Matching Simulator Characteristics to Highway Design Problems

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Driving simulators hold much promise for addressing roadway design issues. However, although simulators have demonstrated their value in experimental research addressing driver performance, their ability to support road design projects has not been as clearly established. This paper describes a design-centered framework to make simulators valuable for traffic engineers and geometric designers. This framework includes several steps: (*a*) identification of design issues that would benefit from driving simulators, (*b*) identification of simulator characteristics to match them to design issues, and (*c*) translation of driver performance data from the simulator to traffic behavior on the road. Several critical obstacles inhibit application of simulators to highway design. First, driving safety researchers and engineers comprise separate communities and their perspectives on how simulators can be applied to address road design issues often diverge. This paper seeks to reduce this divergence and make simulators useful to highway engineers. Interviews with engineers revealed important issues that simulators could address, such as intersection and interchange design. Second, driving simulators are often broadly defined as high fidelity, which provides little value in matching simulators to design issues. A survey of simulators and simulator characteristics clarifies the meaning of simulator fidelity and links it to road design issues. Third, simulators often produce data that do not correspond to data collected by traffic engineers. This mismatch can result from inadequate simulator fidelity, but can also arise from more fundamental sources—traffic engineers focus on traffic behavior and driving simulator researchers focus on driver behavior. Obstacles in using simulators for highway design reflect both technical and communication challenges.

Geometric designers and traffic engineers face considerable challenges in addressing driver behavior in their designs. Drivers often behave in complex and counterintuitive ways, and failing to consider driver behavior can cost lives and millions of dollars if roadways require revision after they are built. Driving simulators provide a promising approach to addressing this challenge because they make it possible to visualize new roadway designs as well as safely expose drivers to demanding situations without the expense of fully implementing the design (*1, 2*). Driving simulators also provide a means of conveying road design concepts to stakeholders through visualization and so can be an important part of policy decisions and public acceptance. Recent advances in simulation technology have resulted in a proliferation of driving simulators that vary in terms of fidelity, complexity of operation, and cost. With such diversity, it is necessary to develop a framework for identifying these elements that are necessary to achieve the goals of a given road design project.

With few exceptions, driving simulators have generally fallen short of their potential as a design aid (*3–7*). The uncertainty regarding what issues designers need simulators to address, the challenge of selecting an appropriate simulator for a given design issue, and the mismatch between simulator data and on-road data are three key reasons why driving safety researchers and designers have not applied simulators to roadway design more often. This paper outlines a design-centered approach to match the type of simulator to the design issue and to interpret the resulting data. As a first step in matching simulators to roadway design issues, this paper describes a general framework that can guide simulator selection. In the context of this overall process, the paper then identifies issues that highway engineers hope simulators can address, describes the range of current driving simulator capabilities, and concludes by discussing the challenge of generalizing driver performance from the simulator to traffic behavior on the road.

SIMULATOR-BASED DESIGN FRAMEWORK

A framework is needed to relate design issues to driving simulator capabilities and also to identify the steps associated with applying simulators to roadway design. Specifically, making driving simulators more useful for highway designers requires a systems-oriented approach to the design issues that highway engineers face. Figure 1 describes such an approach to making simulators useful. The approach begins with the design issues, relates simulator capabilities to these issues, and recognizes that simulator choice depends on the operational and budgetary demands of the engineering context—the highest-fidelity simulator may not always be practical or necessary.

A central aspect of Figure 1 is a focus on design issues. This focus identifies specific driver behaviors that are critical for understanding a particular roadway design issue. Figure 1 highlights six steps in the application of simulators to roadway design, beginning with scenario analysis and concluding with model-based data transformation. The

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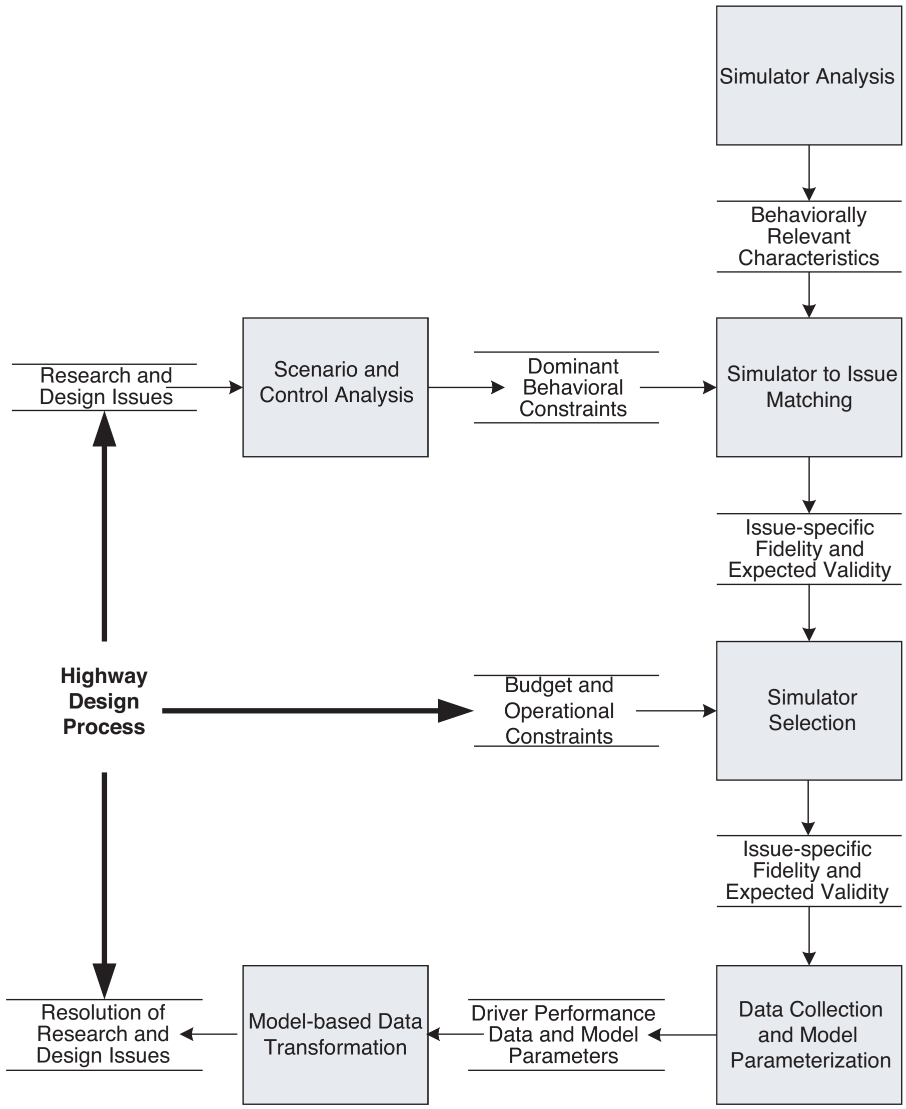

FIGURE 1 Design-centered approach to making simulators useful for highway design.

model used in this process refers to a computational model of driver performance used to integrate and extrapolate the data (*8*, *9*). This paper focuses on the upper half of the diagram, which addresses steps associated with simulator selection and then touches on the final step associated with data interpretation. The process began with interviews of designers to identify pressing design issues.

IDENTIFY ROADWAY DESIGN ISSUES

The first step identifies highway engineering design cases that a driving simulation can help to address. To identify applications of driving simulators that have clear engineering relevance, FHWA conducted a series of discussions with 20 subject matter experts (engineers from federal, state, and local agencies) concerning their use of behavioral data in roadway and infrastructure design and operations. These discussions were conducted to help determine research and design needs of geometric designers and traffic engineers.

Information from the discussions helped document the needs of highway engineers and, thus, identify the corresponding driving simulator features that have highway engineering relevance. Comments from discussions were collected on the following six topics:

1. Data used in the field;
2. Sources of the data used to make design decisions;
3. Design issues associated with data integration, availability, and compatibility (e.g., converting computer-aided design drawings to simulator imagery);
4. Needs not currently being met;
5. Simulator scenarios that would be useful in their roadway design practice; and
6. General comments with regard to design issues.

The first topic identified the data that engineers use for design. These data relate to continuous (e.g., speed) and categorical (e.g., lane selection) dependent measures. The second topic addressed the data sources that are currently used by engineers. Nine of the 20 engineers identified field data as important to their design process. Field data in this context are almost always understood to describe traffic behavior rather than driver performance. These data are often available only after a design is implemented. Consequently, simulator data might fill a useful role by providing such data where existing data do not exist, before the design is implemented.

The third topic identified highway design needs that were not being met by existing data or design standards. Data describing driver speed selection, lane selection, and gap acceptance were most frequently cited as gaps in supporting design, comprising 12%, 12%, and 8% of all the comments, respectively. These scenarios can then be judged with respect to criteria that determine the applicability of driving simulators to address the design issues.

These issues were, in order of frequency of mention,

1. Speed selection,
2. Lane selection,
3. Gap acceptance associated with decision to proceed through an intersection, and
4. Sign comprehension and compliance.

Specific scenarios of interest, in order of frequency of mention, were

1. Intersections and interchanges;
2. Signage;
3. Work zones (speed selection and merging behavior);
4. Speed selection;
5. Traffic control device (TCD) comprehension, such as driver response to permissive left-turn signals;
6. Road departure on curves; and
7. Roundabouts.

The two most needed simulator scenarios were for intersections and interchanges and for signage, comprising 12% and 10% of the comments, respectively. Safety-related design issues with regard to intersections and work zones concern lane and speed selection in the context of maintaining throughput (*10*). TCD comprehension is important from a number of perspectives—from conspicuity of signals to the degree to which pavement markings influence speed and lane selection.

Engineering issues can be considered from two perspectives: geometric design and traffic operations. There are strong interactions between these two perspectives, but each imposes particular requirements on simulators. Geometric design requires that simulators can replicate lane width, pavement markings, and vertical and horizontal curves. Re-creating specific curves to match an actual road in the simulator can involve substantial effort and require specialized expertise in visual database development. Additionally, in some instances, curve following depends on physical cues, such as lateral force, which are difficult to replicate in a simulator. By contrast, traffic operation issues require that the simulator can replicate signal timing, behaviors of other drivers, and, perhaps most challenging, traffic congestion. Congestion poses a particular challenge because simulating the dynamics of hundreds of vehicles can exceed the computational capacity of the simulator. The demands associated with replicating geometric design and traffic behavior illustrate the need to match simulator capabilities to the particular engineering design issue.

The general criterion for matching simulators to highway design issues concerns the need for behavioral data. Design issues that are too dangerous or too expensive in time and money to evaluate in the field represent important opportunities for driving simulators. To determine whether a design issue is a good match for simulator-based data collection, four specific questions should be considered:

- Is the research question relevant to new or existing roadway and infrastructure design that cannot be specified with traditional design standards (e.g., *Manual on Uniform Traffic Control Devices,* AASHTO)?
- Are driver perception, judgment, and decision making likely to influence the performance of the roadway or infrastructure design?
- Is the roadway or infrastructure design dangerous or costly to implement on an actual roadway?
- Are there several alternative solutions that would benefit from analysis to identify best solutions?

Answering these questions can help to determine whether a simulator could provide engineers information that they need, but do not currently have. Emphasis is given to those design issues that have a strong influence on safety and capacity. However, a given simulator must also have sufficient capabilities to address a given issue, a topic that is discussed next.

MATCH SIMULATORS TO ROADWAY DESIGN ISSUES

The second step identifies driving simulator characteristics needed to address highway design issues. Simulators capable of addressing the issues must be accessible to highway engineers (i.e., a moderately priced simulator that does not require extensive programming expertise). While simulator fidelity has increased greatly over the past decade, the corresponding cost of simulators has come down, as has the expertise required to use and maintain a simulator. This development has enabled more engineers and researchers to use simulators in their engineering and research practice. Although simulators are generally useful tools for highway design, they are not always cost-effective or even valid.

Careful consideration of simulator fidelity is necessary to determine whether a particular platform is appropriate for a given engineering question. Simulator fidelity can be described in many ways, from functional fidelity associated with the simulators' ability to replicate the perceptual and cognitive demands of driving to physical fidelity, which relates to the degree to which the simulator replicates the physical properties of the driving situation. Physical fidelity concerns the replication of the physical properties of the driving situation and provides a starting point for ensuring functional fidelity. Fidelity can be described along a number of dimensions:

- Resolution, contrast, and brightness of the visual displays (critical for conspicuity, gap acceptance, sign recognition, and target identification);
- Field of view (FOV) and scene details (critical for situational cues and optic flow associated with speed perception);
- Cab configuration (critical for replicating the visual separation of mirrors);
- Driver control input feel (critical for steering and braking performance);
- Vehicle dynamics (i.e., braking and steering, response characteristics) (critical for assessing different vehicle platforms, such as passenger car versus truck braking);
- Auditory cues (critical for speed control); and
- Motion and vibration (critical for effectively simulating pavement edge drop-offs and speed control through curves).

FOV is one of several important components of fidelity for roadway design and is the simulator characteristic most frequently mentioned in simulator descriptions. A wide FOV is useful for design evaluations that concerns drivers' ability to see traffic and signage in the periphery, such as during the approach to an intersection or when merging into another stream of traffic. For instance, for intersection-related evaluations, having a wider FOV could be useful for the driver to understand the context of the roadway design. For TCD comprehension, such as changeable message signs or speed limit signage, a limited FOV may be sufficient. Generally, a wider FOV corresponds to higher fidelity, but this correspondence might not always hold. In some cases, such as studies of sign recognition and interpretation, it might be better to have a high resolution, but narrow FOV rather than a lower-resolution, wide FOV. In addition, scenarios involving high speeds on freeways might be feasibly investigated with a relatively narrow FOV because drivers tend to focus their gaze on the center of the road (*11*). This example demonstrates that simulator fidelity must be considered in terms of how the particular features of the simulator match the design issue. A further subtlety in describing FOV is whether and how mirrors are implemented. For some scenarios, such as merging, mirrors represent a critical source of information and can be more important than a slightly broader FOV.

Although secondary to visual information, motion, vibration, and sound all guide driver behavior and contribute to immersion in the driving scenario. Motion and vibration become more important when the scenario requires sustained braking and steering performance. For example, simulators used to assess roundabout entry speed, curve negotiation, and physical roadway treatments (e.g., speed tables and rumble strips) may benefit from some form of motion or vibration (*12*). Haptic and vestibular cues can help a driver understand the level of braking or steering to apply. Bittner et al. found that on the most difficult curves (requiring the lowest entry speed), curve entry speeds were lower in the simulator than on the road, while on the least difficult curves (with the highest entry speeds), curve entry speeds were higher in the simulator than on the road (*13*). This finding is consistent with previous studies that show that drivers traverse relatively straight roadways faster in simulators than on the actual road (*13, 14*). Such speed differences have been attributed to the lack of vestibular, sound, and vibration cues that accompany small adjustments on the road, but that are not present in most low-fidelity driving simulators.

The more vehicle control is important to a design issue (e.g., precise braking and steering), the more realistic the driver input controls need to be (e.g., full-size steering wheel driven by active torque motors). If a study is more comprehension oriented, the realistic vehicle controls and the overall vehicle dynamics are less important. For typical highway design applications, vehicle dynamics models that model vehicle types (e.g., cars, SUVs, heavy trucks) will provide enough of a difference in overall handling without the need to use vehicle dynamics for specific makes and models of vehicles.

In general, three broad elements of simulator fidelity can help determine both simulator cost and compatibility of a simulator to demands of a particular roadway design: FOV, motion base, and cab configuration. A wide FOV, a motion base, and realistic driver input controls mounted in an actual vehicle can dramatically increase the cost of a simulator. As a result, it is assumed that most simulators used by highway designers will not have all these capabilities. To determine whether an engineering design issue can be addressed among a large number of simulator platforms, three basic questions can be asked:

- Does the design issue require driver to integrate information from a wide FOV?
- Does the design issue require that drivers respond to motion or vibration cues, such as rumble strips?
- Does the design issue depend on the realism of the driver controls and vehicle dynamics?

The great range of simulators, each with substantially different capabilities and costs, makes it critical to select the appropriate simulator for each evaluation issue. The range of simulator fidelity and cost govern the efficiency and effectiveness of any pairing of evaluation issue and simulator. Efficiency refers to the monetary, time, and personnel resources associated with a particular evaluation approach, whereas effectiveness refers to the ability of a particular evaluation approach to provide valid data that address the particular evaluation issue (*15*). A high-fidelity simulator may provide valid data to address a wide range of issues (i.e., it is an effective way to evaluate many systems), but the simulator may be very expensive and time consuming (i.e., it may not always be the most efficient way to evaluate a system). Because efficiency and effectiveness depend on simulator fidelity, it becomes critical to define simulator fidelity systematically.

Simulator fidelity is often defined by how closely the physical characteristics of the simulator match the actual system, with the degree of similarity being referred to as the physical fidelity. Because physical fidelity relies on engineering measurements, it provides a convenient method to make direct comparisons between simulators and the actual on-road driving environment. Unfortunately, physical fidelity may not be a very useful concept to address the issues of efficiency and effectiveness because it is only indirectly linked to the psychologically relevant aspects of the situation. Functional fidelity may be a more useful way of describing simulator capabilities. Functional fidelity describes the degree to which simulator features induce a psychological experience similar to that induced by the actual domain of application. The meaning of "domain of application," "simulator features," and "psychological experience" must be carefully defined if this definition is to be useful.

Defining the domain of application and the simulator features can be problematic for several reasons. To some extent simulator validity is purpose specific, making it difficult to make any general statements concerning the validity of any particular simulator. Validity depends on the ability of the simulator to replicate the purpose, functions, and physical characteristics of the actual driving environment for a particular evaluation issue. Therefore, the pairing of an evaluation issue with a particular simulator should explicitly consider the simulator capabilities from the perspective of the subset of the overall driving environment associated with the evaluation issue. In addition, the pairing should identify how simulator functions and features combine to realize this purpose.

Table 1 considers some of these pairings in a simplified way by characterizing the effectiveness of different types of simulators for addressing certain design-related evaluation issues. This table covers two aspects of this problem. The first involves a high-level characterization of the importance of specific simulator physical characteristics for meeting the functional requirements (e.g., adequate preview of a curve or of a sign) of different evaluation issues. The evaluation issues were based on the priority design issues identified in the previous section, and the evaluation issues represent a broad range in terms of functional complexity, but are not an exhaustive set.

The second aspect of the problem addressed by this table is the overall effectiveness of different types of simulators in meeting these functional requirements. This definition of fidelity does not imply judgments of quality, but refers to characteristics that influence the level of immersion that drivers experience when driving the simulator. This definition provides a convenient way to stratify the systems into reasonable categories while eliminating the need to consider characteristics shared by simulator types. For example, some aspects

TABLE 1 Matching Simulator Characteristics and Simulator Types to Design Issues

	Simulator Characteristics							Simulator Type			
Design Issue	Display Resolution	Field of View/Mirror	Cab Realism	Control Input	Auditory Cues	Vehicle Dynamics	Motion and Vibration	Desktop	Low-Fidelity	Medium-Fidelity	High-Fidelity
Suitable sign placement and content	●	◒						Possibly effective[a]	Possibly effective[a]	Effective	Inefficient[c]
Lane or path selection (e.g., through roundabouts, intersections, etc.)	◒	●	◒	●		●		Possibly effective[b]	Possibly effective[b]	Effective	Effective
Driver reactions and responses to jersey barriers, columns, barrels, TCDs, lane width, lane shift, taper	●	○		●	○	●	○	Possibly effective	Effective	Effective	Inefficient
Driver behavior on work zone approaches (speed compliance and lane selection)	●	○		●	○	●	○	Possibly effective	Effective	Effective	Inefficient
Driver behavior at large, complex arterial intersection configurations (e.g., gap acceptance, dilemma zones)	●	●	◒	●	○	●	◒	Not effective	Possibly effective	Effective	Effective
Effects of roadway features (e.g., geometric design, driveways, curves, etc.) on driver speed	◒	●	◒	●	○	●	◒	Not effective	Possibly effective[b]	Effective	Effective

NOTE: Blank = no importance; ○ = low importance; ◒ = moderate importance; ● = high importance.
[a]Dependent on display resolution.
[b]Dependent on field of view.
[c]Capabilities far exceed what is required. Method represents inefficient use of resources.

of fidelity rely on the underlying system software; however, the same software might be used across several hardware platforms. It is difficult to reliably characterize simulators as specific types because the feature sets overlap greatly between simulator types; however, four basic types were identified for illustrative purposes:

1. Desktop fidelity. Desktop system using one to three display monitors with software-emulated instrumentation;
2. Low fidelity. Quarter cab with flat-panel (e.g., LCD, plasma) screens and 45° to 140° FOV;
3. Medium fidelity. Free-standing cab, front projection screens, 140° to 240° FOV, high resolution; and
4. High fidelity. Same as Number 3 or better, greater than 240° FOV, plus six-axis motion.

In Table 1 the simulator physical characteristics needed to meet the functional requirements of specific evaluation issues are indicated with circles. By linking specific elements of physical fidelity to specific design issues, this table goes beyond the overly simple labels of high and low fidelity to guide designers to the simulator features needed to address particular issues.

The simulator types reflect data obtained in a comprehensive survey of simulator characteristics conducted with six organizations that operate a representative sample of driving simulators currently in use. The sample included nine simulator configurations, ranging from desktop models to full-vehicle simulators with six or more axes of motion and large displacements that can replicate sustained acceleration (e.g., National Advanced Driving Simulator). The survey included questions about a wide range of characteristics, including cab configurations, controls, display characteristics, sound system, motion base characteristics, haptic feedback, vehicle dynamics, and scenario capabilities.

The table represents a simplification of the general problem of selecting a simulator to address a roadway design issue. The design issues are specified in the table at a more general level than is typically required to assess the functional requirements, and they rely on assumptions not documented in the table (i.e., the specific maneuver, roadway configuration, etc.). Similarly, the effectiveness rating is closely tied to the actual capabilities of particular simulators rather than to broadly defined simulator types. Individual simulator characteristics should be considered when evaluating the appropriateness of a simulator relative to the specific functional requirements of the research questions being examined.

Another simplification contained in Table 1 concerns the importance of scenario and visual database design. The visual database design includes the features of the simulated environment, such as roadway furniture, buildings, and sign clutter. Scenario design also includes the behavior of vehicles and traffic control devices. Obviously, a high-fidelity simulator in which the stoplight signal timing cannot be adjusted would provide little value in a study addressing the dilemma zone and specification of the yellow-light duration. A simulator with generally high fidelity might not be of high fidelity on all dimensions.

Although not typically considered as part of simulator fidelity, the drivers recruited for a study represent an important element of the evaluation context and their characteristics can interact with the simulator features to influence the study outcomes. In roadway design evaluation, drivers' familiarity with an area and the current geometric design could lead to certain expectations that unfamiliar drivers might not share. This difference could be critical for assessing guidance signs and new interchanges. Selecting drivers that are representative of the road situation of interest might be as important as selecting a simulator.

ISSUES WELL SUITED TO SIMULATOR-BASED INVESTIGATION

The analysis of roadway design issues and simulator characteristics combine to reveal several issues that seem compatible with a simulator-based evaluation. These issues range from intersection design to signing and pavement markings.

Lane Choice, Gap Acceptance, and Speed in Intersections and Interchanges

Intersection and interchange design is a critical area in engineering design. Oxley et al. examined the relationship between intersection design features and older driver crashes (*16*). They inspected 62 crash sites and identified 10 probable contributing factors. Inappropriate gap acceptance and task complexity, coupled with the presence of other road users, and limited sight distance were the most common contributing factors. Creating alternative designs and testing them in a simulator is an attractive option relative to conducting expensive roadway changes. The variety of driver responses and the complexity of intersections often demand the most sophisticated simulation capabilities.

Drivers need a wide and tall FOV to provide context of the upcoming intersection and to render visual cues regarding cross-traffic and signage once they reach the intersection. Sustained lateral and longitudinal motion cues are required to minimize simulator adaptation syndrome (e.g., sickness) during 90° turns and repeated braking. For this reason, intersection evaluations that involve repeated turns can be difficult to perform in a simulator. Finally, realistic controls and vehicle dynamics can be critical for this type of research, because vehicle control is central to driver steering and response. For these reasons, intersection and interchange design can be one of the most challenging, and the least compatible, applications of simulators because only a few simulators possess the full range of capabilities needed. However, selected issues, such as roadway treatments to enhance gap estimation and influence approach speed, could be explored even in a relatively low-fidelity simulator.

Retroreflective Raised-Pavement Markers and Lane Delineation

Previous field research has examined retroreflective raised-pavement markers (RRPMs) and lane delineation systems for their ability to keep drivers in a lane as well as maintain appropriate speeds. Applying simulators to this issue is similar to traffic calming and some TCD comprehension studies; most of the information that the driver requires is in the forward view, so a wide FOV may not be necessary (*17*). Traffic-calming treatments are intended to slow or reduce motor vehicle traffic to improve safety for pedestrians and bicyclists. Simulators with a limited FOV have been used effectively for such applications (*2, 17*). While there may be occasions when traffic in parallel running lanes would be of interest, RRPMs and lane markings would be in the forward view. Because speed control is of central interest, some motion or vibration may be useful, but not required. Therefore, lane treatment evaluation may be one area that has broader application among a range of simulator platforms. Because such treatments have application to modulating speed and guiding drivers through work zones, this application has considerable promise.

An important caveat regarding simulator evaluation of RRPMs concerns nighttime driving. Nighttime driving is a challenge for all simulators because projectors lack the dynamic range required to render true black and intense headlights. Rendering this dynamic range is complicated by the challenge of modeling headlamp illumination and the light reflected from retroreflective materials. For these reasons, assessment of RRPMs on nighttime driving presents a ongoing challenge for simulator studies.

Changeable Message Sign and TCD Comprehension

From sign conspicuity to new signal design, TCD comprehension can be addressed by a variety of simulator scenarios and was also deemed relevant by the FHWA discussions. For TCD evaluation, a relatively narrow FOV is often not limiting because TCDs are typically in the forward view. However, high-resolution graphics may be quite important. The same is true for motion. Because drivers will be making decisions (e.g., changing lanes, braking, or accelerating) in response to TCDs, the primary variables focus on measures of comprehension and judgment rather than brake and steering control. Consequently realistic control inputs, a motion base, and vehicle dynamics may not be as important with this type of design research. Dynamic late merge systems and changeable message signs fit into this topic area (*18*). Changeable message signs display lane use instructions to drivers in the section of roadway preceding a lane closure. For fluid traffic, merges can take place earlier, and for congested traffic, merges can take place later, thus increasing capacity and safety. Because these features can be replicated with a relatively narrow FOV, a relatively low-fidelity simulator might be useful to guide sign design.

Traffic Control at Novel Intersection and Interchange Types

Novel intersections and interchanges, such as roundabout design and diverging diamond interchanges, have emerged as important simulator applications. Roundabouts have well-known safety benefits in that the driver has to be vigilant and attentive during roundabout entry and turn selection. However, roundabouts are not common in North America. Therefore, experimental studies may have some novelty effects that may lead to unrepresentative data. It can be argued that roundabouts may require a wider FOV and motion capabilities in a simulator. However, as long as lane choice and speed are the criteria being studied, a wide variety of simulators may be applicable. Roundabout and intersection design has been studied previously in the simulator as well as in the field (*5, 19*). Of particular interest is the interaction between cars and trucks in multilane roundabouts. The willingness of car drivers to drive next to a truck though a roundabout could have a substantial influence on the roundabout capacity. Entry speed and lane position are both areas of interest in roundabout design.

RELATE SIMULATOR-BASED DRIVER DATA TO ROADWAY-BASED TRAFFIC DATA

The third step in applying simulators to roadway design is to relate the driving performance data obtained from the driving simulator to the type of traffic data that is typically required to support road engineering design and policy (*20*). This mapping is complicated because most driving simulator data relate to the behavior of individual drivers (often in the context of safety), whereas most traffic engineering data are aggregated to describe a volume of vehicles over time on a stretch of road or intersection, often in the context of capacity.

Traffic engineers and geometric designers attempt to encourage efficient traffic flow through road design, pavement markings and signing, and traffic control. For instance, chevrons and advisory speeds are placed on sharp curves to encourage drivers to slow down so that they can successfully negotiate the curve. Geometric designers also create a more forgiving environment to mitigate the consequences when drivers do not engage in appropriate driving behavior in a particular roadway or intersection. For example, paved shoulders provide a recovery buffer when drivers leave the roadway because they are distracted or driving too fast for conditions. Traffic engineers and geometric designers generally work at the level of traffic flow and sometimes focus on locations that have a disproportionate number of crashes (e.g., black spots), but generally do not measure how their designs influence driver behavior. Instead, the focus is often on measures of traffic flow and crash frequency.

Measures of traffic and crashes provide a limited view into how roadway design affects drivers. Single point or "spot speed" can provide a measure of aggregate estimates of traffic flow at locations of interest. Volume is a rate of vehicles passing a point during a specific interval of time. Volume measures driver demand and capacity of a facility. Traffic engineers also use records of traffic violations to measure whether drivers engage in unsafe behavior. Violation data can be obtained from enforcement agencies (i.e., number of drunk driving arrests or speeding tickets issued). Such data can also be obtained through observational studies. For instance, data might be collected to assess the number of drivers who run a red light or drivers who turn right on red while pedestrians are present. Site-based instrumentation of the future will equip intersections or other locations of interest with cameras and other sensors. These sensors will provide speed and acceleration profiles, vehicle type, and number and types of vehicle conflicts (e.g., abrupt braking and violations such as red light running). Such detailed information regarding specific driver behavior moves away from the typical traffic engineering measures of aggregate behavior of traffic to measures of individual driver behavior.

Although traffic engineers have begun to measure individual driver behavior, typical measures used by traffic engineers and the typical measures used in driving simulator assessment reveal a substantial gap that must be bridged if driving simulator results are to be applied to roadway design. Both traffic engineers and driving safety researchers face the challenge of measuring driving safety—crashes are rare events in both realistic simulator scenarios and on the road. Collaboration with traffic engineers might identify more sophisticated surrogate measures associated with lapses in steering control or abrupt braking and steering (*5*).

A more fundamental gap also needs to be bridged concerning the focus of roadway designers on traffic and of driving safety researchers on drivers. Many traffic engineering measures focus on the behavior of many drivers and cannot be reduced to the behavior of an individual driver—traffic volume is an emergent property of many drivers that cannot be derived from the behavior of a single driver. This focus on many drivers contrasts with driving safety researchers who focus on measuring individual driver performance, which often fails to consider how this performance affects traffic and how traffic affects behavior. Bridging this gap will require attention to simulator fidelity and scenario design to place drivers in a traffic context that is representative of actual driving. This context, in turn, will require documentation of traffic data so that the context includes key variables, such as traffic conditions, that can influence individual driver behavior in driving simulators. This context also requires developing and using microscopic traffic simulation models to extrapolate the measures of individual driver behavior to measures of traffic behavior. Tools for modeling traffic, such as VISSIM, AIMSUN, PARAMICS, and CORSIM, could help address the challenge of integrating realistic traffic into driving simulators (*21*).

Beyond building a bridge between measures familiar to driving safety researchers and roadway engineers, a more pragmatic challenge concerns the bridge between the tools used for roadway design, such as Autocad and Geopak, as well as microscopic traffic simulation tools, and the driving simulator. Integration of these tools could proceed on two fronts. First, the output of these tools needs to be integrated into driving simulators. Currently, transferring geometric designs or traffic characteristics from these tools to the driving simulator poses a substantial challenge. Often the roadway has to be recreated in the driving simulator, resulting in substantial additional effort and great potential for mismatches that can undermine the data validity of data collected in the simulator. The second potential for better integration concerns visualization of the design. Many design packages, such as Autocad, support visualization of geometry by enabling the designer to fly through the design. As this capability begins to approach that of a driving simulator, carefully designed visualizations could minimize the fine tuning of visual databases used in the driving simulator, greatly accelerating simulator-based testing.

CONCLUSIONS

Driving simulators hold much promise for addressing roadway design issues, particularly with recent improvements of simulator fidelity and availability. Even desktop and low-fidelity simulators reviewed as part of this paper have substantial capacity to address roadway design issues. However, to realize this promise a systematic approach to using simulators is needed. This paper provides an initial step in that direction, showing that for simulators to be useful, the simulator research community must

- Identify roadway design issues where simulators offer most promise,
- Systematically match simulator characteristics to design issues, and
- Bridge the gap between simulator-based measures of driver behavior and traffic engineering measures of traffic behavior.

These obstacles in using simulators for highway design reflect both technical and communication challenges.

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