Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
1732-S		

4. Title and Subtitle REEVALUATION OF RAMP DESIGN SPEED CRITERIA: SUMMARY REPORT	5. Report Date January 2000
7. Author(s) Michael Hunter, Randy Machemehl, and Alexei Tsyganov	6. Performing Organization Code 8. Performing Organization Report No. 1732-S
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-1732
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080	13. Type of Report and Period Covered Project Summary Report (3/1/99 to 8/31/99) 14. Sponsoring Agency Code

15. Supplementary Notes
Project conducted in cooperation with the Federal Highway Administration.

16. Abstract

In this study, the researchers traced freeway ramp design speed criteria contained in current AASHTO and Texas Department of Transportation (TxDOT) design policies through roughly 50 years of technical literature. It was seen that TxDOT ramp design speed criteria are, essentially, the AASHTO criteria. The origins of driver deceleration rates, which are built into AASHTO criteria, are the experimental studies performed during the late 1930s. Several studies have raised questions about the appropriateness of the AASHTO minimum allowable ramp design speed, which is 50 percent of the freeway design speed. Questions have also been raised about the adequacy of high-speed ramp lengths designed using the AASHTO criteria. Clearly, a thorough examination of current ramp design procedures is in order. Simply stated, this examination was the primary objective of this study. The analysis and primary data collected through the study have led to a better understanding of freeway ramp operations. As noted in the report, freeway sections with ramps are usually primary freeway bottleneck locations and are, therefore, operationally critical. Improved understanding of operations in these critical freeway sections constitutes a secondary but significant benefit.

17. Key Words:	18. Distribution Statement
Freeway ramp design speed criteria, geometric design, entrance ramps, exit ramps	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	26	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

REEVALUATION OF RAMP DESIGN SPEED CRITERIA: SUMMARY REPORT

by

Michael Hunter,

Randy B. Machemehl,

and

Alexei Tsyganov

Project Summary Report Number 1732-S

Research Project Number 0-1732
Project Title: *Reevaluation of Ramp Design Speed Criteria*

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

January 2000

IMPLEMENTATION RECOMMENDATIONS

This study examined current freeway entry ramp design speed criteria by undertaking field observations of entry ramp traffic operations and by conducting analyses attempting to identify relationships between vehicle speeds and geometric features. Three specific recommendations were developed:

1. The AASHTO acceleration rate model used to estimate acceleration lane lengths should not be changed.
2. The design criterion defining a ramp's design speed as 50 percent of the freeway design speed should be deleted from AASHTO and TxDOT policy.
3. Acceleration lengths for taper-type entry ramps should include only the lane portions from which ramp drivers can clearly view the freeway right lane traffic. The AASHTO acceleration length model should be clarified to include this specification.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

Randy B. Machemehl, P.E. (Texas No. 41921)
Research Supervisor

ACKNOWLEDGMENTS

The authors express their sincere thanks for the support of TxDOT Project Director Ed Pensock (Texas Turnpike Authority Division) and Program Coordinator A. J. Krejci (DES). The authors also acknowledge the video support provided by personnel at the Houston Transtar and San Antonio Transguide traffic operations centers.

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

PROJECT SUMMARY REPORT

PROBLEM DESCRIPTION

Ramp facilities provide all freeway entrance and exit opportunities. Freeway sections adjacent to ramps are, therefore, analogous to arterial street at-grade intersections in that they create traffic stream friction limiting speeds and capacities. Freeway bottlenecks most often develop in the vicinity of entrance or exit ramp junctions. Clearly, excellent freeway ramp design is a critical freeway operational consideration. Currently, the American Association of State Highway and Transportation Officials (AASHTO) (Ref 1) and the Texas Department of Transportation (TxDOT) (Ref 3) design procedures state that ramp design speeds are to be a percentage of the freeway design speed. The TxDOT design procedures manual [3] states

> All ramps and connections shall be designed to enable vehicles to leave and enter the traveled way of the freeway at no less than 50% (70% usual, 85% desirable) of the freeway's design speed . . .

The choice of ramp design speed can significantly impact ramp curve radii, stopping-sight distances, and speed change lane lengths. Changes in vehicle characteristics and driver behavior may influence predicted vehicle performance, upon which the ramp design speed policy is based. Also, many of today's ramp designs may not fall within the scope of the original studies upon which the designs are being based. There exists a need to thoroughly evaluate not only current freeway ramp design speed policy, but also related ramp facility elements, including acceleration or deceleration lane lengths.

STUDY OBJECTIVES

The study team traced freeway ramp design speed criteria contained in current AASHTO and TxDOT design policies through roughly 50 years of technical literature. Four major findings from the documentation of the evolution of design speed criteria are as follows:

(1) TxDOT ramp design speed criteria are, essentially, the AASHTO criteria.

(2) The origins of driver deceleration rates, which are built into AASHTO criteria, are the experimental studies performed during the late 1930s.

(3) Questions exist regarding the appropriateness of the AASHTO minimum allowable ramp design speed, which is 50 percent of the freeway design speed.

(4) Questions have been raised regarding the adequacy of high-speed ramp lengths designed using the AASHTO criteria.

Clearly, a thorough examination of current ramp design procedures is in order. Simply stated, this examination was the primary objective of this study. The analysis and primary data collected through the study have led to a better understanding of freeway ramp operations.

As noted earlier, freeway sections with ramps are usually primary freeway bottleneck locations and are, therefore, operationally critical. Improved understanding of operations in these critical freeway sections constitutes a secondary but significant benefit.

This study's objectives included both a historical-theoretical and an experimental point of view in order to:

(1) Evaluate through literature review and analysis current ramp design speed criteria.

(2) Evaluate current ramp design speed criteria through a carefully designed sample of ramp operational data.

(3) Provide sufficient evidence to validate current ramp design speed policy or to modify current procedures.

RESEARCH TASKS

Survey of Design Practice

During the literature review, the study team obtained an unpublished survey of design agencies. Even though the survey does not deal explicitly with ramp design speed, the core ramp design speed issue is really speed change lanes, and the survey deals directly with this element. Significant findings developed through this survey were (1) acceleration operations are viewed as more problematic than deceleration; (2) driver behavior during speed changes is not well characterized; (3) virtually all agencies rely upon accident experience as the primary performance evaluation measure; (4) very little operational data describing speed change or ramp operations have been collected; and (5) differing agencies do not use the same design criteria. Additionally, effects of control devices, specifically ramp metering, are not well known.

Although this survey was conducted almost 10 years ago, major changes in these findings are not likely. The literature review confirmed that little operational data have been collected either by agency activities or by research efforts.

Accidents

One aspect of ramp design, and of geometric design in general, that has been sporadically studied over the past decades is the effect of geometric features on accident rates. One of the most thorough and frequently referenced reports on the relationship between accidents and design is *Analysis and Modeling of Relationships between Accidents and the Geometric and Traffic Characteristics of the Interstate System* [16]. This study, based on data from twenty states, considered such items as number of lanes, design speed, lane width, maximum curvature, pavement type, grade, stopping-sight distance, number of information and advertising signs, lighting, volume, and percent commercial vehicles. This study presented several findings of interest, including (1) increased traffic volumes resulted in an increased number of accidents, (2) traffic-oriented variables (i.e., volume, percent trucks, etc.) contributed most to the variance in accidents on the Interstate system, (3) geometrics alone accounted for only a small portion of the variance in accidents, and (4) no relationship could be determined between the geometrics studied and fatalities.

The third and fourth points, which involve geometrics, are clarified within the Interstate system report. The sites chosen for study by each contributing state were supposedly "representative" locations rather than high-accident locations. This selection process probably eliminated from study those interchanges and ramps whose under-designed geometric features would cause excessive accidents, although a small fraction of the data submitted did seem to show exceptionally high accident frequencies. For these interchanges, a separate "failure analysis" was performed. This analysis better highlighted the effects of unusual design features, geometrics, and traffic characteristics not seen in the "representative" samples. While high traffic volumes are still regarded as the primary cause of accidents, additional information relating to geometrics revealed that (1) design speeds that are too low can, to a considerable degree, cause accidents; and (2) on most of the ramp types, poor geometric features (short speed change lane, sharp curvature, and too short stopping-sight distance) can, to a considerable degree, cause accidents.

More recently, *Accidents and Safety Associated with Interchanges* [12], which provided a review of data and experience from other research efforts, reported that (1) an increase in accident rates occurs with increasing maximum curvature; (2) increasing accident rates occur with increasing average daily traffic; (3) horizontal curvature is a more significant factor in accident rates than grades; (4) both roll-over and skidding potential must be checked when designing ramp horizontal curves to accommodate trucks; and (5) the relative safety of an urban interchange is enhanced where 800 ft (244 m) or longer acceleration or auxiliary lanes are provided [20, 21, 22, 23].

Other points were raised in another study [13] in which the general conclusion was that current AASHTO design standards (specifically open road horizontal curve design parameters) provide safe operation for both passenger cars and trucks, though accidents (rollover and skidding) were observed to occur at undesirable levels when unrealistic design speeds were used. Where AASHTO design assumptions (i.e., speed of vehicle) are not violated, adequate margins of safety are provided; but where vehicles exceed design speeds, unsafe conditions are created. The conclusion of this study highlights the need for careful selection of design speed and certainly leads one to question whether AASHTO allowance of minimum ramp design speeds at 50 percent of the freeway design speed is reasonable.

Data Collection and Reduction

Evaluation of freeway entry ramp design speed criteria requires examination of not only assumptions regarding ramp vehicle acceleration and deceleration rates, but also gap seeking and acceptance behavior. Such an examination should include a study of freeway driver activity and ramp driver actions. This approach essentially involves recording the position and speed-time histories of entering and freeway main lane vehicles as they operate through freeway sections containing entry ramps.

Although a variety of measuring and recording techniques were considered, the study team determined that videotaping was the most practical technique. Since standard video cameras capture images at a rate of thirty frames per second, a video record would provide an adequate time resolution; that is, a vehicle traveling at 60 mph would travel less than 3 ft during 1/30 second. However, video recording introduces a series of questions regarding camera angles, fields of view, distances from objects being viewed, and location and spacing of fiducial marks defining speed measurement resolution. Prior to selecting sites and beginning data collection, the researchers conducted experiments and analyses to verify the appropriateness of video data collection. Approximately 200 hours of video data were collected at twenty freeway entry ramps in Houston, San Antonio, Dallas-Fort Worth, and in Austin.

Several data reduction considerations were important to the field data collection plan. For example, the speed and potential accuracy of data reduction were to determine the quantity and nature of the experimental data. After examining automated and manual data reduction procedures, the study team procured image tracking software developed by CMS Engineering Systems in Long Beach, California, called "Mobilizer-PC." Although the software was able to track well-defined images quite reliably, camera movements, particularly vibrations, were problematic. Software tracking reliability was also dependent on lighting and on the angle between the camera axis and the earth's surface. A 90-degree angle produced the best results, with any smaller angle impairing reliability. Also necessary was a lighting arrangement that produced the greatest contrast between vehicles and the pavement surface. Thus, the software application was constrained by limited camera angles, vibrations, and lighting problems. Consequently, most data reduction was performed manually.

Considerable effort was required to manually reduce videotape data. There were three primary tasks in the manual video data reduction. First, traffic counts were made by reviewing the videotapes in real time; second, individual vehicles were tracked along the merging area; and, finally, times and locations where ramp vehicles merge into the freeway were recorded. Locations of these occurrences were identified by the fiducial marks where they took place. Fiducial marks were extended across the acceleration lane and freeway lanes directly on a transparency superimposed on the video monitor.

The vehicle tracking process required videotapes to be played back at slow speed or frame-by-frame to ensure precise recording of the time vehicles crossed each fiducial mark. The video resolution permitted tracking vehicles at 0.03-second time intervals (30 frames/sec).

The primary data reduced from the videotapes were a set of times at which each ramp and freeway right-lane vehicle crossed each fiducial mark. This reduction was performed by tracking ramp and freeway right-lane vehicles. This procedure allowed the tracing of time-distance histories of ramp and freeway right-lane vehicles moving along the acceleration lane.

Five primary operational characteristics are calculated from the time-distance histories for ramp and right-lane vehicles: speed, acceleration, headway (freeway right-lane vehicles only), accepted gap (ramp vehicles only), and merge point (ramp vehicles only). Once the operational characteristics are determined for each vehicle throughout an analysis period, summary statistics are calculated. The statistics utilized are mean, standard deviation, 85th percentile, and 15th percentile. These measures were chosen because, when taken together, they provide a concise, simple, and understandable description of the ramp and freeway operations. Additional potential statistical measures were also considered, though these were eliminated as they were deemed to offer little additional insight into the roadway operations.

The statistical measures are determined for each operational characteristics data point along the ramp or highway lanes. For example, headways are determined at each mark along the freeway. Therefore, for each mark a mean, 85th percentile, 15th percentile, and standard deviation of headway are determined.

Analyses of Time-Distance Histories

Time-distance histories of ramp and freeway vehicles contain massive amounts of significant information. Graphical representations of those data were developed to specifically address this study's fundamental research question: Should the current entry ramp design speed criteria be modified? Using those representations, the study team investigated the relationships between entry ramp geometric design features and speed and other operational characteristics. One means of studying such relationships was comparing operational characteristics of ramps having "good" versus poor geometrics. Generally, ramps characterized as having "good" geometrics are those exceeding AASHTO and TxDOT criteria, while those characterized as poor only marginally meet or fail to meet current criteria.

Three primary types of comparisons may be made for each operating characteristic. The first is observed characteristic changes along the ramp under particular volume conditions. For example, a study area may have 1,000 and 500 vehicles per hour on the freeway right lane and ramp, respectively. For this condition, speed observations are made as a vehicle traverses the ramp facility; that is, this study tracked how speed changes (or does not change) as vehicles travel downstream.

The second comparison type consists of comparing operational characteristics of an individual ramp under different volume combinations (i.e., ramp volume and right-lane volume pairs). Data have been collected for three to six volume combinations for each of the ramps under study. In this type of comparison the focus will typically be on apparent trends or the absence of any predictability or similarities among volume combinations.

The third comparison type compares different ramps. Observations are made regarding operations on different ramps having similar volumes. Important observations include consistent versus highly variable operating characteristics, and differing or similar operating characteristic magnitudes.

The primary focus of these comparisons is on the entrance ramps from Richmond Avenue to NB IH 610 (Houston) and from Oltorf Street to NB IH 35 (Austin). Respectively, these ramps provide excellent examples of "good" and "bad" design features. The Richmond Avenue entry ramp and adjacent freeway main lanes have essentially no grade, ramp drivers can see freeway traffic from the frontage road and all ramp elements, and the speed change lane length exceeds current criteria. On the other hand, the Oltorf ramp and adjacent freeway lanes have grades that limit ramp drivers' views of freeway traffic until they pass the ramp gore, and the speed change lane does not meet current length criteria. Observations based on the comparisons of these two ramps are further supported through additional entrance ramp observations, including San Felipe Road to NB IH 610 (Houston), considered an acceptably designed ramp; 38th Street to SB IH 35 (Austin) and Haskell Road to NB US 75 (Dallas), both considered marginal designs; and, finally, Airport Boulevard to SB IH 35 (Austin), considered a substandard ramp design.

Ramp Speeds: Ramp speed is one of the more telling ramp characteristics. Graphics depicting mean, standard deviation, 85th percentile, and 15th percentile ramp speeds for six example entry ramps are presented in the main report. For Richmond Avenue the ramp speed versus distance plot is seen to be smooth for all studied volume combinations. Several volume combinations exhibit a slight increasing trend, while the other volume combinations exhibit unchanging speeds.

The behavior seen on the Oltorf Street ramp is strikingly different. For all volume combinations the speed is seen to "dip" in the gore area. Mean speeds expressed in miles per hour tend toward the high 40s both upstream and downstream of the gore, and to the mid- to lower 40s in the gore area.

These and other observations lead to the development of several hypotheses that are further supported in the study of the other ramps and other operating characteristics. The first hypothesis is that a low design standard has a negative effect on ramp operations upstream of the gore. Of specific importance is sight distance from the ramp to the freeway lanes, which is constrained by vertical alignment effects and is practically nonexistent prior to the Oltorf Street ramp gore. Drivers are not able to begin their gap search process or any meaningful analysis of the freeway operation until they are in the ramp gore area. At this point, having an imminent need to merge, drivers must direct primary attention to the freeway traffic, only peripherally watching for ramp vehicles that might occupy their current path. This situation prompts deceleration, or at least inhibits acceleration. On the Richmond Avenue ramp the driver's view of the freeway traffic is not limited by any vertical alignment feature. This unrestricted view allows the driver to task share between navigating the ramp and preparing for the freeway merge. Thus, at no point along the "good" ramp does the typical driver feel compelled to focus complete attention on the previously unseen freeway traffic.

Ramp Accelerations and Decelerations: A review of ramp driver acceleration and deceleration characteristics offers additional insight into the effects of design on vehicle operations. Mean acceleration/deceleration rates on the Richmond Avenue ramp follow a consistent, low value (less than 2 mphps) for all ramp volume combinations.

Several volume combinations exhibit mean acceleration/deceleration values that hover around 0. The maximum change in mean acceleration/deceleration rate measured between two consecutive points along the ramp for any volume combination does not exceed roughly 1 mphps and, except for the lowest ramp volume scenario, the standard deviations maintain a smooth, consistent centering around approximately 1 mphps.

The Oltorf Street ramp displays different characteristics. Upstream of the ramp gore the mean acceleration/deceleration rates are highly variable, both from location to location along the ramp and at the same location under different volume combinations. There is no observable or predictable trend except for the wide scattering of possible acceleration/ deceleration values, with each volume combination following a different waveform.

Freeway Right-Lane Speed: In addition to the insight gained through a study of the effects of ramp design on ramp vehicle operating characteristics, insight may also be gained through the study of freeway vehicle performance. For example, a clear change in speed characteristics is observed on the freeway lanes adjacent to "bad" ramp designs but not adjacent to "good" ramp designs. The Richmond Avenue right freeway lane speed characteristics are smooth and unchanging upstream and downstream of the ramp gore. Under all studied volume combinations, the freeway right-lane demonstrates no notable change in the mean speed. Freeway right-lane speeds, for the Oltorf ramp, however, seem to be significantly affected by ramp vehicle operations.

Freeway Right-Lane Acceleration and Deceleration: Along with the freeway right-lane speed characteristics, the acceleration/deceleration characteristics demonstrate clear differences between "good" and "bad" ramps. Both the Richmond Avenue and San Felipe Road ramps display consistent mean acceleration/ deceleration rates along the ramps and among the different volume combinations. The mean acceleration/deceleration rates range between approximately -2 to 1 mphps, with the 85th and 15th percentile falling within a range of roughly -3.5 to 3.5 mphps. The maximum difference between any two consecutive mean acceleration/deceleration points does not exceed approximately 1.5 mphps. The Oltorf Street ramp displays high variability both along the ramp and among the different volume combinations.

Headway: Among the operating characteristics studied, the right-lane freeway headways experienced the least notable influence owing to ramp design. The primary factor in the distribution of headways seems to be the freeway volume.

Accepted Time Gap: An initial, seemingly reasonable hypothesis was that a poorly designed ramp would likely force vehicles to accept smaller gaps. Interestingly, when reviewing the accepted gap trends among the six comparison ramps, this trend does not seem to occur. There is no appreciable difference among the mean, 15th, or 85th percentile accepted gaps on the different ramps. The factor that appears to primarily influence accepted gap is right-lane volume, not ramp design.

Merge Location: Larger percentages of merge maneuvers are completed further along the speed change lane as volumes increase. Under the largest traffic volumes, most merges are completed near the end of the 300 ft of monitored speed-change lane length on the Richmond ramp. However, under similar high volume conditions, a large fraction of Oltorf ramp users attempt to merge long before the ramp end. This fact likely contributes to the effects on freeway main lane speeds and reflects erratic, uncertain driver behavior associated with the lack of sight distance and short speed-change lane.

FINDINGS AND RECOMMENDATIONS

The observations and analyses of this study yielded the following findings and recommendations:

1. Average ramp driver speeds on all observed entry ramps are consistently greater than 50 percent of the freeway design speed, even where the freeway design speed is 70 mph. Designing facilities for speeds lower than the speeds at which drivers typically operate would be inappropriate.

   Recommendation: The design criterion allowing a ramp design speed to be 50 percent of the freeway design speed should be deleted from AASHTO and TxDOT policy.
2. Ramp driver speed-distance histories on ramps with adequate sight distance and speed-change lane lengths exhibit smooth appearances, having no abrupt speed changes. Speed-distance histories for ramp-freeway facilities with vertical profiles limiting ramp driver sight distance and marginal speed-change lane lengths exhibit undulating waveforms, indicating significant ramp driver speed changes.
3. Acceleration/deceleration rate histories for ramps with "good" and "bad" geometrics have patterns similar to speed histories. Ramps having adequate sight distance and speed-change lane lengths typically produce small positive acceleration rates (0 to 2 mphps). The observed values are comparable to the implied rates contained in AASHTO Table X-4 (acceleration lengths). Ramps

with inadequate sight distance and/or inadequate acceleration lane lengths produce larger values of positive and negative acceleration (-4 to +4 mphps).

Recommendation: The AASHTO acceleration rate model used to estimate acceleration lane lengths should not be changed.

4. Freeway right-lane speeds are not largely affected by ramp vehicles if the ramp has adequate sight distance and speed-change lane lengths. Inadequate sight distance and/or inadequate acceleration lane lengths tend to cause significant reductions of freeway right-lane speeds, particularly under high freeway and ramp traffic volumes.
5. Freeway right-lane time headways tend to be influenced not by complex ramp design, but rather by traffic volume.
6. Freeway right-lane volume is the factor that primary seems to influence the size of time gap accepted by merging ramp drivers.
7. Under high traffic volume conditions, most ramp drivers travel to the end of a ramp with adequate sight distance and speed-change lane length before merging. If a ramp has inadequate sight distance and/or inadequate acceleration lane length, this trend is much less pronounced, as drivers aggressively merge from any location so as to avoid being trapped at the speed-change lane end.
8. Drivers tend to begin the merge acceleration process only after gaining a clear view of freeway right-lane traffic. If grades, structures, or barricades obstruct the ramp driver's view of the right lane, acceleration does not begin until near the ramp gore where the view becomes unobstructed. The AASHTO acceleration length model for taper-type ramps includes a large fraction of the acceleration length prior to the ramp gore. If the driver's view is obstructed prior to the ramp gore, the AASHTO model could incorrectly estimate available acceleration length.

   Recommendation: Acceleration lengths for taper-type entry ramps should include only the lane portions from which ramp drivers can clearly view the

freeway right-lane traffic. The AASHTO acceleration length model should be clarified to include this specification.

9. At lower design speeds the TxDOT design standard may provide for a shorter taper length than the AASHTO standard. This difference stems from the method of inclusion of the taper length from full lane width to lane elimination.

Finally, driver behavior upstream and downstream of the ramp gore may exhibit different characteristics. A design procedure that allows for a flexibility of choosing separate design speeds upstream and downstream of the gore may provide for overall superior designs. For example, the current 50 percent criteria produces a very desirable long acceleration lane but permits speed limiting horizontal and vertical alignment elements upstream of the ramp gore. Provision of a high design speed for upstream features and a low design speed for downstream features may provide for an optimal design standard. This item is not listed as a recommendation, as it somewhat exceeds the scope of this research effort; nevertheless, the researchers believe that such a broad change in design philosophy should be considered, studied, and potentially implemented.

BIBLIOGRAPHY

1. American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets,* Washington, D.C., 1990.
2. Johansson, G., and K. Rumar, "Drivers' Brake Reaction Times," *Human Factors*, Vol. 13, No. 1, February 1971, pp. 23–27.
3. State Department of Highways and Public Transportation, *Highway Design Division Operations and Procedures Manual,* February 20, 1987.
4. American Association of State Highway Officials, *A Policy on Geometric Design of Rural Highways,* Washington, D.C., 1965.
5. Loutzenheiser, D. W., "Speed-Change Rates of Passenger Vehicles," *Highway Research Board,* 1938, pp. 90–99.
6. Prisk, C. W., "Passing Practices on Rural Highways," *Highway Research Board Proceedings*, 1941.
7. *Speed-Change Lanes Final Report,* National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Project 3-35, December 1989.
8. Wilson, E. E., "Deceleration Distances for High-Speed Vehicles," *Highway Research Board Proceedings*, 1940, pp. 393–398.
9. Bealey, John, "Acceleration and Deceleration Characteristics of Private Passenger Vehicles," *Highway Research Board Proceedings*, 1938, pp. 81–89.
10. American Association of State Highway and Transportation Officials, *A Policy on Design of Urban Highways and Arterial Streets,* Washington, D.C., 1973.
11. Lunenfeld, Harold, "Human Factors Associated with Interchange Design Features," *Transportation Research Record,* No. 1385, pp. 84–89.
12. Twomey, J. M., M. L. Heckman, J. C. Hayward, and R. J. Zuk, "Accident and Safety Associated with Interchanges," *Transportation Research Record,* No. 1385, pp. 100–105.

13. Harwood, D. W., and J. M. Mason, Jr., "Ramp Mainline Speed Relationships and Design Considerations," *Transportation Research Record,* No. 1385, pp. 121–125.
14. Koepke, Frank J., "Ramp Exit Entrance Design — Taper Versus Parallel and Critical Dimensions," *Transportation Research Record,* No. 1385, pp. 126–132.
15. Keller, J. A., "Interchange Ramp Geometrics — Alignment and Superelevation Design," *Transportation Research Record,* No. 1385, pp. 148–154.
16. Cirillo, J. A., S. K. Dietz, and R. L. Beatty, *Analysis and Modeling of Relationships between Accidents and the Geometric and Traffic Characteristics of the Interstate System,* Office of Research and Development, Traffic Systems Division, USDOT/FHWA/BPR.
17. Michaels, R. M., and J. Fazio, "Human Performance and Highway Visibility, Design, Safety, and Methods," *Driver Behavior Model of Merging,* Transportation Research Board Report 1213, pp. 4–10.
18. Loutzenheiser, D. W., "Proposed Design Standards for Interregional Highways," *Highway Research Board*, 1944, pp. 105–126.
19. Seneviratne, P. N., and M. N. Islam, "Speed Estimates for Roadway Design and Traffic Control," *Transportation Research Record,* No. 1375, pp. 37–43.
20. Yates, J. G., "Relationship between Curvature and Accident Experience on Loop and Outer Connection Ramps," *Highway Research Record 312*, National Research Council, Washington, D.C., 1970, pp. 64–75.
21. Lundy, R. A., "The Effect of Ramp Type and Geometry on Accidents," *Highway Research Record 163,* National Research Council, Washington, D.C., 1967, pp. 80–117.
22. Ervin, R., M. Bames, C. MacAdarn, and R. Scott, *Impact of Special Geometric Features on Truck Operations at Interchanges,* Transportation Research Institute, University of Michigan, Ann Arbor, 1985.
23. Cirillo, J. A., "Interstate System Accident Research Study II, Interim Report," Research Record 188, National Research Council, Washington, D.C., August 1968, pp. 71–75.

24. Hunter, M., and R. Machemehl, *Reevaluation of Ramp Design Speed Criteria: Review of Practice and Data Collection Plan,* Report 1732-1, Center for Transportation Research, The University of Texas at Austin, 1997.

25. Kou, C., and R. Machemehl, *Modeling Driver Behavior during Merge Maneuvers*, SWUTC Report 472840-00064-1, The University of Texas at Austin, 1997.