IMPROVING SAFETY, MOBILITY AND LIVABILITY WITH BETTER GEOMETRIC DESIGN PRACTICES

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ABSTRACT

When it comes to transportation, the United States is compelled to do more with less because of financial and environmental limitations. As a result, U.S. geometric design engineers are squeezing every bit of capacity and safety out of the country's highway system by using innovative new designs, approaches, practices and policies.

This paper describes some of the key U.S. geometric design developments that have emerged over the past five years. This paper also examines the anticipated impacts of these new developments on the transportation community and how they are expected to be documented in various U.S. manuals and guide books.

Some advancements occurring in the United States include the formal inclusion of roundabouts and other innovative intersection configurations in national policy. Also, U.S. policies are adapting to fully exercise flexibility for sustainable and environmentally sensitive approaches in design to meet the numerous and diverse needs of U.S. society. New and better tools have been developed for safety and operational analysis, and to improve the decision-making process.

This paper also documents where the innovation is taking shape to address the many challenges and concerns in the country's current transportation environment. Practices such as managed lanes, innovative intersections and higher-order analysis tools for safety and operations are only beginning to make a difference today. Through these future design progressions many of the country's more complicated challenges will be met and overcome.

Introduction

As geometric design steadily evolves in the United States, new and improved design approaches, practices and policies are researched, investigated, and then documented in various national guides and manuals. This paper describes some of the key U.S. geometric design developments that have emerged over the past five years. This paper also examines the anticipated impacts of these new developments on the transportation community and how they are expected to be documented in various U.S. manuals and guide books.

Some advancements occurring in the United States include the formal inclusion of roundabouts and other innovative intersection configurations in national policy. Also, U.S. policies are adapting to fully exercise flexibility for sustainable and "context-sensitive" approaches in design to meet the numerous and diverse needs of U.S. society. Context-sensitive solutions (CSS) are collaborative, interdisciplinary strategies that seek to integrate a transportation facility seamlessly into its environment while meeting safety and mobility goals.

As these sustainable and context-sensitive approaches are applied, risk- and performance-based design practices are becoming more prevalent. Risk- and performance-based design is a process in which variances from established design standards are evaluated for a specific project location, giving consideration to benefits, impacts, and risks of incorporating the variance into the design. A risk-based approach considers the safety and performance tradeoffs associated with the use of minimum or lower geometric criteria and standards. Supporting guidance on evaluating design exceptions to FHWA's 13 controlling criteria is provided in the FHWA *Mitigation Strategies for Design Exceptions (2007)*.

New approaches will be included in the forthcoming *Highway Safety Manual* published by the American Association of State and Transportation Officials (AASHTO), a national non-profit association that advocates for transportation-related policies and provides technical services to states[i] and local transportation agencies. These new approaches are providing designers with more options and better analysis tools to ensure that these new approaches do not compromise the integrity of projects when balancing competing interests or needs.

This paper also identifies where advancements in fundamental knowledge in specific topic areas is aiding the United States in making better design decisions. For example, information on human factors is playing a bigger role in the design decision-making process. Human factors, as it pertains to geometric design, involve the study of the capabilities and limitations of the user and then applying that knowledge to the road system.

Evolution is a key theme for design in the United States. Evolution, as it relates to transportation, involves continuously researching and adopting the most successful design practices that arise, thereby supplanting certain outmoded practices that yield less than optimum results. It is moving the country to adjust to ever-changing needs of diverse users and shifting demands of a dynamic transportation environment. Increases in pedestrians, bicyclists, and older drivers on America's roadways, as well as more traffic congestion and aging infrastructure, are forcing transportation agencies to adapt their processes and design facilities to improve safety and mobility for all users, not just those who drive automobiles. All of this is being accomplished within limited funding and other constrained resources.

Beyond these developments, actions are currently taking place in the United States that will bring significant changes in future design practices. This paper documents where the innovation is taking shape to address the many challenges and concerns in the country's current transportation environment. Practices such as managed lanes, innovative intersections and higher-order analysis tools for safety and operations are only beginning to make a difference today. Designers are taking advantage of new tools and technologies to improve the quality and effectiveness of transportation facilities. As these methods become more integrated into standard practice, their effects on design policy and standards will become apparent in the future. Through these future design progressions many of the country's more complicated challenges will be met and overcome.

Changing Design Practices

In recent years, State departments of transportation (DOTs) and professional engineers have sometimes met resistance from the public and community interests, particularly when highway projects are perceived as having clear and measurable adverse impacts on the communities through which they pass. With the expanding role of public involvement and the push to address concerns beyond engineering in highway projects come added responsibilities and considerations in geometric design.

Today, highway designers face many complex tradeoffs. A quality design must satisfy the needs of a variety of users, and must balance cost, safety, and mobility with historical, cultural, and environmental impacts. Quality design increasingly requires more analysis than simply assembling elements from the available tables, charts, and equations of criteria outlined in design manuals. Highway engineers and designers work within complex relationships that allow an acceptable level of flexibility in roadway designs that require managing the related risks. Over the past decade – through policies, guidelines, conferences, training, and new partnerships – FHWA and State DOTs have been bridging knowledge gaps and enabling engineers to design with flexibility and employ context-sensitive approaches with greater confidence and regularity.

Context-Sensitive Solutions and Livability

DOTs use CSS and design flexibility as tools to contribute to creating more livable communities. FHWA defines livable communities as "places where the young and old can walk, bike, and play together; where historic neighborhoods are preserved; where farms, forests, and other green spaces are protected; where parents spend less time in traffic and more time with their children, spouses, and neighbors; where older neighborhoods can thrive once again. A livable community has safe streets, good schools, and public and private spaces that help foster a spirit of community."

U.S. Transportation Secretary Ray LaHood has identified community livability as a top priority. In June 2009, LaHood entered the U.S. Department of Transportation (USDOT) into a partnership with the U.S. Department of Housing and Urban Development and the U.S.

Environmental Protection Agency to implement six livability principles that the three agencies will use to coordinate Federal investments in transportation, housing, and environmental protection. The partnership aims to help U.S. families in all communities—rural, suburban, and urban—gain better access to affordable housing, more transportation options, and lower transportation costs. The three agencies will work together to achieve these housing and transportation goals while simultaneously protecting the environment, promoting equitable development, and helping to address the challenges of climate change.

Flexibility in Design

Since its publication in 2004, the AASHTO *A Guide for Achieving Flexibility in Highway Design* has been widely adopted and stresses the need for knowledgeable, experienced highway engineers if the execution of a context-sensitive project is to be successful. Flexible thinking is about making informed choices. Simple application of the highest or lowest value within a range of design values without explicit consideration of context might not always lead to the most informed choices that best meet a project's objectives. The guide stresses the importance of having skilled professionals.

In another example, Massachusetts updated its project development manual in 2006 to provide designers and decision-makers a framework for incorporating context-sensitive design and multimodal elements into transportation improvement projects. Context-sensitive design is one of three guiding principles for the new design guide, along with multimodal consideration and a clear project development process. MassHighway's manual expands the flexibility afforded designers in the selection of design speeds. It encourages engineers to consider the roadway context, implications for the safety and comfort of pedestrians and bicyclists, and implications for regional mobility. Specifically, flexibility is provided to allow design speeds that are lower, the same, or higher than existing operating speeds, depending on the project's purpose.

Safety and Operational Analysis during Geometric Design

Recognizing the importance of integrating safety considerations into a project development process, AASHTO and the Transportation Research Board (TRB), a national organization that promotes transportation innovations through research, have jointly developed the *Highway Safety Manual* (HSM). The HSM contains new tools for quantitative and substantive estimation of safety impacts of design decisions.[ii] The TRB led the effort to develop this methodology and approach, and AASHTO has accepted the new manual by ballot. The HSM advances analytical prediction tools to improve roadway planning, design, operations, and maintenance decisions based on explicit consideration of their safety consequences.

The models in the HSM provide analytical predictions based on research that may be used by practitioners to compare the expected crash frequency and severity of design alternatives. This effort is intended to encourage evidence-based decision-making and innovative approaches to improving safety. The first edition will have limitations due to the infancy of the safety-prediction modeling. However, the HSM is a tool that will grow and evolve over subsequent editions.

The FHWA is leading parallel activities in supporting this HSM work. These activities include the software development of SafetyAnalyst, Interactive Highway Safety Design Model, and a Web-based Crash Modification Factors Clearinghouse. Additional efforts leading to the development of new safety predictive models for freeways and interchanges are also currently being conducted by the TRB.

Risk- and Performance-based Approach

To maximize the available funding and functionality of existing infrastructure, agencies and designers are implementing a risk-based approach to geometric design. As mentioned earlier, this approach considers the safety and performance tradeoffs associated with using minimum or alternative geometric criteria and standards. The fundamental question in a risk-based approach is this: Can the purpose and need of a project be addressed through a minimal design that achieves the desired level of safety and operational performance, but at a level of risk an agency is willing to accept?

This "back-to-basics" approach – called "practical design" by many practitioners – challenges designers to be creative, allowing them to engineer a solution that is consistent with the principles of the traditional design criteria but allows the designer maximum flexibility to consider the context and interaction of various design decisions, the associated impacts to safety and operations, and the cost-effectiveness and risk associated with those decisions.

This approach identifies the risks related to a design, followed by evaluating and mitigating for those risks. No facility will ever be designed risk-free. But this approach to geometric design encourages designers to weigh and manage the risks inherent to operating a road network compared to a strictly standards-based approach. The transportation agency can decide what risks, if accepted, can be turned into rewards, such as reduced cost and time, minimized environmental impact, reduced right of way, and preserving community assets.

There are several recent notable examples of the performance and risk-based approach to design. One is AASHTO's *Guidelines for Geometric Design of Very Low-Volume Local Roads (2001)*, which acknowledges the lower risk associated with very low-volume (400 vehicles per day or less) facilities and provides criteria to achieve an appropriate level of performance. The guide is even more important considering that most of the U.S. road network is made up of low-volume, rural two-lane roads that are unlikely to receive a high priority for future major investment. Therefore, the design recommendations set forth in this guide allow scarce resources to be stretched further for correction of identified safety problems instead of full reconstruction to the criteria established for higher volume facilities.

A second risk-based publication is the FHWA *Mitigation Strategies for Design Exceptions (2007)*, which examines the associated safety and operational tradeoffs of design elements that do not fall within the established acceptable range of values in design criteria and standards. Similarly, the upcoming first edition of the AASHTO *Highway Safety Manual*, expected to be published in 2010, is intended to provide practitioners with a resource to quantify and predict the safety performance of the various elements to assist in decision-making throughout the project development process.

To maximize performance of the overall system, designs are based on achieving performance-based goals and objectives. Many State DOTs are adopting performance criteria, such as the Virginia DOT's Dashboard. Performance-based design analysis is an emerging approach for geometric design decision-making at the project level. The future of geometric design will need to emphasize performance criteria and measures, and for all modes of transportation. The SHRP 2 Report S3-CO2-RR *Performance Measurement Framework for Highway Capacity Decision Making* describes specific factors considered in design, both transportation and non-transportation related.

Another aspect of performance- and risk-based design deals with whether a proposed design can adequately meet the needs of its users. In order to craft designs that truly consider the needs of all users, while meeting the safety expectations of the public, designers in the United States are employing new techniques and tools to enhance safety and operation of highways, roads and streets. Notable among these new techniques and tools are the application of human factors guidelines, the implementation of road safety audits (RSAs), and public policy-oriented approaches that seek to design and construct facilities that meet the needs of all users, not just those driving automobiles.

Human Factors

Human factors are important considerations in design decision-making. Human factors pertain to the capabilities and limitations of human beings as vehicle drivers, bicyclists and pedestrians, and then applying that knowledge to the road system. Highway agencies and design practitioners are increasingly applying this approach and criteria based on better understanding of user behavior. Armed with knowledge about how a given type of user is likely to respond, road designers can make better decisions about how to reduce the likelihood of user error, or at least minimize the consequences of an error should one occur.

The Federal Highway Administration can estimate human capabilities and limitations on various highway designs using this simulator at the agency's Turner-Fairbank Highway Research Center near Washington D.C.

Human factors issues related to a variety of geometric designs are being explored and documented in guidance. The National Cooperative Highway Research Program (NCHRP) Reports 600A and B, *Human Factors Guidelines for Road Systems, Collections A and B* describe human factors principles and findings for consideration by highway designers and traffic engineers. The reports help design engineers to more effectively consider the roadway user's capabilities and limitations in the design and operation of highway facilities. Additional chapters will be developed under NCHRP Project 17-41 and are expected in late 2010. The Human Factors Guide (HFG) is a resource document for highway designers, traffic engineers, and other practitioners and provides factual information and insight on road users' characteristics to facilitate safe roadway design and operational decisions. The impetus behind the HFG was the recognition that current design references have limitations in providing the practitioner with adequate guidance for incorporating road user needs and capabilities when dealing with design and operational issues.

Accommodating left turns at intersections is an example of how human factors have directly influenced the evolution of highway geometric design. Crashes involving left turns can be particularly severe. Left turns also are a particularly challenging maneuver for older drivers to execute since this group generally has more difficulty judging safe gaps and approaching vehicles speeds. Based on these understandings the design community has developed innovative left-turn concepts that address safety concerns while not posing significantly adverse impacts to intersection operation. Types of innovative left-turn designs that have resulted from a human-factors-oriented approach include:

- **Angled Positive Offset Left Turns –** By slightly modifying the design of conventional left-turn lanes, a positive offset between opposing left-turn vehicles can be achieved and vehicle can be oriented in a way that facilitates enhanced sight distance, allowing drivers to better judge approaching vehicle gaps.
- **Reverse Jug Handle Left Turns –** One of the various forms of the New Jersey jug handle, the reverse jug handle is essentially a small loop located at the far side of an intersection, where traffic desiring to turn left instead passes through the intersection and makes two rights.
- **Median U-Turn Left Turns –** This treatment is also discussed later in the section on innovative intersection and interchange geometrics

Road Safety Audits (RSAs)

Another important design development in the United States is the implementation of road safety audits (RSAs), which have continued briskly in the United States since the publication of the 2004 *NCHRP Synthesis 336*, a study that examined the practices and benefits of RSAs worldwide.

This multidisciplinary team conducts a road safety audit (RSA), which has become an effective tool in the United States for evaluating a roadway's safety performance.

An RSA is a formal examination of the safety performance of an existing or future road or intersection by an independent, interdisciplinary audit team. RSAs are conducted by qualified professionals who are not involved in the project. FHWA has continued to advance RSAs as a best practice for enhancing project safety. RSAs have become a popular tool for evaluating the safety performance of in-service roads and are often used by the safety community to provide independent, multidisciplinary review of a road that requires some attention due to public inquiries, political interest or increased crashes.

While the use of RSAs on existing roads has been widely embraced, RSAs are also done proactively before safety problems develop. Designers are using the RSA as tool to create safer new roadways. By identifying and mitigating for potential safety issues before a facility is constructed, the resulting safety performance is enhanced from the very first day of operation. Over the past two years, and due largely to the FHWA Road Safety Audits Case Study initiative, more highway departments have begun conducting RSAs during the design stage of projects that have high-profile or high-cost, such as major corridor projects or freeway interchanges in metropolitan areas.

The latest development in incorporating RSAs into the design process has occurred mostly over the past year. The FHWA has worked with the U.S. value engineering (VE) community to explore how RSAs and VE studies can be integrated or coordinated in a way that ensures safety is appropriately considered during the value analysis process. Value engineering is a review or analysis of a proposed design to identify and recommend alternative solutions that reduce life-cycle costs while adding value to the facility.

At the 2009 AASHTO Value Engineering Conference, the FHWA sponsored a half-day workshop to explore what an integrated VE/RSA effort would look like. Feedback from the VE community has been positive, and based on the strong interest in developing guidelines on how to successfully integrate the two practices, the FHWA is poised to begin developing case studies and guidelines.

Non-Motorized Facilities

Although much has been done over the past decade to increase awareness of pedestrian and bicycle safety and design issues, only in recent years have actual infrastructure improvements that benefit these users become a more common design element. Some experts attribute the increased interest in bicycling and walking to high fuel prices and increased public awareness of the health benefits of physical activity.

Provisions for on-street bike accommodations, sidewalks, recreational paths and safer crosswalks are now routinely expected as part of any significant roadway construction project. Design policies have also changed, thanks to safety research and organizations like Walkable Communities (http://www.walkable.org/) and Complete Streets (http://www.completestreets.org/). By working to advance pedestrian and bicycle-friendly facilities, these organizations have succeeded in getting state and local transportation agencies to adopt statutes, ordinances, and policies requiring designers to provide appropriate features that meet the needs of all facility users.

Design of Work Zones

Increased travel and congestion on the nation's existing, aging roadways and infrastructure have increased the need to maintain and improve the safety and mobility of these facilities. Roadway construction, rehabilitation, preservation, and maintenance activities are all critical components of these efforts. Construction and maintenance activities themselves have a significant impact on safety and mobility.

This combination of more traffic, more congestion, and growing safety concerns, and public frustration with more work zones, led the FHWA to publish the *Work Zone Safety and Mobility Rule* on September 9, 2004. The intent of the regulation was to "facilitate the systematic consideration of the broader safety and mobility impacts of work zones and the development and implementation of management strategies to reduce these impacts."

Work-zone impacts often extend beyond the physical construction or maintenance activity. Impacts, especially congestion, are often seen on the roadway where work is performed and on other roadways within the transportation network. The new regulation requires designers and practitioners to shift from thinking in terms of work-zone traffic control to work-zone transportation management.

The concept of work-zone transportation management extends beyond accommodating traffic through the physical work zone to emphasizing the safety of the traveling public and workers. The concept also focuses on regional mobility and operations. A critical component of this transportation management concept includes an information and outreach campaign to communicate to the public, road users, area residents, businesses, emergency responders, and other public entities about a road construction project and how it will impact them.

With the publication and subsequent implementation of the *Work Zone Safety and Mobility Rule*, consideration of work-zone impacts has become ingrained into the entire project development and delivery processes from planning through construction. Designers and practitioners must now work with numerous stakeholders to provide for construction sequencing in the design, and to develop comprehensive transportation management plans (TMP), which include detailed temporary traffic control (TTC) plans, and address traffic operations and public information components. Details that were often left for construction contractors and maintenance forces to handle in a reactive manner are now being proactively studied by practitioners early in the process and often influence design decisions as a project develops.

Managed Lanes - HOV/HOT Lanes

Increased vehicle-miles traveled (VMT) and worsening traffic congestion have compelled transportation agencies to consider ways to expand freeway capacity. But scarce funding, limited land availability, and social and environmental impacts limit the ability to increase capacity by adding more freeway lanes. Transportation officials are exploring new ways to more effectively manage the existing transportation network through a combination of modest capacity expansion and enhanced operational strategies. The "managed lanes" concept is a tool that is used successfully across the United States and is gaining increasing interest.

Managed lanes are defined in the United States as facilities, or a set of lanes, where operational strategies are actively managed in response to changing conditions. Toll lanes and high-occupancy vehicle (HOV) lanes are examples of managed lanes. Managed lanes may also include part-time use of shoulders during peak hours for additional capacity.

The distinction between managed lanes and other forms of freeway management is the concept of "active management." This occurs when the operating agency proactively manages demand and available capacity on the facility by applying new strategies or modifying existing strategies. Active management involves defining the operating objectives for the managed lanes from the outset and the kinds of actions that will be taken once pre-defined performance thresholds are encountered. For example, in response to an increasing traffic demand on the managed lanes, an agency may decide to raise the toll rates or increase the occupancy rate in hopes of reducing the demand and maintaining congestion-free travel on the managed lane system.

This toll lane in Minneapolis, Minnesota, is an example of managed lanes, which are used in the United States to manage traffic demand and maintain a desired performance

Lane management applications fall into several broadly defined operational strategies: pricing, vehicle eligibility, and access control:

- **Pricing –** When an agency applies a toll to a lane during certain time periods to manage demand and maintain a desired performance threshold.
- **Vehicle eligibility –** When lanes are managed by allowing or restricting certain vehicles according to the number of vehicle occupants.
- **Access control –** Lanes where all vehicles are allowed, but access is limited during long stretches of the facility, thus minimizing turbulence in vehicle flow.

The premise of active management is one of the distinguishing features of managed lanes. Transportation agencies can define the desired performance objectives and the kinds of actions taken to maintain the performance thresholds. Some examples of active management include:

- Raising the occupancy requirement to use an HOV lane so that operating speeds of 50 mph [convert to metric] can be maintained.
- Closing an on-ramp to express lanes during peak periods so that the express lanes can operate within a volume threshold of 1,500 vehicles per hour per lane.

HOV lanes were early examples of managed lanes in the United States. Design guidelines for HOV lanes have evolved based on various operational practices and strategies. The AASHTO *Guide for High-Occupancy Vehicle (HOV) Facilities, 3rd Edition (2004)*, suggests methods and designs for dedicated facilities and preferential treatments to encourage greater use of existing transportation systems for HOVs. Guidance is given for planning and design of preferential treatment for high-occupancy vehicles (HOVs). Portions of the guide have been excerpted from the previous edition of the guide, the NCHRP *HOV Systems Manual*, and recent research from the Texas Transportation Institute.

This photo shows an example of two types of managed lanes operating side by side: a high-occupancy vehicle (HOV) lane to the left and a toll lane to the right.

Adapting existing HOV-only lanes into managed lanes concepts is evolving and allowing transportation agencies more choices and flexibility for a wider range of users and facilities. Value pricing, or congestion pricing, was introduced through a federal pilot program included as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and continued in the Transportation Efficiency Act for the 21st Century (TEA-21), the United States' primary surface transportation laws during the 1990s.

Dynamic message signs, such as this one on a U.S. interstate, are used on managed lanes to provide drivers with up-to-date traffic information.

The program allows agencies to work with the FHWA to employ road pricing strategies, including charging motorists a toll for travel during the most congested times or offering a discount for traveling in off-peak periods. The program ushered in high-occupancy-toll (HOT) lanes as an operational strategy.

HOT lanes take advantage of available unused capacity in an HOV lane by allowing vehicles that do not meet the minimum occupancy requirement to pay a toll for access to the lane or lanes. The price may be set in a regular toll schedule, changed by time of day or day of the week, or changed dynamically in response to current levels of congestion. HOT lanes use both vehicle eligibility and pricing to regulate demand.

A successful example of a managed lane facility is the Interstate-15 FasTrak® project in San Diego, California. FasTrak® is an electronic toll collection system that allows drivers to prepay their tolls, thereby eliminating the need to stop at the toll plaza. Prior to the FasTrak® system, the heavily congested I-15 corridor included two reversible express lanes in the I-15 median. These lanes are separated from the general-use lanes with concrete barriers. Initially, the express lanes were restricted to HOVs carrying two or more occupants. With this restriction the express lanes were underutilized while the adjacent mainline lanes of I-15 were heavily congested.

The San Diego Association of Governments, the area's metropolitan planning organization, acting with the California Department of Transportation and FHWA, implemented a demonstration program whereby single-occupant vehicles could use the HOV lane by paying a toll. The toll varies from $U.S. 0.50 to $U.S. 4.00 (50 cents to $4) depending on the level of congestion.

The FasTrak project has been operating successfully since 1996. HOVs continue to use the lanes for free and solo drivers can decide whether to pay the toll for a faster commute. The operating agencies are now using the roadway capacity more effectively, and the program also generates revenue that funds transit improvements in the corridor.

Design criteria play a key role in the feasibility of managed lanes. The development of appropriate geometric criteria for the elements of a managed lane system is evolutionary since many new applications are emerging for which there is little or no prior experience. Elements such as lane configuration and access treatments of a managed lane facility are challenging. Research needs have been identified for developing design criteria for treatments for terminating and originating managed lanes in a freeway section. Research is also needed from a human-factors perspective since the decision-making process to enter a managed lane facility may be more complex than drivers are accustomed to. Elements such as the signing and providing geometry that allows the appropriate driver decision-making process are critical, especially when using multiple operating strategies that may change the eligibility requirements of vehicles using the managed lanes over the course of a day or week.

As new projects and managed-lane operating strategies are assessed, the complexity of the design may increase. Critical design issues are:

- Access design
- Driver information and signing
- Provisions for manual and automated enforcement
- Pricing infrastructure
- Design flexibility
- Integrated transportation opportunities

- Separation of the managed lanes from adjacent general-purpose roadways

The design of access and egress points for managed lanes is a critical issue that impacts the operating conditions within a managed lanes facility and affects the ability to modify operating strategies. The HOT lane facilities that currently exist in the United States generally have distinct separation and very limited access. In studies where unlimited access HOV lanes are considered for implementing pricing, one significant impediment is access. The more access that is added, the more difficult it is to manage the facility.

Even with physical separation, a greater frequency of access to the managed lanes can degrade the ability to manage controls for ensuring an acceptable level of service. Spacing of at-grade ramp connections and length of weaving sections could impact safety and operating conditions, both within the managed lanes and in the adjacent freeway lanes. Terminal access at either end of the facilities can also be a design challenge, particularly in fitting the facility within an existing freeway or arterial street system.

For managed lane facilities that utilize pricing, the needs for manual and automated enforcement are critical design considerations. Separation of the managed lanes from adjacent general-purpose roadways is another critical design challenge. The separation can be accomplished in several ways, ranging from painted stripes to plastic pylons to concrete barriers. Lane separation represents a safety concern because the parallel traffic could operate at very different speeds during congested periods.

How to communicate information on managed lanes to drivers in a clear, concise manner while avoiding information overload is a difficult task that requires careful evaluation. Information that must be communicated may include ingress and egress locations, occupancy requirements, operating hours, and toll amounts. Drivers must process this information, along with standard directional and informational signage, and still safely operate their vehicles. The driver may also need to make a decision on whether to use the facility. This can be particularly challenging for drivers who are unfamiliar with the corridor.

A variety of techniques, such as HOV lanes, dedicated lanes, and improved signage, have been used to improve the safety and operations of this complex interchange in Atlanta, Georgia.

Design flexibility of managed lanes facilities must consider potential changes to user groups or varying tolls based on user groups. Management strategies such as charging based on distance or access point, or a combination of both will, present more challenges in designing a facility that can accommodate various operational strategies. Designing for complex operational scenarios will also have to consider multiple tolling and enforcement zones. Key design-related topics to managed lanes that require further research are lane separation, access, and driver communications.

Innovative Intersection and Interchange Geometrics

Transportation professionals in the United States are challenged to meet the increasingly complex safety and mobility needs of a growing population, and to do so with limited resources. In particular, at many highway junctions, congestion continues to worsen. Drivers, pedestrians and bicyclists experience longer delays and greater exposure to risk. Traffic and safety problems are more complicated than ever, and conventional intersection designs are sometimes found to be insufficient to mitigate transportation problems. Increasingly, design engineers are investigating and implementing innovative intersection treatments.

The FHWA has published an *Alternative Intersection/Interchange Informational Report* (AIIR) that presents information on selected intersection and interchange designs that may offer advantages compared to conventional at-grade intersections and grade-separated diamond interchanges. The information presented in the AIIR provides information on the geometric design features, operational and safety issues, access management issues, costs and construction sequencing, and applicability. The six alternative treatments covered in the report are:

- **Displaced left turn (DLT) intersection.** Also referred to as continuous flow intersections (CFI) and cross-over displaced left turn (XDL) intersections. Left-turn traffic is laterally displaced as it crosses over the opposing through-movement at a location several hundred feet upstream of the major intersection.
- **Median U-turn (MUT) intersection.** Also referred to as Michigan Lefts. Left turns are not allowed at the major intersection; rather, drivers can make a u-turn at a location downstream, travel back toward the intersection and execute a right turn onto the crossroad.
- **Restricted crossing U-turn (RCUT) intersection.** Also known as a Superstreet intersection. Similar to the MUT, however through and left turn maneuvers are not allowed from the side road; rather, this traffic must turn right on the major road then travel a distance to make a u-turn.
- **Quadrant roadway (QR) intersection.** Mainline left turn movements are relocated to a connector roadway located in one of the quadrants.
- **Double-crossover diamond (DCD) interchange.** Also referred to as diverging diamond interchange (DDI).

This restricted crossing U-turn (RCUT) intersection is located in Maryland.

The traffic directions of the crossing roadway are reversed within the interchange area, such that left turns from the major road onto an on-ramp can be made without conflict from opposing traffic.

- **Displaced left-turn (DLT) interchange.** A DLT intersection that is implemented at a diamond interchange.

The four alternative at-grade intersection designs share a common feature to remove one or more of the conventional left-turn movements from the major intersection. By removing one or more of the critical conflicting traffic maneuvers from the major intersection, fewer signal phases are required for signal operation. This can result in shorter signal cycle lengths, shorter delays, and higher capacities compared to conventional intersections.

The displaced left-turn (DLT) intersection is located near Salt Lake City, Utah.

Visualization Applications in Geometric Design

Highway design engineers traditionally analyze problems in two dimensions (2-D), which are simplified to 2-D plan and profile drawings and cross-sectional views. These representations, however, lack the information necessary to fully understand how a project will perform in the real world. Current design software combines 3-D highway design modeling and visualization with traditional 2-D engineering design and drafting.

Automated machine guidance (AMG) integrates the digital design surface model with precise positional information onboard construction machinery. The construction equipment operator uses the 3-D design surface modeling and computer-assisted or automated controls of the cutting blades to construct the roadway instead of interpreting stakes in the ground and operating the cutting blades manually.

Four-dimensional traffic simulation visualization enables the designer to view traffic information output from traffic analysis tools, overlaid onto a 3-D design surface model, and displayed as animation. The visualization of traffic flow information includes the types of vehicles in the traffic stream, bicyclists, and pedestrians. The visualized information ranges from basic flow parameters of the collective traffic stream to data on individual traffic elements, e.g. vehicles and pedestrians, output from software simulating microscopic traffic flow. The 4-D simulation of moving vehicles becomes especially useful and adds value to the design process when the combined physical and traffic element models are visualized and experienced from the driver's perspective operating within the stream of traffic.

Several projects using the design-build contracting method have adopted visualization to assure quality, expedite delivery and reduce cost. In the design-build method, cost savings have more direct rewards than in the traditional design-bid-build approach. An example is New Mexico's Rail Runner Express commuter rail project that connects Belen, Albuquerque, and Santa Fe in the state of New Mexico along a corridor generally following I–25. The design firm used a 3-D modeling system during and after the bid process, enabling the design team to bring up plans and views and critique them in different offices in real time.

A 3-D, model-centric approach enables designers to analyze safety issues from different perspectives than the traditional 2-D drafting-centered design approach—most important, from the perspective of the end user, whether a driver, bicyclist, or pedestrian. Among the advantages is enhanced analysis of sight distances for stopping, passing, intersections, and directional decision-making. Transportation agencies are beginning to use visualization as a tool for road safety audits (RSAs) during preconstruction planning. RSA teams typically visit project sites to view existing conditions firsthand but must rely on interpreting 2-D drawings to assess safety issues of proposed design improvements. Visualization helps the team better understand the design and the user's perspective.

Visualization has become an important tool to help designers ensure that the physical layout of a roadway is recognizable to drivers, bicyclists, and pedestrians, and intuitive to navigate. By applying 3-D modeling and visual analysis, design engineers can reduce some of the complexity of interchanges and intersections and make them easier to recognize and maneuver through, leading to safer and more efficient operations. FHWA's Human Centered Systems team at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia, helped Missouri DOT (MoDOT) build a simulation of the proposed Diverging (crossover) Diamond Interchange in FHWA's Highway Driving Simulator using 3-D and 4-D visualization. The simulation enabled MoDOT and FHWA engineers to drive through their own design using real-time, 3-D software and to optimize the final design.

Design Policy Changes, 2005-2010

How are all of these aforementioned recent trends and developments in geometric design expected to be documented in various U.S. policy and design guides? Several publications providing policy, guidance, and tools for making geometric design decisions are being introduced or updated in 2010. Some documents will be part of the continuous evolution of design practice, while others will represent a significant shift in approach.

Green Book Updates

AASHTO's *A Policy on Geometric Design of Highways and Streets*, also known as the Green Book, has been published in various forms since 1950. The first edition was a compilation of earlier AASHTO policies.[iii] Each subsequent edition builds upon the information in the previous editions and is updated based on new research results and evolving experience in nationwide practice.

The purpose of the Green Book is to provide guidance to designers by discussing a range of recommend values for critical design dimensions. The Green Book provides flexibility to encourage independent designs tailored to project context; balancing safety and mobility, and preserving scenic, aesthetic, historic, cultural, and environmental resources.[iv]

Since the guide is based on research and practical experience, the policy reflects the state-of-the-practice for geometric design in the United States rather than recent untried innovations. The current Green Book was last updated in 2004 and is among the standards adopted by the FHWA for geometric design on the National Highway System.[v] State highway agencies have typically incorporated the information from the Green Book into their own policies and design manuals.

The next edition of the Green Book, expected in 2010, incorporates the results of several research efforts and editorial changes for improved clarity and emphasis on key topics. Research on the characteristics of trucks currently in the nation's fleet[vi] has resulted in some changes to the design vehicles and corresponding changes to vehicle turning paths, values for horizontal curve design, and turning movements at intersections.[vii] Research on the behavior of drivers during passing maneuvers has resulted in a reduction in the values recommended for passing sight distance, because shorter distances for such maneuvers have been found to have very few crashes.[viii]

Some of the key updates in the 2010 Green Book are described in the following paragraphs.

2+1 Roadways

Another design concept for accommodating passing maneuvers with 2+1 roadways is also incorporated based on research on the European experience with such designs. A 2+1 roadway uses a center lane for passing maneuvers, providing alternating opportunities for each direction of travel. This configuration may be suitable for roadways with traffic volumes higher than can be served by isolated passing lanes, but not high enough to justify a four-lane roadway. A 2+1 road will generally operate more efficiently (at least two levels of service higher) than a conventional two-lane highway serving the same traffic volume.[ix]

Rumble Strips

The 2010 Green Book edition also adds discussion of rumble strips, which are raised or grooved patterns constructed in the pavement that cause a sound and vibration that are discernible to motorists driving over the strips.[x] Rumble strips have been found to be effective in reducing run-off-the-road crashes caused by inattentive drivers when constructed along the edge or shoulder of the roadway.[xi] They may also be installed along the centerline of rural highways to reduce head-on collisions and transverse to highways to alert drivers at approaches to toll plazas, horizontal curves, intersections, and work zones. While rumble strips are effective at reducing crashes, they can result in a loss of control for bicyclists and therefore should be located so that bicyclists can avoid them.

Intersections

As innovative intersection configurations have become more widely accepted, guidance on these designs have been added to the Green Book. Increased implementation of roundabouts in the United States has led to expanded guidance on their design. The guidance addresses design considerations for single- and multi-lane roundabouts and for mini-roundabouts. The geometry of the approaches and vehicle paths around the circulatory roadway is critical to the intersection's smooth operations. Guidance has also been incorporated for the displaced left-turn intersection (DLT) configuration discussed previously.

Flexibility

The editorial changes to the Green Book further highlight the flexibility available to highway design agencies in considering the highway context and then selecting suitable design criteria to provide for the safety and mobility of the full range of highway users.[xii] This is in recognition that always applying the limiting design values may favor one type of user over another – cars, trucks, transit, pedestrians, or bicyclists – and is not appropriate for every setting or type of highway, from freeway to local roads.

Highway agencies exercise engineering judgment to balance the competing needs of the highway users while preserving the natural and human environment in response to the values of the community.[xiii] The anticipated changes to the Green Book also recognize that designing for free-flowing traffic conditions may not be a practical objective in many of the nation's urban settings where traffic volumes are high and costly development is already in place.[xiv]

Update of AASHTO's *Roadside Design Guide*

Another AASHTO publication being updated in 2010 is the *Roadside Design Guide* (RDG). The RDG is a synthesis of current information and operating practices related to roadside safety. The guide focuses on the "forgiving roadside philosophy," those safety treatments that can minimize the likelihood of serious injuries when a motorist leaves the roadway.

The current, 3rd edition of the RDG was published in 2002. In 2006, AASHTO issued an updated Chapter 6, revised to include updated guidance on the median barrier, to include a new section on high-tension cable barrier systems (only recently introduced in North America), as well as additional guidance on the placement of cable barrier. Since 2002 and 2006, more research findings and practical experience have been collected and analyzed, leading to a perceived need for a significant re-write of the entire document.

One principal emphasis of the 2010 update is to further contrast and clarify the distinction between the term "clear zone" and similar terms such as "horizontal clearance." This effort is being guided by the results of a research report titled *Identification of Conflicts related to Clear Zones within AASHTO Publications NCHRP 20-7(Task 171)*.

The updated RDG will introduce a new chapter called Low Volume Roadways, intended as a companion chapter to AASHTO's *Guidelines for Geometric Design of Very Low-Volume Local*

Roads, 2001. It will include guidance on clear zone, drainage placement, slope and ditch cross-sections, barriers (TL-2), sign supports, and utility-pole placement.

The new RDG will also significantly revamp the existing Chapter 10 titled Urban and Restrictive Conditions to incorporate enhanced guidance for urban roadsides, based largely on research findings reported in NCHRP Report 612 *Safe and Aesthetic Design of Urban Roadside Treatments.* The revamped chapter will include guidance on clear zone, lateral offset (4-6 ft), landscaping (including median applications), sidewalk placement, slope and ditch cross sections, sign supports, utility-poles placement, traffic signals, and mailbox locations

Conclusion

Geometric design is fundamental to everything in the development and improvement of the U.S. highway transportation systems. Whether addressing highway safety problems, reducing congestion, or meeting the needs of a growing and diverse population and user base, the choices that designers make are essential for success. This paper has illustrated how design practices and policies in the United States have advanced in the past several years. These practices and policies will continue to adapt and be enhanced to better address existing and emerging challenges. In this sense, the investments of countless individuals and organizations are maintaining a dynamic and vibrant focus on the essential contribution of design to the social and economic benefit of the country.

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