth of all U.S. traffic fatalities occurring at intersections, the FHWA has been promoting the implementation of safer designs as widely and routinely as possible. To assist in these efforts, the FHWA has developed numerous technical guides as well as outreach and education materials. Because innovative intersections generally look or function differently from conventional designs, public outreach and education is critical. The FHWA guides place emphasis on strategies to design innovative intersections to benefit pedestrians, bicyclists and transit users.

Arguably the greatest success in advancing innovative designs has been the proliferation of the DDI. The DDI improves safety and operations of the intersections at a diamond-style interchange by reducing the number of conflict points and by allowing more efficient two-phased signalized intersections at the ramp terminals with the interchange crossroad. This is accomplished through geometry and channelization that transposes traffic direction on the crossroad between the ramp terminals, thus allowing a left-turn movement without the need for an exclusive signal phase. The result is more efficient traffic signalization schemes that allow more vehicle throughput along the crossroad with fewer lanes needed. Since the first DDI in the U.S. opened to traffic in 2009 more than 100 DDIs have been constructed within the US and many more are currently in design and study.

INTERSECTION CONTROL EVALUATION (ICE) PROCESS

ICE is defined by the FHWA as a data-driven, performance-based framework and approach used to objectively screen alternatives and identify an optimal geometric and control solution for an intersection [32]. The development of ICE policies and procedures have linked efforts to advance implementation of innovative intersection designs with the application of PBPD to intersection projects. ICE is intended to first inform project scoping and planning decisions that take place very early in the project development process, and then subsequently guide the alternative selection process that occurs later with a transparent performance-based approach.

Specifically, ICE consists of a policy and process that is developed and adopted by a state or local transportation agency that requires consistent, objective and quantifiable consideration of a full array of intersection design alternatives of varying geometry and traffic control, including both conventional and innovative designs. The policy component establishes that the full array of alternatives *must* be considered for any intersection project that meets the criteria. The process component lays out a consistent series of steps and procedures that must be followed, so that each intersection project is considering the alternatives in highly similar ways using identical performance metrics. An added and intentional feature of ICE is that the process requires the decisions and rationales be documented, providing greater transparency about how and why a preferred alternative is ultimately selected.

Conducting an ICE involves a 2-stage process. Stage 1 is a high-level, project scoping and planning exercise, intended to vet the complete array of intersection design and control options and narrow the list of possible alternatives to a small number, often as few as 2 or 3. Stage 2 is conducted as part of the preliminary engineering phase of project development, where more detailed design is developed for each alternative, and various safety and operational analyses, as well as environmental and benefit-cost considerations, are conducted in greater depth for the project users (e.g. automobiles, trucks, transit, pedestrians, bicyclists). Upon completing Stage 2, a preferred alternative is typically evident.

The performance metrics can vary based on the policy needs of the state or local agency. All the ICE policies in place as of October 2019 include metrics for safety performance (based on predicted or expected crash analysis) and operational performance (measures of effectiveness such as volume-to-capacity ratio, average delay, queuing, travel time reliability, and level of service). Other metrics varied based on what information would typically be available at the different stages that would facilitate meaningful analysis, but this list includes pedestrian and bicycle considerations, right-of-way impacts, capital costs, and freight movement.

In the U.S., as of October 2019, there are nine state departments of transportation with active ICE policies (Minnesota, Wisconsin, California, Indiana, Washington, Georgia, Florida, Pennsylvania, Nevada), four additional states with ICE policies nearing completion (Virginia, Arizona, Louisiana and Colorado), and many States actively developing or showing interest in ICE policies.

As more states adopt ICE policies and procedures, there is also a growing number of ICE tools with which the process can be efficiently completed. Through the Highway Safety Manual Implementation Pooled Fund Study, and in partnership with the FHWA, the Safety Performance for Intersection Control Evaluation (SPICE) tool [33] was developed to facilitate a Stage 1 safety analysis. This Microsoft Excel-based spreadsheet tool is a faithful implementation of the Highway Safety Manual, 1st Edition, using safety performance functions and crash modification factors to characterize relative safety performance among the various intersection options. The FHWA Primer on ICE [32] lists other tools available to support ICE, including several developed to meet specific states' needs.

EMERGING TECHNICAL AREAS

In the U.S., the continued advancement of the use of three-dimensional (3D) design software in the project design phase has further enabled the use of automated machine guidance (AMG) on construction projects. Designers using 3D software packages can visualize the geometric improvements and identify potential issues and conflicts early in the design process. In addition, rather than providing staking reports in the contract, a refined 3D terrain model can be provided. During construction, the need for survey staking during the earthwork and fine grading operations can be minimized thereby increasing project safety. Also, if field conditions dictate the need to make changes to the design, then adjustments can be generated by the designer and transferred back to the contractor without regenerating plan sheets. The use of 3D design software in conjunction with AMG are transforming the way projects are designed and constructed in the U.S.

The concept of Building Information Modeling (BIM) is a collaborative work method for structuring, managing, and using data and information about transportation assets throughout their lifecycle (from planning, design, and construction to asset management and maintenance) to maximize the benefit of the data collected at various stages of a project, resulting in cost savings and efficiencies. BIM provides critical information to anyone who needs it, when they need it. Once built, a BIM model becomes a virtual and accurate collection of transportation infrastructure asset data used for system-wide decision-making.

The focus on a project's life cycle recognizes that digital data and models that are created in project design can be used to more efficiently and safely build projects during project construction. Using the data from construction to develop digital as-builts provides key information as agencies maintain those assets over time. The FHWA efforts are on promoting an open exchange of data so that the investments made during project development and construction can be realized throughout the project lifecycle.

INTEGRATING HUMAN FACTORS INTO DESIGN

Human factors pertain to the capabilities and limitations of human beings as vehicle drivers, bicyclists, motorcyclists, pedestrians, and other roadway users. Applying the knowledge of human factors is a critical component for safe and efficient road design. Highway agencies and design practitioners are increasingly applying human factors principles in the design decision-making process. Knowledge about how certain user groups are likely to respond to given conditions can help designers reduce the risk of user error, or at least minimize the consequences of an error should one occur.

An important new focus area for the FHWA Human Factors Program is research into connected and distributed multi-modal simulation. Connected simulation technology offers enormous potential to study interactions between drivers, pedestrians, and bicyclists and assess the impact of new technologies on safety and mobility. Two FHWA Exploratory Advanced Research (EAR) sponsored projects are conducting research and development of an innovative mixed-mode connected driving, pedestrian, and bicycling simulator system. Graphical avatars that represent the live movements of drivers, bicyclists, and pedestrians will be incorporated into the simulation and new methods of scenario control techniques will be developed to conduct full-fledged experiments examining the interactions between these road users.

Virtual Reality (VR) is an immersive technology which users navigate within a rich 3D environment. VR technology offers the opportunity to study vulnerable road user behavior without the potential risk on on-road, real-world conflicts with vehicles. At present, the FHWA Human Factors Team is exploring the potential benefits of Vehicle-to-Everything Communications [34] applications for bicyclists. Bicyclists navigate a virtual environment and encounter several hazards (e.g., red light runner, car overtaking bicyclist) and accompanying alerts. The efforts are being performed in conjunction (via a CRADA, or Cooperative Research and Development Agreement) with a Small Business Innovation Research funded project, with Charles River Analytics. Data from approximately 35 people have been collected and a preliminary report with results from 100 cyclists is expected to be completed soon. [38]

The goal of these projects is to transform simulation technology to enable studies of how the expectations, anticipations, and responses of all road users are influenced by futuristic vehicle technologies, new infrastructure designs, and by each other. We hope to use the research results of these EAR projects to help virtually connect our Highway Driving Simulation, VR Bike simulator, and VR pedestrian simulator into a connected simulation virtual environment.

Until very recently, highway safety research has primarily relied on studies employing historical crash data, as well as simulators and small, limited time field studies. To complement these efforts, a large naturalistic driving study [39] was designed and conducted over a three year period (2010-2013) in six states (Florida, Indiana, North Carolina, New York, Pennsylvania, Washington) to provide the research community with a resource to better understand driver behavior and how drivers are interacting with the vehicle, mobile devices, traffic, vulnerable road users (bicyclists /pedestrian), and road characteristics and features.

The Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) data and its companion database – the SHRP2 Roadway Information Database (RID) [36] became available for use beginning mid-2015. The NDS provides real-world information regarding driving behavior and vehicle performance, and the RID provides roadway features and characteristics, historical crash, traffic, weather, and 511 information. These databases are linkable allowing researchers to investigate driver behavior in association with actual roadway characteristics and driving conditions.

Since these data were implemented in 2015, over 300 research projects have been initiated including, but certainly not limited to, on-going FHWA sponsored projects which are addressing a variety of issues including: interactions between drivers and pedestrians at signalized intersections; evaluating near-term safety impacts of speed limit increases; recommendations for work zone safety countermeasures; assessing the impacts of roadway lighting in reducing crashes; and investigating driver performance and behavior in adverse weather conditions.

Candidate research projects being developed under the U.S. Department of Transportation's Transportation Pooled Fund Program [37] include: incorporating the impacts of driver distraction into highway design and traffic engineering; validation of performance-based design; investigating how multimodal environments affect multitasking driving behaviors; reducing information overload for freeway guide sign at complex interchanges: verification and calibration of microscopic traffic simulation; developing speed crash modification factors; effects of varied route choice behavior on road networks; effects of weather, traffic, and roadway infrastructure on interstate secondary crashes; and development of facility specific drive cycles for emission modeling.

CONNECTED AND AUTONOMOUS VEHICLES

Automated vehicles (AVs) have the potential to transform the U.S. roadways. They could increase vehicle safety, improve transportation system efficiency, and enhance mobility for many people who may be unable to drive today. Although they offer a wide range of benefits, they may also introduce uncertainty for the agencies responsible for the planning, design, construction, operation, and maintenance of the U.S. roadway infrastructure.

In June 2018, the FHWA initiated the National Dialogue on Highway Automation which consisted of a series of meetings held across the country to facilitate information sharing and engage the transportation community in a conversation on how to safely and efficiently integrate automated vehicles into the road network [38]. A diverse group of stakeholders provided input on key issues regarding automation. This input will help inform future and existing FHWA research, policies, and programs. The FHWA is focused on the following objectives relating to how CAV technology will impact transportation programs:

- Understand the potential impacts of automated vehicles on national highway infrastructure, safety, policy, operations, and planning.
- Prioritize actions to inform the integration of automation into existing FHWA programs and policies.
- Create models for sustained information sharing among public agencies and the private sector. Support newly developed partnerships among these organizations and define a clear path of communication among FHWA and automation stakeholders.
- Gather insights from infrastructure owners and operators (IOOs) and inform the development of possible technical guidance actions at the Federal level.
- Validate or provide direction into highway research priorities and roles among the FHWA, national partner organizations, industry, and State and local governments.
- Develop an engaged national community or coalition on integrating automated vehicles into the roadway system, using inputs from States, local governments, industry, and associations, alongside the FHWA and other Federal agencies.

Existing infrastructure standards do not necessarily reflect the introduction of automated vehicles. As a result, they may require updates to accommodate new infrastructure requirements needed for AVs to operate safely and efficiently on public roads. Notably, the importance of reviewing infrastructure standards, such as the MUTCD, to assess needed updates. Given the rapid pace of AV technology development, the standards development process may need to accelerate to keep pace with AV technology.

The nature of automated truck platooning applications may introduce different challenges. Agencies are looking at how load issues of truck platooning may affect bridges, as they were not initially designed with automated platoons in mind, as well as how truck platooning may affect the harmonics of a bridge.

The safety of all users must remain a primary focus as AVs are widely introduced onto public roads and accordingly, the safety mission of state and local transportation agencies and the need to balance potential safety benefits offered by AVs with any potential risks. Automated vehicles will need to be able to interact safely with human drivers, bicyclists, pedestrians, and all road users. Additionally, the vehicle fleet will likely remain diverse in terms of the mix of automated and non-automated vehicles in the near future. As a result, AVs should have the capability to interpret the intent and movements of human drivers and other road users. Human drivers and vulnerable road users often use nonverbal cues to communicate (e.g., hand signals). The ability of AVs to interact safely with all road users is critical for public safety and acceptance.

The specific infrastructure requirements for enabling AVs remain unclear. Some developers of AV technology have suggested that changes in the roadway design, condition, and level of maintenance can enable operations of AVs. Yet, other AV technology developers suggest that infrastructure changes are not needed because they are designing AVs to operate on the roadway infrastructure as it exists today. IOOs seek greater clarity, not only on the infrastructure requirements and conditions needed to enable AV technology, but also the funding implications that may result from any infrastructure improvements. New funding mechanisms may need to be explored as AV infrastructure requirements become better understood.

CONCLUSION

Transportation professionals responsible for geometric design are utilizing new technology, analysis tools, and approaches to meet priorities in the United States. The progress being made among the technologies described herein will help transportation agencies improve performance, mobility, and safety needs for projects and systems. A key challenge facing the U.S. involves how to safely accommodate our most vulnerable users as vehicular and non-motorized activity is expected to continue to increase.

Reducing fatalities and serious injuries is the top priority for transportation agencies. Changes in geometric design toward a performance-based approach enables a clearer understanding how design may influence safety performance which is a critical factor when prioritizing project performance goals. Another critical factor where progress is being made is the interaction between the human factors and design as it relates to performance. Nationally, we must continue to embrace flexibility and innovation to leverage our increasing understanding of how our decisions affect performance to deliver performance in a cost-effective manner and meet transportation priorities in the U.S.

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References

[1] U.S. Department of Transportation, Federal Highway Administration, "MAP-21 - Moving Ahead for Progress in the 21st Century," 2018. [Online]. Available: https://www.fhwa.dot.gov/map21/. [Accessed 11 November 2019].

[2] U.S. Department of Transportation, Federal Highway Administration, "Fixing America's Surface Transportation Act or "FAST Act"," 2017. [Online]. Available: https://www.fhwa.dot.gov/fastact/. [Accessed 11 November 2019].

[3] American Association of State Highway Transportation Officials, "AASHTO Standing Committee on Highways Administrative Resolution entitled “Direction on Flexibility in Design Standards”," AASHTO, 2016.

[4] Transportation Research Board, "Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Analysis," Transportation Research Board, 2016.

[5] U.S. Department of Transportation, Federal Highway Administration, "Interactive Highway Safety Design Model (IHSDM)," 2019. [Online]. Available: https://highways.dot.gov/safety/interactive-highway-safety-design-model/interactive-highway-safety-design-model-ihsdm.

[6] World Road Association (PIARC), "Road Safety Manual," World Road Association (PIARC), 2019.

[7] Transportation Research Board, "Planning for a Comprehensive Update and Restructuring of AASHTO’s A Policy on Geometric Design of Highways and Streets (8th Edition)," 2019. [Online]. Available: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4472. [Accessed 7 November 2019].

[8] U.S. Department of Transportation, Bureau of Transportation Statistics, "Transportation Statistics Annual Report 2018," 1 December 2018. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/37861. [Accessed 26 September 2019].

[9] U.S. Department of Transportation, National Highway Traffic Safety Administration, "2018 Fatal Motor Vehicle Crashes: Overview," October 2019. [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812826. [Accessed 11 November 2019].

[10] U.S. Department of Transportation, Federal Highway Administration, "United States Department of Transportation Policy Statement on Bicycle and Pedestrian Accommodation Regulations and Recommendations," 2010. [Online]. Available: https://www.fhwa.dot.gov/environment/bicycle_pedestrian/guidance/policy_accom.cfm. [Accessed 11 November 2019].

[11] U.S. Department of Transportation, Federal Highway Administration, "Bicycle and Pedestrian Facility Design Flexibility," 20 August 2013. [Online]. Available:

https://www.fhwa.dot.gov/environment/bicycle_pedestrian/guidance/design_flexibility.cfm. [Accessed 11 November 2019].

[12] U.S. Department of Transportation, Federal Highway Administration, "Bicycle Facilities and the Manual on Uniform Traffic Control Devices," 7 July 2017. [Online]. Available: https://www.fhwa.dot.gov/environment/bicycle_pedestrian/guidance/mutcd/. [Accessed 11 November 2019].

[13] U.S. Department of Transportation, Federal Highway Administration, "Separated Bike Lane Planning and Design Guide," 2015.

[14] Massachusetts Department of Transportation, "Separated Bike Lane Planning & Design Guide," 2015. [Online]. Available: https://www.mass.gov/lists/separated-bike-lane-planning-design-guide. [Accessed 11 November 2019].

[15] U.S. Department of Transportation, "Pedestrian and Bicycle Information Center - Safety," [Online]. Available: http://pedbikeinfo.org/factsfigures/facts_safety.cfm. [Accessed 11 November 2019].

[16] U.S. Department of Transportation, Federal Highway Administration, "Center for Accelerating Innovation - Every Day Counts," [Online]. Available: https://www.fhwa.dot.gov/innovation/everydaycounts/. [Accessed 11 November 2019].

[17] U.S. Department of Transportation, Federal Highway Administration, "Safe Transportation for Every Pedestrian (STEP)," 13 November 2019. [Online]. Available: https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/step2.cfm. [Accessed 17 November 2019].

[18] U.S. Department of Transportation, Federal Highway Administration, "Guidebook for Measuring Multimodal Network Connectivity," 2018.

[19] U.S. Department of Transportation, Federal Highway Administration, "Bikeway Selection Guide," 2019.

[20] National Association of City Transportation Officials, "Urban Bikeway Design Guide - Don't Give Up at the Intersection," May 2019. [Online]. Available: https://nacto.org/publication/urban-bikeway-design-guide/dont-give-up-at-the-intersection/. [Accessed 19 November 2019].

[21] U.S. Department of Transportation, Federal Highway Administration, "Bicycle and Pedestrian Program Publications," 2019. [Online]. Available: https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/. [Accessed 11 November 2019].

[22] U.S. Department of Transportation, Federal Highway Administration, "Pedestrian and Bicycle Information Center," 2019. [Online]. Available: http://www.pedbikeinfo.org/topics/micromobility.cfm. [Accessed 11 November 2019].

[23] United States Access Board, "Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way," 26 July 2011. [Online]. Available: https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/proposed-rights-of-way-guidelines. [Accessed 2019 11 November].

[24] United States Access Board, "Supplemental Notice of Proposed Rulemaking," 13 February 2013. [Online]. Available: https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/proposed-rights-of-way-guidelines. [Accessed 11 November 2019].

[25] U.S. Department of Transportation, Federal Highway Administration, "Accessible Shared Streets: Notable Practices and Considerations for Accommodating Pedestrians with Vision Disabilities," October 2017. [Online]. Available: https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/accessible_shared_streets/index.cfm. [Accessed 11 November 2019].

[26] Transportation Research Board, "TCRB B-46 Tactile Wayfinding in Transportation Settings for Travelers Who Are Blind or Visually Impaired," 2019. [Online]. Available: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4513. [Accessed 11 November 2019].

[27] American Association of State Highway Transportation Officials, "Highway Safety Manual," [Online]. Available: http://www.highwaysafetymanual.org/Pages/About.aspx. [Accessed 11 November 2019].

[28] U.S. Department of Transporatation, Federal Highway Administration, "Roadway Safety Data Program - Model Inventory of Roadway Elements (MIRE)," [Online]. Available: https://safety.fhwa.dot.gov/rsdp/mire.aspx. [Accessed 20 November 2019].

[29] Transportation Research Board (TRB), "NCHRP 17-71 - Proposed AASHTO Highway Safety Manual, Second Edition," Kittelson & Associates, Inc (KAI), 12 October 2015. [Online]. Available: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3874. [Accessed 30 July 2019].

[30] U.S. Department of Transportation, Federal Highway Adminstration, "Performance Based Practical Design," 2017. [Online]. Available: https://www.fhwa.dot.gov/design/pbpd/. [Accessed 20 November 2019].

[31] K. Z. R. B. S. C. B. B. Kay Fitzpatrick, "The Texas A&M Transportation Institute," March 2007. [Online]. Available: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-5544-1.pdf. [Accessed 11 November 2019].

[32] United States Department of Transportation, Federal Highway Administration, "Active Transportation and Demand Management," [Online]. Available: https://ops.fhwa.dot.gov/atdm/index.htm. [Accessed 1 December 2019].

[33] United States Department of Transportation, Federal Highway Administration, "Use of Freeway Shoulders for Travel — Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy," [Online]. Available: https://ops.fhwa.dot.gov/publications/fhwahop15023/index.htm. [Accessed 2 December 2019].

[34] U.S. Department of Transporation, Federal Highway Administration, "Every Day Counts - 2: Intersection and Interchange Geometrics," 12 February 2018. [Online]. Available: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/geometrics.cfm. [Accessed 18 November 2019].

[35] U.S. Department of Transportation, Federal Highway Administration, "Primer on Intersection Control Evaluation (ICE)," 2018. [Online]. Available: https://safety.fhwa.dot.gov/intersection/ice/fhwasa18076/. [Accessed 11 November 2019].

[36] U.S. Department of Transportation, Federal Highway Administration, "Resources for Countermeasure Selection: Safety Performance for Intersection Control Evaluation (SPICE)," 2018. [Online]. Available: http://www.cmfclearinghouse.org/resources_selection.cfm. [Accessed 19 November 2019].

[37] U.S. Department of Transportation, "Vehicle-to-Everything (V2X) Communications," 14 June 2019. [Online]. Available: https://www.transportation.gov/v2x. [Accessed 2019 November 2019].

[38] United States Small Business Administration, "Multimodal Alerting Interface with Networked Short-range Transmissions (MAIN-ST)," 2016. [Online]. Available: https://www.sbir.gov/sbirsearch/detail/1156997. [Accessed 2019 1 December].

[39] Transportation Research Board, "Strategic Highway Research Program (SHRP2) Naturalistic Driving Study," 2019. [Online]. Available: https://insight.shrp2nds.us/documents/shrp2_background.pdf. [Accessed 11 November 2019].

[40] Iowa State University, Center for Tranportation Research and Education (CTRE), "SHRP2 - Roadway Information Database," 2019. [Online]. Available: https://ctre.iastate.edu/shrp2-rid/. [Accessed 11 November 2019].

[41] U.S. Department of Transportation, "Transportation Pooled Fund Program, SHRP2 Naturalistic Driving Study Pooled Fund: Advancing Implementable Solutions," 2019. [Online]. Available: https://www.pooledfund.org/Details/Study/613. [Accessed 11 November 2019].

[42] U.S. Department of Transportation, Federal Highway Administration, "National Dialogue on Highway Automation," 28 October 2019. [Online]. Available: https://ops.fhwa.dot.gov/automationdialogue/. [Accessed 11 November 2019].

[43] U.S. Department of Transportation, National Highway Traffic Safety Administration, "Bicyclist and Pedestrian Safety," 5 March 2019. [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/14046-pedestrian_bicyclist_safety_resources_030519_v2_tag.pdf. [Accessed 11 November 2019].

[44] United States Department of Transportation, Federal Highway Administration, "Managed Lanes," [Online]. [Accessed 1 December 2019].