Review of Basic Research in Bicycle Traffic Science, Traffic Operations, and Facility Design

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Recent emphasis on alternatives to automobile transportation has brought to light deficiencies in basic research performed in bicycle traffic science. Because of limited opportunities to fund such research, it is prudent to use past research to develop design guidelines and provide a basis for planning future research efforts. Mainly toward the latter end, a comprehensive review of published basic research in bicycle traffic science (with relevance to U.S. traffic) is presented, and suggestions are made for research priorities.

Recent emphasis on alternatives to automobile transportation has brought to light deficiencies in basic research performed in bicycle traffic science, traffic operations, and facility design. For example, because of a lack in understanding the characteristics of bicycle-automobile mixed traffic, there is uncertainty in the appropriate use of wide curb lanes and bike lanes. Because of limited opportunities to fund such research, it is prudent to use past research to develop design guidelines and provide a basis for planning and motivating future research efforts. Toward these ends, a comprehensive, organized review of published basic research in bicycle traffic science, traffic operations, and facility design is presented.

The reviewed studies are restricted to those published in English that have relevance to U.S. traffic environments. The primary criteria used to distinguish "basic" research are that it provides fundamental insight into the behavior of (or designs to accommodate) bicycles in traffic and uses some combination of theoretical/conceptual, experimental, and observational study of traffic involving bicycles. Except for initial conceptual work, this precludes work based primarily on engineering judgment or crash (accident) data.

Because of the breadth of studies reviewed, detailed evaluation of each study is left for future researchers. At most, only a brief narrative summary of a study is provided, along with related commentary on the current state of (and future needs for) basic research in each area. Details, such as actual numeric results and analysis methodologies, usually are not given.

The review is organized according to the framework in Table 1. The intent is to provide a category for all topics, not to list all possible topics. Furthermore, each level is developed to a different degree. The seven main outline divisions correspond to the first seven sections. The final section contains some concluding comments, including the authors' suggested high-priority research areas.

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BICYCLE/RIDER UNIT CHARACTERISTICS

There does not seem to be a great need for research on the static and dynamic characteristics of bicycle/rider units (e.g., length and height). Most published data consist of simple measurements of a few bicycle/rider units. Three studies, however, evaluate devices designed to increase the spacing between a bicycle and passing vehicles, most notably a flag mounted on the rear of the bicycle and projected horizontally into the road (*1–3*).

Published research on operating characteristics is reviewed, beginning with perception-reaction time, followed by speed, deceleration, acceleration, and obeying "rules of the road." Design values, seemingly based on engineering judgment, for cyclist perception-reaction time following a yellow traffic signal are given in two design guides (*4,5*). Wang and Wei (*6*) report that research in China indicates bicyclists' start-up perception-reaction times at traffic signals are more than one second less than motorists'.

Bicycle travel speed distributions have been measured by several researchers, including Smith (*7*), Opiela et al. (*8*), Forester (*9*), Taylor (*10*), and Pein (*11*), in various environments. However, besides profile grade, which is discussed below in the geometric design section, no significant basic research was found that relates bicycle travel speed to factors that might affect it.

Taylor (*10,12*) measured comfortable bicycle deceleration rates by experimentation on willing cyclists who were told they had just seen a yellow light. Rice and Roland (*13*) related "hard" stopping distances to speed, brake type, and cyclist weight for "a large number" of experimental tests. Both Whitt and Wilson (*14*) and Taylor (*10*) discuss the theoretical limits of bicycle braking decelerations, such as wet weather limits and limits to prevent cyclists from rotating "over the handlebars." Finally, as pointed out by Taylor (*10*), the state of bicycle braking systems in the general population is unknown, and assessing it is of some importance.

Pein (*11*) estimated bicycle acceleration from a stop from trailside observations. His estimation method also might be used with similar on-road data, such as that collected by Smith (*7*) at stop, yield, and signal-controlled intersections. Design bicycle acceleration values, seemingly based on engineering judgment, are given in two design guides (*4,5*). Taylor (*10*) measured bicycle acceleration from cruising speed for a small number of experimental participants.

Analyses of crash data usually show that most bicycle-automobile collisions are caused by cyclist or motorist error (*9,15–18*). A hypothesis explaining this is that vehicle operators not obeying the "rules" cause confusion that can lead to collisions. Thom and Clayton (*19*) found that only about one-half of 900 observed bicyclists obeyed all the rules. Dewar (*20*) found that riding errors were

TABLE 1 Organizing Framework for Topics in Bicycle Traffic Science, Traffic Operations, and Facility Design

I. Bicycle/Rider Characteristics
- A. Static
  - a. Length
  - b. Width
- B. Dynamic
  - a. Height
  - b. Weight
- C. Operating
  - a. Perception-reaction
  - b. Speed
  - c. Work on upgrades
  - d. Braking
  - e. Accelerating
  - f. Turning
  - g. Obeying "rules of the road"

II. Traffic Flow
- A. Characteristics
  - 1. Mid-block
  - 2. Intersections
- B. Models
  - 1. Macroscopic
    - a. Speed, flow, density relations
  - 2. Microscopic
- C. Gap Acceptance
- D. Queuing

III. Intersection Control
- A. At-grade
  - 1. Uncontrolled
  - 2. Yield
  - 3. Stop
  - 4. Signalized
    - a. Signal timing
    - b. Actuated control
- B. Interchanges

IV. Capacity and Level of Service
- A. Uninterrupted Flow
  - 1. Separate Paths
  - 2. Bike Lanes
- B. Road Suitability Analysis
- C. Interrupted Flow

V. Networks
- A. Arterial progression systems

VI. Computer Models
- A. Simulation
- B. Optimization

VII. Geometric Design
- A. Cross-Section Elements
  - 1. Facility Width
  - 2. Cross Slope
  - 3. Lateral Clearances
- B. Pavement Surface
  - 1. Pavement Depth & Sub-base
  - 2. Coefficient of Friction
  - 3. Obstacles and Obstructions
- C. Vertical Alignment
  - 1. Profile Grade
  - 2. Vertical Curves
  - 3. Sight Distance
- D. Horizontal Alignment
  - 1. Radius of Curvature
  - 2. Sight Distance
  - 3. Superelevation
  - 4. Transitions
- E. Intersection Configuration
  - 1. Roadway Intersections
  - 2. Separate Paths

committed by 32 percent of approximately 2,200 observed bicyclists and that 3 percent made multiple errors.

Engineers often assume that vehicle operators obey the "rules of the road" while recognizing that facility design also influences behavior. For example, bike-lane striping at intersections often is thought to affect whether motorists and bicyclists obey the rules (*21*). The fundamental insight pertaining to the design and operation of bicycle facilities is that too many bicyclists and motorists disobey the rules to an extent that seems to cause crashes. Forester (*9*) developed a training course for bicycling in traffic based on obeying the rules, and experts often propose that correct bicycle-automobile interaction be included in standard driver education courses and driver license testing. Although training, education, and enforcement are important components in solving this problem, engineers also must be concerned with how facility design and operation might affect such behavior.

The weakness of the basic research in this area is that it is based mostly on theory and the analysis of crash data, which has several inherent problems. Crash data from agency record systems (*a*) include a low percentage of bicycle crashes, which usually are not indicative of the larger population, and (*b*) usually are configured to record motor vehicle crashes, which often do not fully capture important factors related to a bicycle crash. These problems require that supplemental work be conducted for bicycle crashes. Creation of an effective supplemental crash recording system is a very difficult undertaking. A possible next step would be to conduct experimental or observational analysis to relate factors, such as bicyclist and roadway environment characteristics, to obeying the rules.

Bicycle/rider unit turning characteristics and capabilities are important to the geometric design of bicycle facilities. Several mechanical engineering-type studies were located, but they are not reviewed because of space limitations.

TRAFFIC FLOW

Studies reviewed in this section have implications for capacity and level of service. Similarly, some studies reviewed in the "Capacity and Level of Service" section (see p. 105) also apply to this area.

Characteristics

Several researchers have performed observational studies attempting to characterize midblock bicycle-automobile mixed-traffic flow (*9,21–29*). The predominant study methodology used is observing lateral lane position and speed before, during, and after an automobile passes an adjacent bicycle. Attempts then are made to correlate speed and position changes with factors such as characteristics of the bicycle facility (e.g., width of curb lane or presence of bike lane), automobile speeds, and automobile volumes. One general conclusion is that the presence of bicycles negatively affects auto flow (in terms of speed reduction and lateral movement) by limiting the usable roadway width. Another is that these negative impacts seem to be reduced or removed if a bike lane or a wide enough curb lane is provided.

Each researcher makes guarded recommendations (e.g., design widths for curb lanes and bike lanes) based on his or her perceptions of the limitations of the study. The most comprehensive recommendations are self-described as requiring further assessment and refinement because they are highly based on assumptions regarding policy goals, the state of practice, and engineering judgment (*30*). Further basic research of this type is needed to provide planners a richer basis on which to recommend on-street bicycle facility types for specific situations and engineers a more complete basis on which to design such facilities. Additional research in this area could include studying the operational effects of other bicycle facility-related pavement markings, such as different bike-lane color treatments, special roadway stencils to delineate the bicycle space in a wide curb lane, and stripe width/style for bike lanes.

Using a specially developed system of sensors, Botma and Papendrecht (*31*) collected bicycle data on unknowing cyclists on one-directional paths at four locations in The Netherlands. They present the average length of passing maneuvers and percentiles of the distribution of lateral positions during passing and conclude that the passing maneuver length is shorter and the separation between side-by-side cyclists is less on narrower paths. Smith (*7*) also measured separation between side-by-side cyclists on different paths, using willing participants. Another interesting finding of Botma and Papendrecht (*31*) is that the frequency of passing maneuvers is proportional to the squared volume.

Smith (*7*) reports bicycle saturation flow rates obtained by experimentation for three different bike-lane widths. One of these is compared with a rate derived from observing bicyclists disperse from “queues” at an actual signalized intersection with a bike lane of similar width. Ferrara and Lam (*32*) conducted observational experiments on bicycle-automobile mixed-traffic behavior at intersections.

Models

Smith (*7*) observed unwilling cyclists on paths and derived speed-density-flow relations. With a small number of participants, Navin (*33*) experimentally derived a speed-volume relation for bicycle-only traffic. He compared it to those found by Botma and Papendrecht (*31*) (who found a weak relation between bicycle path flow in “platoons” and mean speed) and Liu et al. (*34*) and a theoretical upper bound. Navin (*33*) also experimentally determined a circulation zone, a comfort zone, and a collision zone around a bicycle traveling in a bicycle-only traffic stream. The sizes of these have implications for level of service and bike-path design width. Navin’s (*33*) experimental methods might be worthy of repeating with larger and more diverse samples.

When attempting to model bicycle-automobile mixed-traffic flow, one might look to modify methods such as the one Lebacque et al. (*35*) proposed for integrating buses into a first-order macroscopic flow model. Khan (*36*) reviews a few methods to evaluate traffic flow in a mixed, non-lane-based context for developing countries. These methods attempt to capture the “unique characteristics of traffic composition, driver behavior, roadway geometry, maneuverability and vehicular interactions that require a separate set of tools to study the flow and performance of the roadway.” As such, models of this type may be conceptually superior to ones developed for homogenous (automobile-only) traffic and subsequently modified for heterogeneous traffic. In some environments, in which traffic involving bicycles becomes “heterogeneous enough” (e.g., busy downtown streets), such models may prove useful in the United States. In addition to flow models, Khan reviews several studies of speed-flow-density relations for heterogeneous traffic and concludes that the measure “a real density” (the total area projected by vehicles on the ground per unit area of roadway) has great potential.

Gap Acceptance

The prevailing notion of the critical gap is that it is the minimum gap duration that will be accepted by an individual vehicle/operator unit in a specific situation (*37*). This critical gap varies across the population, and some percentile can be used for analysis and design. Smith (*7*) estimated the mean value of the critical gap distribution for motorists accepting gaps in bicycle traffic at the intersections of two-lane streets and for bicycles crossing motor vehicle traffic on a two-lane street. Opiela et al. (*8*) did the same for bicycles crossing two lanes of one-way motor vehicle traffic but did not use the standard method of measuring the accepted gap. Taylor (*12*) estimated discrete choice (probit) models of both motorist and cyclist gap acceptance behavior when crossing and merging with bicycle-automobile mixed traffic at three low-speed, stop-controlled intersections near a university campus. He not only estimated the mean value of the overall critical gap distributions but also the magnitude and direction of the effects of various factors on the mean critical gap. Significant factors included (*a*) the size and type of the vehicle closing the gap, (*b*) the type of maneuver, and (*c*) the lane position of the cyclist attempting the maneuver.

Each study observes a limited number of gap acceptance decisions in a limited number of situations. Only Taylor’s study (*12*) attempts to quantify factors that affect the behavior. Future research should focus on the factors affecting bicyclist gap acceptance in a greater variety of situations. Specific consideration should be given to studying intersections with a variety of curb lane and bike lane widths, with higher speeds, and that are not close to college campuses. Richer data on more general cycling populations also are required.

INTERSECTION CONTROL

Past work in the area of intersection control is concentrated around signalized intersections. No basic research was found regarding the operational effects of intersection traffic-control devices for bicycles, with the possible exception of an English study (*38*), which was not located. This would seem to be an area for future research. Work in signal timing is reviewed first, followed by actuated control and interchanges.

Wachtel et al. (*39*) analyzed the minimum green time required for cyclists stopped on a red. Several researchers, including Forester (*9*) and analysts in Oregon (*16*), have concluded through analysis of crash data that inadequate clearance intervals (i.e., the combination of the yellow change interval and any all-red clearance interval) exist for bicycles at some intersections. Taylor (*10,12*) and Wachtel et al. (*39*) use standard deterministic equations to show that this is the case if the design clearance point (i.e., the point cyclists must reach) for safety is much inside the stop bar. The limitations of this approach include (*a*) the fact that the location of the design clearance point varies over intersections and is unknown, (*b*) the lack of data on perception-reaction times, and (*c*) the small sample of data on which to base the required design deceleration (*10,12*). If a designer decides extra clearance is warranted, Taylor (*12*) and Wachtel et al. (*39*) suggest various ways to provide it and various ways to convey the signal change warning to cyclists while limiting impacts to automobiles.

Taylor (*12*) developed a probability-of-stopping model from roadside observations of cyclists' behavior at the onset of yellow and found several factors that affected this behavior. He shows how such models provide insights for the design of clearance intervals and how they can be used to evaluate the effects of different intervals and different methods of providing the signal change warning. He suggests that the main limitation is a lack of observational study of the impacts of clearance intervals longer than those normally provided for automobiles and that the logical next step is such analysis using "before and after" probability-of-stopping models.

Since detection is required for actuated control, studies of bicycle detection technology apply, including those on standard loop detectors (*40,41*). Several studies also were found on more advanced detection systems, such as pattern recognition and classification (*42–44*). No basic research was found that explores the use of detection to design actuated control systems for cyclists.

Liu et al. (*34*) diagram four different types of bicycle interchanges used in China and analyze their capacity. Wang and Wei (*6*) also diagram two Chinese bicycle interchanges.

CAPACITY AND LEVEL OF SERVICE

Along with the discussions that follow, many issues pertaining to this area were presented in the previous section on "Traffic Flow."

Uninterrupted Flow

Analysis of uninterrupted flow conditions along facility segments where uniform flow conditions exist and interference from lateral or adjacent facilities is minimal is used to establish relationships among width, speed, and quality of flow. Traditional applications of this approach are used extensively in the *Highway Capacity Manual* (HCM) (*45*).

Separate Paths

Botma (*46*) developed capacity evaluation procedures relating level of service (LOS) to impedance by evaluating the frequency with which a cyclist would encounter other cyclists and pedestrians on paths in The Netherlands. Based on field observations of the number of bicycles passing and meeting, and the number of pedestrians passing and meeting an average cyclist, constants and coefficients were identified to constitute a best fit. Data pertaining to volume peaking, facility width, and speed distributions were used to establish a predictive formula. LOS is determined from a prediction of the number of bike/pedestrian events encountered.

Virkler and Balasubramanian (*47*) verified this approach by applying the suggested methodology to two case-study locations. Allen et al. (*48*) used Botma's method as the basis for updating the HCM 2000 for bicycles.

Bike Lanes

Allen et al. (*48*) evaluated bike-lane capacity and LOS by treating bike lanes as a one-way separate path. However, the interaction among cyclists, motor vehicle traffic, and other adjacent roadway factors such as the presence of parking was not taken into account.

Roadway Suitability Analysis

Prior to the determination of capacity and LOS for bicycle facilities based solely on flow parameters, a number of research efforts evaluated the compatibility or suitability for bicycle travel along existing roadways based on an array of factors. Using field data, Sorton and Walsh (*49*) evaluated the *stress level* for casual and experienced cyclists based on curb lane width, adjacent traffic volume, and adjacent traffic speed. Davis (*50*) used data collected along eight route segments in Atlanta, Georgia, with varying combinations of conditions to evaluate *cyclist perception of exposure* to traffic volume, traffic speed, lane width, grade, pavement condition, and several other factors. Cyclist perceptions and variations were compared with empirically derived suitability predictions based on measured values. Other work on this aspect of cycling includes Landis (*51*) and Kahn (*52*).

Putman and Ross (*53*) used various suitability analysis methods to evaluate 700 roadway segments in Madison, Wisconsin. The results demonstrated the effectiveness of the methods for management-related purposes when used on a network basis. Two hundred participants evaluated video-recorded conditions for three roadway locations in different cities and provided a value indicating their comfort level (*54,55*). Physical measurements at each site were used in a regression analysis to determine a *bicycle compatibility index.* Factors used in the prediction formula included curb lane width, presence of a bike lane, exposure to parking, 85th-percentile speed, lane volumes, and type of developed area.

Interrupted Flow

Interrupted flow analysis relates to operational characteristics at signalized and unsignalized intersections. The capacity analysis and LOS procedures (based on converting bicycles to an equivalent number of passenger cars) presented in the HCM (*45*) essentially are structured to determine the inconvenience of bicyclists to motorists. Allen et al. (*56*) studied six signalized intersections using video surveillance to evaluate the impact of cyclists on motor vehicle saturation flow rates. Regression analysis was used to predict percent occupancy of bicycles versus bike volume per hour of green time. This was used to calculate impedance factors similar to those used for pedestrian flows. Pedestrian and bicycle flows were analyzed to determine how these travel modes impede the flow of right- and left-turning motor vehicle traffic. Impedance values are used as reduction factors for saturation flow rates of the various turn-lane groups.

NETWORKS

It seems as if the only published work regarding networks for bicycle traffic is on signal coordination for progression along a street segment. Taylor (*12*) developed a framework for analyzing simultaneous bicycle-automobile mixed-traffic progression (or bicycle-only progression) along signalized streets. First, principal considerations for bicycle progression were articulated. Second, several techniques that provide improved (or alternative) multiobjective solutions were analyzed. Finally, a multiobjective framework for solving the design problem was proposed. It incorporates both the principal bicycle considerations and the techniques. The primary limitations of this work are that it is purely conceptual and it assumes constant (average) bicycle speeds. As suggested by Taylor (*12*), the next logical step would seem to be a test project or projects to study bicycle speed variability under actual conditions, in addition to determining actual benefits, perceived benefits, and any characteristics of bicycle "platooning."

COMPUTER MODELS

No computer simulation or optimization programs developed for bicycles were found. As pointed out by Sharples (*57*), the basic research on which to base bicycle traffic simulation is insufficient. A few limited attempts have been made, however. Khan (*36*) reviews several attempts to simulate heterogeneous traffic in developing countries. A few simulations have been developed to investigate intersection control, conflicts, and delay (*7,32,58,59*). Sharples (*57*) investigated how to include bicycles in existing simulation software (SATURN).

GEOMETRIC DESIGN

Primarily for the purpose of identifying basic research needs related to the design of bicycle facilities, this section provides brief overviews of the principal design guidelines and identifies the primary sources used to develop them. Unless otherwise noted, the authors found little need for future research in the associated sub-area.

In general, there is a series of nationally adopted criteria and design guidelines (*4,60,61*) pertaining to roadway (including separate paths) and geometric design for bicycle facilities in the United States. Most guidelines have been developed primarily using a combination of engineering judgment and the extensive research and knowledge pertaining to design and construction of roadways for motor vehicles. This is the case unless otherwise stated in the following subsections. In some instances, however, research on bicycle traffic has been used to supplement the motor vehicle research. Much of this bicycle research has been reviewed above. In this section, further basic bicycle research is reviewed, and reference is provided to sections above where appropriate.

Cross-Section Elements

Facility Width

AASHTO (*4,62*) uses the bicycle width, generally taken as 0.75 m, with operational clearances to derive design widths for all facility types. See the Characteristics section in "Traffic Flow" (p. 103) for a discussion of related refinements to guidelines for curb lane and bike lane widths. Studies on truck windblast document the importance of this factor to shoulder-width design (*7,63*).

Widths for separate bicycle paths generally comprise the minimum aggregate width (2.4 m) of two bike lanes (1.2 m) (*62*). For mixed operations with pedestrians, joggers, roller-bladers, and so forth, recommended minimum widths increase based on engineering judgment and on aspects discussed previously in the "Capacity and Level of Service" section.

Cross-Slope

Cross-slopes for roadway pavements are commonly in the range of 2 percent. This value has proven effective in reducing motor vehicle hydroplaning and has been carried over to bicycle facilities. On separate paths, a uniform minimum cross-slope of 2 percent usually is recommended (*61,62,64*). There is no evidence that bicyclists are as prone to hydroplaning as motor vehicles. However, proper drainage serves to preserve the life of the pavement and reduce debris on paved surfaces.

Lateral Clearances

Design guidelines in the area of lateral clearances include minimum graded shoulder widths of 0.6 m for separate paths (*62*) and offsets to obstructions such as bridge rails and ground-mounted signs (*61, 62,64*). However, Botma and Papendrecht (*31*) observed bicycles on separate paths to obtain the distribution of shy distances from the curb and concluded that shy distance did not depend on curb height. Smith (*7*) also measured shy distances from various obstructions in both on-road and separate path situations.

Pavement Surface

Pavement Depth and Sub-Base Design

Unlike design criteria for the pavement and sub-base thickness of on-street bicycle facilities, roadway design practice does not translate well to design for separate paths. Pavement thickness for roadway design is based on 18-kip equivalent single axial loading that will occur over the 20-year design life of the roadway. Pavement thickness for separate paths is recommended to be a minimum of 7 to 15 cm for asphalt and 4 to 5 cm for concrete, assuming proper subgrades and base courses (*61,64*). These depths generally are based on the minimum lifts at which paving materials can be constructed. With regard to asphalt pavements, design criteria for use of high-asphalt content to reduce stress cracking (as in low-volume roads) appear most appropriate for bicycle path design. The authors, however, are not aware of research conducted to verify this or other bicycle path paving design criteria.

Coefficient of Friction

Values for coefficient of friction, extrapolated from highway design, are taken to range from 0.31 to 0.21, dependent on speed, pavement type, surface roughness, tire type/condition, and wet/dry surface (*62*). These values affect the minimum radius of horizontal curvature and stopping sight distance. The authors are not aware of any basic research that has been conducted to verify these important values.

Shoulder Rumble Strips

Garder (*65*) reviews the basic issues of rumble-strip use on highway shoulders used by cyclists. Using small samples of bicycle/rider units and rumble-strip test sections, both Garder (*65*) and Ardekani et al. (*66*) tested several designs. Proposed FHWA policy recommends that rumble strips (either raised or milled) be placed within 1.2 m of the inside edge of the pavement edge line and not be allowed on shoulders less than 2.2-m wide. Alternating gaps in the patterns will be provided near intersections (*67*). These criteria are being addressed by FHWA and AASHTO based on engineering experience.

Obstacles and Obstructions

Typical obstacles or obstructions addressed in the design of bicycle facilities include drainage grates, railroad crossings, and motor vehicle barriers (located at entrances to separate paths). Details for providing safe designs (*61,64*) for bicycle operation have been developed through sound engineering judgment similar to the approach effectively used in the nationwide effort during the 1970s and 1980s to eliminate roadside hazards to motorists.

Vertical Alignment

Vertical alignment or profile issues related to on-street bicycle facilities are controlled by the higher design speeds required to accommodate motor vehicle traffic. Discussion related to the following design issues is limited to separate paths.

Profile Grade

Design of profile grades for separate paths is recommended to be 5 percent or less (*61,62,64*), primarily due to the difficulty cyclists have in climbing long grades. Recommendations for increased grades along with maximum grade lengths are suggested for grades up to 12 percent (*62*). Navin (*33*) verified these guidelines in an experimentally based study on a small number of participants. Smith (*7*) derives relations between human work effort and gradient based on theory and experimental measurements and demonstrates their use for design. Additional recommendations related to increased path width, longer sight distances, and descent speed signing are cited in AASHTO (*62*) for steeper-than-desirable grades. However, Navin (*33*), like the authors, found no basic research to verify downgrade impacts.

Vertical Curves

Similar to roadway design, vertical curve design (for a crest curve) is based on a parabolic curve equation established to accommodate a desired stopping distance between points related to eye height and object height. For roadway design the driver eye height is 1000 mm and the object height is 150 mm. For bicycle path design the cyclist eye height is 1400 mm and the object height is 0 mm (*62*). The length of crest vertical curve is determined using a methodology based on sound engineering principles governing geometric relationships. However, sag vertical curve criteria and passing sight distance criteria for crest vertical curves on bicycle paths are not addressed in AASHTO (*62*) or other design guidelines.

Sight Distance

A nomograph has been developed to estimate minimum stopping sight distance for various downgrades at predetermined operating speeds ranging from 10 to 50 km/h (*62*), based on a total perception-reaction time of 2.5 s and a coefficient of friction of 0.25. Computation of this value is used to determine the crest-vertical-curve formula. Future basic research is needed only for verifying perception-reaction time and coefficient of friction, not in the theory underlying the nomograph.

Horizontal Alignment

The curvature and sight distances resulting from the horizontal alignment of a bicycle facility directly relates to the maximum travel speed of a cyclist along the facility. Horizontal alignment issues related to on-street bicycle facilities are dictated by the more stringent requirements associated with motor vehicles. Discussion related to the following design issues is limited to separate paths.

Radius of Curvature

AASHTO (*62*) has developed two empirical formulas (based on bicycle lean angles of 15 and 20 degrees) for the minimum curvature of a bicycle path relating travel speed to the radius of curvature and rate of superelevation. These formulas are based on geometric principles of centrifugal force related to speed, coefficient of friction, and radius of curvature. Similar to roadway design, pavement widening is recommended in curves that are sharper than cyclists normally would expect along a given bicycle path (*61,64*).

Sight Distance

Stopping sight distance issues associated with horizontal alignment are related to line of sight as obscured by a lateral obstruction. A required value is computed for the line of sight and compared with the stopping sight distance determined from a nomograph as previously described. The line of sight is determined from the radius of curvature, object distance from the center of the lane, and design speed. AASHTO (*62*) provides a tabular summary of minimum lateral clearance dimensions for various radii and sight distance values.

Superelevation

Roadway guidelines commonly recommend use of superelevation as high as 8 to 10 percent. Even though superelevation is analytically associated with horizontal curvature, its effect is limited in bicycle path design due to the Americans with Disabilities Act limitation of a 2 percent maximum (*62*). Furthermore, the ability to consistently construct superelevated curves on the narrow widths used for bicycle paths is problematic.

Transitions

Lengths for transitioning laterally away from obstructions or along a facility without providing horizontal curvature are based on the width (or offset) of the obstruction and the design speed (*62*). Considering that bicycles typically operate at speeds well below those of motor vehicles, this method should serve as a more than adequate criterion for bicycle paths.

Intersection Configuration

Roadway Intersections

Geometric design treatments have been developed to deal with many of the inherent conflict problems between bicycles and automobiles at intersections, such as when cyclists turn left or negotiate exclusive right-turn lanes/merge areas. These treatments typically involve bike-lane placement, delineation of weaving areas, and/or widening of shared lanes (*62*) and require that a bicyclist operate according to the "rules of the road" (see "Bicycle/Rider Characteristics" section). Wang and Wei (*6*) present several unique Chinese intersection designs that attempt to handle bicycle-automobile conflicts, including "bicycle banned areas" and "second stop lines."

Separate Paths

Design criteria for separate paths commonly recommend that roadway crossings be aligned to allow cyclists to cross in areas typically used as pedestrian crosswalks (*62*). Other criteria derived from traditional roadway design methods include the use of an approximate 90-degree angle of intersection, use of advance warning signs, use of pavement markings, and provision of Case I, II, and III sight-distance lengths.

CONCLUDING COMMENTS

Some of the knowledge gaps highlighted by this review may be addressed by studies that were not reviewed, such as those not published in English. Efforts should be made to uncover such studies. Efforts also should be made to find and apply analysis techniques from studies not related to bicycles.

The contributions of this review are fourfold. First, the key sources are organized and briefly summarized in one document. Second, it provides researchers with a background for selecting and designing research studies. Third, the review organization lends itself well to the development of graduate seminar courses on bicycle traffic engineering. Finally, it can aid in the development of a prioritized research agenda.

When one can review "all" the published basic research in a paper of this size, it is obvious that significant research is required in almost all areas. For example, research directed at gaining a fundamental understanding of rudimentary bicycle/rider unit behaviors, such as perception-reaction, deceleration, and gap acceptance, seems long overdue, since measures of such behaviors are fundamental to numerous design calculations. Recognizing the lack of funding for basic bicycle traffic research, the authors make the following three suggestions for high-priority areas of future basic research.

First, there is still controversy surrounding the choice of wide curb lanes or bike lanes (and their appropriate widths). Therefore, a high priority should be placed on enriching the basic research on bicycle-automobile traffic-flow characteristics to assess and refine the most comprehensive design recommendations (*30*) pertaining to these choices. (Recently completed research at the University of North Carolina may reduce this priority.)

Second, with the success of current efforts to advance the understanding of bicycle capacity and LOS analysis, future research should focus on improving methods to analyze mixed-use characteristics of both separate paths (bicycles/walkers/joggers/rollerbladers) and shared roadway facilities (bicycles/motor vehicles). Uninterrupted flow research should be expanded to take in additional factors (beyond flow and event encounters) that relate to cyclist perception of LOS, especially with regard to shared-use facilities. Interrupted-flow research for mixed-traffic operation at intersections is required to develop composite capacity and LOS criteria rather than merely evaluating bicycles in terms of motor vehicle impedance.

Third, evaluation of previously constructed facilities (especially separate paths) is needed to determine adherence to national design criteria. Design issues such as inadequate pavement construction, nonconsistent cross-section elements, and uncontrolled horizontal/vertical alignment all can significantly compromise the effectiveness of a facility if contractors are not adhering to design criteria.

In a broad sense, the basic research in this field needs to be augmented by more advanced and comprehensive works to help facilitate the paradigm shift to the more multimodal transportation system that is underwritten in the Intermodal Surface Transportation Efficiency Act of 1991 and TEA-21 legislation.

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