NCHRP

REPORT 559

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Communicating Changes in Horizontal Alignment

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Communicating Changes in Horizontal Alignment

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SUBJECT AREAS
Highway Operations, Capacity, and Traffic Control

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2006
www.TRB.org

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NCHRP REPORT 559

Price $30.00

Project 3-61

ISSN 0077-5614

ISBN 0-309-09851-3

Library of Congress Control Number 2006923872

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 3-61 by the Department of Civil and Environmental Engineering, Michigan State University (MSU). Portions of the project were also done under subcontract by the Department of Civil Engineering, North Carolina State University (NCSU).

The primary investigators for this project and authors of this report are Professor Richard W. Lyles, principal investigator, and Professor William C. Taylor of MSU. Other major contributors were Fred Vanosdall, consultant, who developed and executed the driver observation study; Professor Joseph Hummer of NCSU, who was responsible for the parts of the driver surveys and practitioner focus groups done in North Carolina; Stephanie Aldighieri (formerly a graduate student at MSU and currently with the Michigan DOT), who developed and executed the driver focus groups and who was an observer in the driver observation study; John Elliott (formerly a graduate student and currently director of the Erie Redevelopment Authority in Erie, Pennsylvania), who did much of the literature review and who developed and executed the practitioner focus groups in Michigan and Indiana; and several other graduate students who were responsible for preparing materials, coding data, and analysis, but principal among them was Xinguo Jiang (Joe) and Anthony Ingle. Special recognition is also offered to Hannah Remtema, who assisted with initial work on the original project proposal and worked on the project for its duration (survey development and execution, data coding, data analysis, and observation in the driver study) as an undergraduate and then as a graduate student.

FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report presents the findings of a research project to develop guidelines for the use of traffic control devices for communicating changes in horizontal alignment for two-lane, two-way rural roads. The report will be of particular interest to traffic engineering personnel with responsibility for roadway signing.

Highway curves tend to be high-rate crash locations. The average crash rate for highway curves is about 3 times the average rate for highway tangents, and the average run-off-the-road crash rate for highway curves is about 4 times that of highway tangents.

In lieu of curve-flattening practices or other geometrically based enhancements that are rarely employed on local road systems, traffic control devices offer the most potential for reducing crash rates on horizontal curves. Warning signs (such as turn, curve, winding road, large arrow, and chevrons) with or without advisory speed plaques and a variety of delineation devices (such as wide edge lines, post delineators, raised pavement markers, and rumble strips) are used to communicate changes in horizontal alignment. Nevertheless, such devices are used inconsistently from one jurisdiction to another and even from one location to another within a single jurisdiction, and they are sometimes used improperly. The devices related to horizontal alignment are rarely considered as a system, but merely a collection of individual devices.

Jurisdictions have varying practices regarding the spacing of delineation devices with changes in horizontal alignment; existing devices for roads with multiple changes in horizontal alignment do not provide speed information for each individual alignment change. For example, in a reverse curve with a 40-mph advisory speed, the first curve may be negotiable at 50-mph, leading to a false sense of security and a failure to slow for the second curve that has the 40-mph advisory speed or a single curve with a 30-mph advisory speed may be negotiated at 45-mph leading to distrust for advisory signing. Several recent studies have concluded that the current methodology for selecting advisory speeds is outdated and needs to be reevaluated. Elements such as weather, roadway classification, road user familiarity, and commercial vehicle types may also affect the appropriate advisory speed

Under NCHRP Project 3-61, "Communicating Changes in Horizontal Alignment," Michigan State University researchers developed three recommendations for changes to the Manual of Uniform Traffic Control Devices.

The research team reviewed the literature and ongoing research to identify design methods, practices, and problems in determining and communicating horizontal curve information to road users. Focus group exercises and interview sessions involving practitioners were held in Michigan, North Carolina, and Indiana. And a national survey was conducted. The objective was to determine the perceptions and actual practice of practitioners regarding traffic control devices used for horizontal curves: are they adequate, are they used consistently, and should guidelines for use be changed?

A driver behavior study using Driver Performance Monitoring (DPM) techniques was also conducted. Randomly selected drivers were observed as they traversed a 25-mile predetermined route, negotiating 43 curves. Trained observers assessed the driver's "search, speed, and direction control" as they negotiated the curves. The vehicle's speedometer readings at various points were also recorded as were comments on driving behavior.

Using the information from the literature review, survey responses, input from the focus groups, and the DPM study the researchers developed several recommendations for changes to the Manual of Uniform Traffic Control Devices.

CONTENTS

COMMUNICATING CHANGES IN HORIZONTAL ALIGNMENT

SUMMARY

NCHRP Project 3-61 examined the use of traffic control devices (TCDs) for communicating changes in the horizontal alignment of roadways. Although the initial scope had been fairly broad, the emphasis that emerged was on two-lane, two-way rural roads. The objective was to develop guidelines and/or recommendations for the consistent and uniform use of TCDs for horizontal curves. Activities included a literature review; focus group exercises involving practitioners in Michigan, North Carolina, and Indiana with some supplemental interviews of other practitioners in North Carolina and Tennessee; a nationwide survey of practitioners; focus groups with drivers in Michigan; a survey of crash-involved and typical drivers in Michigan and North Carolina; a field observation study of 40 drivers in Michigan, including three "expert" drivers from the Michigan State Police; and a final nationwide survey of practitioners to assess their response to proposed changes to the *Manual on Uniform Traffic Control Devices* (*MUTCD*).

Initially, the outcomes of this project had been envisioned to include a comprehensive set of guidelines for using various TCDs—including advisory speed plaques—for changes in horizontal alignment on different components of the road system. Over time, the emphasis changed to two-lane, two-way rural roads. Moreover, as the literature was reviewed and practitioners consulted, it became clear that with limited resources, it would be impossible to develop comprehensive guidelines for use of different TCDs in myriad combinations of circumstances. Finally, most practitioners felt that existing guidelines and engineering judgment were adequate for determining when different devices should be used. Thus, the suggested changes in guidelines became more general, and even those were subject to debate. For example, while something as straightforward as changing the language from "may" to "should" in warning signs was supported by a significant majority of practitioners, there was still substantial opposition. Thus, it is unlikely that widespread support for more explicit guidelines would be well received.

In this context, three recommendations are made for changes in the *MUTCD.* The first recommendation is a somewhat more emphatic statement regarding the use of standard horizontal alignment signs and a clearer statement regarding the winding road sign. Specifically, the first option statement in §2C.06 of the 2003 edition of the

MUTCD is proposed to be changed as follows (changes to the *MUTCD* will be marked **bold** throughout the report):

> The horizontal alignment Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5) signs (see Figure 2C-1) may be used in advance of situations where the horizontal roadway alignment changes, **and should be used when the alignment change would result in an advisory speed equal to or lower than the posted speed limit.** A One-Direction Large Arrow. . . .
>
> **The Winding Road (W1-5) sign should be used where there is a series of turns or curves that requires driving caution and where curve or turn signs would be too numerous to be effective. Where any of the curves has an advisory speed that is 10 mph or more below that of the first curve, then a curve or turn warning sign and an advisory speed plaque should be used.**

Although this suggested change was seen by some practitioners as potentially resulting in (1) additional costs to already strained budgets and (2) a potential increase in liability due to the use of the word "should," a threshold of use for basic signs is more clearly established that will result in more uniform application of these signs.

The second recommendation concerns the use of advisory speed plaques. Again, the intention is to introduce more uniformity in the use of these signs. The change is intended to specify when advisory speed plaques should be used for horizontal curves. While this is, in part, a further clarification of existing language in §2C.46, it is intended to be inserted as a new part of §2C.06, which relates to horizontal curves:

> **An Advisory Speed (W13-1) plaque should be used to indicate the advisory speed for a change in horizontal alignment when the advisory speed is 10 mph or more below the applicable speed limit.**

Alternatively, §2C.46 could be changed by replacing the language there with a statement similar to the above, but striking the reference to horizontal alignment and making the statement apply to all situations in which advisory speed plaques might be used. The key to making use of this sign more consistent is the provision of the threshold of 10 mph.

Related to the use of the advisory speed plaque is reference in the 2003 edition of the *MUTCD* to the use of a 16° ball-bank reading to set the magnitude of the advisory speed appearing on the plaque. In discussion, it is argued that use of this criterion will result in an increase in the lack of uniformity as this value is differentially adopted by different jurisdictions over time. In addition, more study is needed to assess motorist reaction to what are typically expected to be posting of higher advisory speeds for most curves. It may be that this will result in motorists increasing their speeds to a potentially unsafe level.

The third recommendation concerns the further definition of the term "engineering study." This term is not adequately defined in the specific context of horizontal curves although several references are made to conducting such studies. Thus, the third recommendation is a definition of the factors to be included in such a study done in regard to horizontal alignment. This language would be included in a new section, most likely between existing §2C.05 and §2C.06:

> **Standard:**
>
> **After an engineering study has been made in accordance with established traffic engineering practice or where engineering judgment determines the need for horizontal alignment signs, advisory speed plaques, and/or supplemental guidance, these TCDs shall be used.**
>
> **Guidance:**
>
> **The factors that should be considered in determining the system of TCDs to be displayed when there is a change in the horizontal alignment of the highway include**

- **The difference in the posted speed limit and the 85th percentile speed of free-flowing traffic (or a 16° ball-bank reading);**
- **The approach sight distance to the beginning of the curve;**
- **The visibility around the curve;**
- **Unexpected geometric features within the curve, such as an intersection or a change in the curve radius;**
- **Curve and roadway geometry;**
- **Accident history; and**
- **As appropriate, the position of the most critical curve in a sequence of relatively closely spaced curves.**

In this context, defining the factors that should be considered in an engineering study doesn't really increase the level of obligation for a jurisdiction doing studies or periodic evaluations, but rather provides a list of the factors to be considered. The list of factors was modified based on input from practitioners in response to an initially proposed list. While it was argued that this language should be added to the *MUTCD* because that document is the most widely accessible and widely used in the field, similar language and further amplification should be added to the *Traffic Control Device Handbook.*

In addition to the changes in the *MUTCD* just described, there were recommendations for additional research. They came in two areas. The first is the need for the investigation of development of an expert system. Because of the myriad combinations of conditions encountered in the field, an expert system would seem to represent a viable tool to be used by engineers in assessing the need for different TCDs at specific locations. Used properly, it would help engineers identify the options that "best practices" might indicate for TCDs at an explicit site. Development of an expert system should also be linked to experience with and results from the implementation of the third recommendation.

The second area is further research into motorist reaction to wholesale changes in determining the appropriateness of advisory speeds using a ball-bank reading of 16°. Based on feedback from both motorists and practitioners, it is important to ascertain how motorists will respond to what will generally be higher advisory speed values on many curves. If motorists, and especially "unfamiliar" ones, continue to routinely exceed the new speed advisories by the same margins as they do now, dangerous situations could easily exist. Moreover, it is expected that "conversion" to a new method would lead to considerable inconsistency in the use of advisory speed plaques for several years. This would occur, if for no other reason, because of the apparent disparities in budgets of different county road commissions, resulting in some counties, states, or parts of states "converting" their advisory speed plaques immediately while others lag for several years until the advisory speed plaque and other curve-related TCDs might otherwise be updated as a part of normal maintenance.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

The appropriateness and effectiveness of traffic control devices (TCDs) used to inform drivers of the presence of, and appropriate speed for, horizontal curves remains a subject of interest to researchers; to practicing engineers at federal, state, and local levels; and, most importantly, to the motoring public. While horizontal curves in general have long been identified as high hazard locations, many of these curves are perceived as "simple" highway situations by drivers while others stand out as very hazardous. Many of the previous studies of horizontal curves have identified inconsistencies in using TCDs to convey the appropriate message to the driver as an issue. For example, how severe is "this" curve? What driver action is required here? In this context, the underlying objectives of this research were to develop guidelines regarding when and how to communicate horizontal curve information to drivers in a credible, effective, consistent, and timely manner. This includes recommendations for changes to the *Manual on Uniform Traffic Control Devices* (*MUTCD*). It should be noted that "TCDs," in this context, is meant to include all traffic control devices such as advisory signs, advisory speed plaques, regulatory signs, pavement markings, and delineators. However, the emphasis that emerged was on signing.

SCOPE OF STUDY

The original scope of the study was fairly unrestricted in terms of curves and types of TCDs, but as the project progressed, the scope changed. The types of roads were reduced to an emphasis on two-lane, two-way rural roads with a "client" who was more likely to be practicing at the county-road or similar level. Thus, while some attention was given to the full range of TCDs including "high-tech" solutions such as speed-triggered sign messages or flashing lights, the emphasis was on more routine treatments likely to be used by lower-budget jurisdictions.

In order to develop comprehensive guidelines for the use of various TCDs in different horizontal curve situations, a full-factorial experiment design matrix would have been necessary that would have considered the permutations and combinations of TCDs and site conditions. For example, the treatments to be tested would start out with stand-alone applications of the basic curve signs; then progress to those signs in combination with each individual supplementary sign such as chevrons; then progress with combinations of supplementary signs, adding striping, post-mounted delineators, raised pavement markers, and so on. The number of treatments to be tested alone would have numbered in the dozens. Then, curve characteristics such as geometric characteristics, presence and absence of intersections or driveways in and near the curve, and parameters such as design speed for the curve would have to be varied. This would result in a test matrix with hundreds of cells.

Given the number of combinations, the use of field studies to develop universal and explicit guidelines for use of selected TCDs was prohibitive in terms of time and funds available. Thus, this research relied on focus groups and surveys augmented with limited and more qualitative field work. With the exception of the field work, most of the project activities made use of participants/respondents ranging from national samples to groups from two states; the latter included drivers from Michigan and North Carolina.

RESEARCH APPROACH

The project included the following tasks:

- A traditional literature review;
- Focus group exercises involving practitioners from four states and two jurisdictional levels, state DOTs, and county road engineers;
- A nationwide survey of practitioners;
- Focus group exercises involving crash-involved and typical or "average" Michigan drivers;
- A survey of crash-involved and typical or "average" drivers in Michigan and North Carolina;
- A limited field study of behavior as Michigan drivers negotiated a pre-determined route and encountered various horizontal curves;
- Development of recommendations for changes in the *MUTCD;* and
- A final nationwide survey of practitioners to assess the perceived need for, and practical utility of, the recommendations.

REPORT ORGANIZATION

In the remainder of the report, summaries of findings from each of the tasks listed above are presented.

CHAPTER 2

FINDINGS

LITERATURE REVIEW

The literature review included examination of traditional sources and readily available reports. It should be noted from the outset that there appears to be a considerable body of literature that is not documented in any traditional way and thus is not included. This includes work done by various agencies that is either not documented in any usable way or only available within the agency. An example of the former would include a TCD treatment that was implemented in the field but never documented or studied in any methodical way; an example of the latter would include an interoffice memo that might summarize an implementation and a brief study at a specific location. Such documents include unwritten guidelines for placement of various devices. For example, a local jurisdiction (in Michigan) has "rules" for when chevrons are used as well as for choosing the number and placement locations—these "rules" are not published but simply "known" within the agency.

Such problems notwithstanding, some of the more interesting overarching results from the literature review are summarized immediately below and then followed by comments regarding specific types of devices:

- The *MUTCD* provides only general guidance on the selection and application of TCDs used to inform drivers of a change in horizontal alignment.
- Novelty effects should be carefully considered in any new TCD evaluation.
- Currently, advisory speed signing appears to be largely ineffective if the goal is for drivers to actually travel at the posted advisory speed: drivers either fail to notice advisory speed plaques, or, more likely, they simply reject the literal advisory speed recommendations, driving at a reduced speed that they feel is appropriate.
- Because raised pavement markers and post-mounted delineators provide both far and near guidance up to and through a curve, delineation should be part of a comprehensive curve-risk reduction program. Also see more specific comments below.
- Specific recommendations for curve TCDs on low-volume rural roads are not provided.
- Benefits and guidance for using new TCDs in the *MUTCD* (e.g., the combined alignment/advisory speed sign) are not provided in the literature.

Summary comments from the literature review pertaining to different types of devices follow.

Curve and Turn Signs

The literature review pertaining to curve and turn signs resulted in the following summary comments:

- The messages conveyed by curve-related warning signs are likely more generic than traffic engineers might hope. Messages are probably weakened by driver limitations in perceiving and understanding nuanced curve/turn warning signs, which reaffirms the need for redundancy at highest-risk locations.
- While there are varied results regarding whether curve-related signs reduce crashes, run-off-the-road (ROR) and single-vehicle crashes are, nonetheless, probably reduced when such signs are used (when compared with no signs).
- If conventional curve-related signs are ineffective at high-crash locations, there is some evidence that special treatments such as oversized or traffic-actuated signs with beacons are effective.
- The longitudinal placement for curve signs is typically based on the 85th-percentile or posted speed. This is consistent with the sign placement table in the *MUTCD*.

Advisory Speeds

The literature review pertaining to advisory speeds resulted in the following summary comments:

- Some studies indicate that advisory speed plaques are no more effective than curve/turn signs alone. Conversely, others found that there was some speed reduction associated with the placement of advisories although not to the posted speed *per se*—that is, advisory speeds are routinely exceeded.
- Drivers may underestimate their actual speeds on curves.
- Surveyed practitioners feel that guidelines for assigning advisories are sufficient.
- Some results indicate that single-vehicle and ROR crashes are reduced when advisories are posted and that "sections" (i.e., a segment of road with numerous curves) with advisories posted experience fewer crashes.

Chevrons

The literature review pertaining to chevrons resulted in the following summary comments:

- Drivers have been noted to shift away from chevrons as they negotiate curves—toward the centerline on curves to the left, away from it on curves to the right.
- Several studies noted that average (day and night) speeds increased when chevrons were added.
- Crash reductions have been noted on curves marked with chevrons where standard curve-related signs have not been effective.
- While chevrons provide additional guidance for the driver, perhaps not more than post-mounted delineators or raised pavement markers.
- Chevrons have more effect at night, on sharper (>7°) curves, and when used in conjunction with edgelines.

Edgelines and Centerlines

The literature review pertaining to edge- and centerlines resulted in the following summary comments:

- Results regarding increase or decrease in vehicle speeds when edge- and centerlines are used are varied: some studies show an increase, and others show a decrease.
- Freshly painted lines tended to decrease lateral placement variance.
- As above, edgelines seem to have more effect when used with chevrons.

Post-Mounted Delineators

The literature review pertaining to post-mounted delineators (PMDs) resulted in the following summary comments:

- Similar to chevrons, drivers tend to shift away from PMDs—that is, away from the edge of road and toward the centerline.
- Day- and nighttime speeds tend to increase when PMDs are used.
- PMDs have been shown to reduce variance in lateral placement.
- PMDs should only be placed on the outside of the curve and could be confusing if placed otherwise.
- PMDs have more effect when used with freshly painted centerlines.

Raised Pavement Markers

The literature review pertaining to raised pavement markers (RPMs) resulted in the following summary comments:

- RPMs are more effective at reducing crashes at high-crash locations than elsewhere although general reduction was not noted.
- RPMs tend to have more effect during the night than the day.
- RPMs had more effect on lateral placement over and above freshly painted centerlines over time.
- The variability of speed and lateral placement was decreased with RPMs.
- There was some evidence that RPMs had greater effect than PMDs and chevrons.

It is also worth noting that the recent *NCHRP Report 518: Safety Evaluation of Permanent Raised Pavement Markers* contains a definitive review of the effectiveness of permanent RPMs. While some results were mixed and/or inconclusive, significant crash reductions were noted for wet-weather crashes and especially at night.

Discussion and Comments

Notwithstanding the impact of different TCDs in different circumstances, improvements to road geometry are clearly preferred to warning signs or delineation at locations with hazardous changes in horizontal curvature. However, where right-of-way, economic, or other practical limitations prohibit or delay desirable improvements, standard TCDs can be used effectively to warn drivers and to guide them through the potentially hazardous road segment.

Identifying hazardous road segments is best accomplished by considering curve operational and physical properties and crash history. Posted, design, and operating speeds alone cannot predict overall safety on horizontal curves. It appears that aggregated crash rates are positively correlated with high degrees of curvature: curvature of approximately 5° or greater poses an increased hazard of which the driver should be warned. Other results showed that, in practice, the sharpest curves already have extensive TCD treatment and that some modest curves were among the most problematic in terms of higher crash rates and less treatment.

TCDs used on horizontal curves should be applied uniformly to foster desirable driver expectancies. In placing curve signs, engineers should consider preview sight distance, driver perception of road geometry, and drivers' expectations for curve warning. In addition to curve warning signs, delineation will improve driver perception of alignment changes. Other roadside information is also an important information carrier—any practical measures that can be taken to improve a driver's curve perception should take priority over warnings.

While most of the TCDs for curves have been shown to be effective in certain experiments, the testing on which the results are based was rarely comprehensive or conclusive across the spectrum of conditions encountered in the field. For example, some work has shown that chevrons, PMDs, and RPMs result in higher speeds on curves. Given that most curve crashes occur because the motorist enters the curve at too high a speed, would we want to increase motorist speeds on all, or any, curves? Clearly, a definitive guideline is hard to develop based on the results of existing work.

A couple of general recommendations emerge from the literature review. The first is the need *to define more explicitly what constitutes an "engineering study"* in the context of horizontal curves. Items that should likely be included in such a study for TCD selection and placement at horizontal curves include consideration of the following:

- How other potentially limiting factors such as weather conditions would affect curve perception and vehicle performance;
- Natural features of the road and roadside environment that provide delineation;
- Alignment that drivers may find difficult to perceive or interpret;
- Driver expectations;
- Application of both the preview sight distance concept and 85th-percentile speed to longitudinal warning sign placement guidelines;
- Degree of curvature and other parameters associated with high-risk alignments;
- Guidelines for when redundant warning or warning along with delineation is recommended; and
- Guidelines for when curve warning is *not* recommended based on curve or volume parameters apart from crash history.

The second need is *to recommend advisory speeds based upon driver comfort* or an assessment of how fast drivers are already driving. Associating current operational speeds under ideal conditions with curve properties and ball-bank indicator ratings would suggest a more realistic and, perhaps, a more respected advisory speed recommendation.

Implicit in the above is the need for consistent messages to be given to drivers. While drivers may not respond as well to different speed advisories as engineers would like insofar as drivers don't slow down to the advisory level, it seems clear from prior studies that there is some response.

Given the findings from the literature review, it was necessary to ascertain the current state of the practice relative to the specification and use of curve-related TCDs as well as determining how drivers respond to them. For example, when and how are curve-related TCDs used and is that use consistent across different jurisdictions? Likewise, do drivers use the information from TCDs as intended and are the TCDs perceived to be used consistently across jurisdictions?

The next sections document the tasks that were undertaken to determine the perceptions of practitioners and drivers with respect to the TCDs used for horizontal curves: are they adequate, are they used consistently, and should guidelines for use be changed? Practitioner input was captured through the use of focus groups, discussions in several states, and a nationwide survey.

It should be noted from the outset that there were some problems throughout the project with specifying exactly which edition of the *MUTCD* is relevant. When this project began, the 2003 edition of the *MUTCD* was not in wide use and, indeed, some practitioners weren't even aware of the millennium edition. It still had not been officially adopted or used by all jurisdictions in mid-2005. So, somewhat arbitrarily, the millennium edition was used as the default "standard" throughout the project—e.g., as a reference point for practitioner survey instruments. Differences between the millennium and 2003 edition are addressed in later chapters.

PRACTITIONER FOCUS GROUPS

The practitioner focus group exercises were held in three states: Michigan, Indiana, and North Carolina. During the exercises, the practitioners who were responsible for specifying and implementing TCD treatments for horizontal curves—including both engineers and technicians—were brought together to discuss those treatments. The focus of the discussion was on local, typically county-level, two-way, two-lane, rural roads. Topics included the adequacy of existing guidelines for the specification and placement of various TCDs, the adequacy of currently used TCDs, the identification of "problem" curves, the use of engineering judgment and studies, the appropriateness of advisory speeds and methodologies for setting them, and the reasons for perceived differences in treatments among jurisdictions and general inconsistency in the use of curve-related TCDs. In all, there were four formal focus-group exercises (the number of practitioners attending is shown in parentheses): two in Michigan (15, 9) and one each in Indiana (5) and North Carolina (10). In addition to the formal focus groups, there were also two separate interview sessions with practitioners in North Carolina and one in Tennessee. The interview sessions included only one to three participants and therefore lacked the interactive nature of the focus groups. Nonetheless, some useful information was gleaned from the sessions.

The four focus-group exercises provided valuable information regarding the state of the practice for using curve-related TCDs. While all groups were familiar with and regularly used the *MUTCD* or a state-level variant as a guide for their curve treatments, some agencies supplemented them with additional materials that were not necessarily written. For example, there was a guideline in some Michigan counties that indicated that chevrons should be used on any curve requiring a speed advisory. As a general statement, the *MUTCD* was perceived to provide sufficient guidance but leave room for judgment on the part of the practitioner. In this context, the standard curve signs (W1-1 through W1-8) were considered sufficient in most situations. The winding road (W1-5) and reverse curve or turn signs (W1-3, W1-4) cause some confusion in application, especially when advisory speed plates are to be used. The confusion results from the determination of which curve in a sequence should be the basis for the advisory—the first or the most severe? Beyond the standard curve-related signs, RPMs, chevrons, and large target arrows appeared to be widely used as supplemental devices.

Engineering judgment, as defined by the practitioners, is decisionmaking based on engineering or other technical training, experience, and/or common sense although the latter is defined by the practitioners. While there was an implicit understanding of engineering judgment and engineering studies, it was clear that not many studies were done to support the TCD-related judgments that were routinely rendered. In many instances, it appears that the day-to-day specification of TCDs for curves is left to technical support staff and not necessarily done by engineers except in atypical cases.

To assess appropriate advisory speeds, most of the practitioners used a ball-bank indicator in some way. Based on more informal discussion with some of the practitioners, it is suspected that some practitioners still often use a "tried and true" method of simply driving the curve to assess the need for an advisory plate. Notwithstanding the assertion that ball-bank readings are typically used to assess appropriate advisory speeds, practitioners generally agreed that almost all curves signed with advisory speed plates can easily and safely be traversed at "+10" mph over the posted advisory speed with the possible exception of roads in mountainous areas. The practitioners also believe that drivers perceive the advisory speeds for curves in the same way: as a general guideline that says that one should slow down. It was not clear, however, if any of the practitioners had ever actually done a study at a curve to see whether deployed TCDs were effective in getting drivers to slow down or "comply" with the suggested advisory speed. At the same time, there were no advocates for changing the perception that posted advisory speeds were "too low"—in fact, the opposite view was typically expressed.

All groups of practitioners agreed that there is some variance in curve-related TCD selection and placement in their state although not within their own jurisdiction or other geographic area for which they are responsible. Most typically, practitioners thought their own practice and/or practice within their jurisdiction was consistent but that "other jurisdictions" introduced inconsistency. The Michigan group indicated that this is partially due to the flexibility afforded by "engineering judgment" but mostly because of the differences in budgets allocated to TCD deployments. The latter resulted in practitioners in some jurisdictions being "comprehensive" when it came to signing and marking horizontal curves. Others tried to get by with a bare minimum of TCDs. It was the general feeling that additional guidance in placing TCDs is needed, but it was fairly clear that the guidance that the *MUTCD* does offer was not necessarily being followed. There was also a concern noted that more clearly expressed guidelines might lead to more litigation. This was interesting in Michigan given that there is currently a high degree of legal protection for TCD use by practitioners and jurisdictions. Given that in many county departments signing curves is a small part of a typical engineer's job, charts or tables that would make the job easier and more consistent would be welcomed. At the same time, there are problems with such simple guidelines unless the words "should" or "shall" are used. One Michigan group mentioned that such guidelines might also help to prevent over-signing of curves.

Virtually all practitioners noted that horizontal curves are most dangerous to drivers in combination with other risk factors such as driveways, vertical curves, geometric or design problems such as inappropriate superelevation, weather, and anything that leads to a violation of driver expectancy.

As stated earlier, one of the objectives of this project was to identify the need for an improved methodology to determine what information about horizontal curves is needed and how best to communicate it to drivers in a consistent and credible manner. From the practitioners in the focus groups and interviews, it is clear that inconsistency in use and deployment of curve-related TCDs is perceived to exist. However, the reasons for this inconsistency were thought to be related to budgets, personnel turnover, the exercise of engineering judgment, and differences in topography between areas rather than differences in interpreting manuals or other rules or methodologies. Overall, there was a disconnect regarding the need or desire for well-defined guidelines or rules—while it was allowed that more refined or explicit guidelines would lead to increased consistency, many, if not most, practitioners still valued flexibility and discretion based on "judgment," and some objected to guidelines that could lead to liability issues if they were not followed.

The practitioners in the focus groups believe that the worst kinds of curves are those where there is a combination of the curve with other risk factors, a condition that does not lend itself to a straightforward or necessarily uniform solution. These concerns are not easily converted into new or improved guidelines or, at least, not into very explicit ones.

With regard to advisory speeds, most practitioners appeared to use the ball-bank indicator. While the "rules" that they used varied, there was consistency in the perception that advisory speeds were typically lower than they need to be. However, in the discussions, no alternative method for assigning the advisory speed received endorsement although some were opposed—for example, some practitioners thought that drivers already go too fast on curves and thus opposed using average or 85th-percentile speeds as being "biased" toward the high side. As a general rule, all practitioners indicated that in their view, drivers expect advisory speeds to be low and often exceed them. (This latter point was clearly not something that the practitioners had either done studies on or collected any data to support their view.) Changing the method of determining the numeric value of the advisory speed to be more consistent may not be necessary since different methods yield the same results. Changing practice to be more credible would imply raising the advisory speed in most cases. This would actually lead to larger inconsistencies in the short term, and the risk associated with such a wholesale change in practice and driver education may not be worth taking. Practitioners should be consulted once a standard methodology is developed to gain their input on how well the procedure would work and the likelihood that those responsible for placing curve signs will comply.

PRACTITIONER SURVEY

To obtain a broader view, a nationwide survey of practitioners responsible for specifying and implementing TCD treatments for horizontal curves was undertaken. Consistent with other project tasks, the emphasis was on rural two-way, two-lane roads. An estimated total of 1,250 practitioners from state, county, and city agencies in all 50 states were sent a 20-question survey by mail or e-mail; 344 responded. Those who received the survey were asked to respond and forward it to as many people as they deemed qualified to answer the questions. For this reason, an exact response rate cannot be determined. However, based on the 1,250 that were sent out, 344 responses would represent a response rate of ~25%. Of the 344 practitioners that responded, 177 (52%) were from state agencies, 144 (42%) from county agencies, and 20 (6%) from city agencies. City officials were not targeted for responses because of the project's rural-road focus. In states where the state DOT has jurisdiction over all roads within the state, county responses were not available. The largest number of responses (37, 11% of the sample) came from Michigan counties, which could influence the results. In most cases, however, the Michigan responses did not vary significantly from the others. In cases where the responses from Michigan were substantially different from the rest of the sample, both sets of responses were examined and reported.

The practitioner survey provided some valuable information about the state of the practice for curve-related TCDs. Based on the relatively high level of response and the numerous comments made on survey forms, it is clear that the signing and marking of horizontal curves is an issue that many practitioners find important. However, some responses were not easily interpreted. For example, one of the primary responses to the question "Which horizontal curves are the most difficult to sign and mark appropriately?" was "intersection on curve." However, there is a standard intersection-on-a-curve sign (W1-10) available in the *MUTCD,* so it would be expected that this situation would not be difficult to sign. It could be that respondents who checked this answer felt that this sign was not adequate for communicating the situation to drivers, or they may not routinely use all TCDs at their disposal.

Not surprisingly, agencies generally sign their own roads. When they do not, it is usually done by a higher government authority. While states and counties usually employ engineers and technicians, cities and townships often have other personnel such as a sign manager or road foreman responsible for the selection of TCDs for horizontal curves. The large numbers of non-engineers involved in day-to-day signing calls to question when, how, and by whom "engineering judgment" is being used in signing and marking curves. It may well be that routine decisions are made by technicians with engineers becoming involved only when atypical or more difficult situations are encountered. However it is still the non-engineer who is defining such situations.

The *MUTCD* is the most widely used guideline because most respondents claimed that it (or a similar state version) was used in their jurisdiction. The ball-bank indicator is the most common device for determining advisory speeds although many respondents use road geometry or test-drives in addition to or instead of the ball-bank indicator. Many respondents indicated that much of the training for sign specification is done "in-house." While standards and guidelines are accepted, they are not always followed. In-house and other forms of peer-to-peer training can lead to consistency over the years within a jurisdiction, but not necessarily among jurisdictions. This inconsistency among jurisdictions can also be seen in the low level of response to questions asked about practices in *other* jurisdictions and in the fact that respondents thought that practice such as setting advisory speeds was done less consistently in "other" jurisdictions relative to their own. Respondents also often answered "I don't know" or left these questions blank, which also implies a potential lack of sharing of best practice among jurisdictions.

Curves within the respondents' jurisdictions were reported to usually be signed and marked according to the standards. Advisory speeds seem to be determined somewhat consistently within jurisdictions but not among jurisdictions or across a state. The potential differences in procedures for determining advisory speeds notwithstanding, the consensus is that many, if not most, speed advisories are lower than needed and, most assuredly, not too high. Questions about consistency in the use of curve signs and in particular advisory speed signs yielded lower response rates. This may be due to the fact that respondents are worried about liability or to the fact that they are not confident that all the curves in their area have appropriate signs or advisory speeds. Respondents did not feel that curve TCDs were overused, and some even commented that signs might be underused in places. One common observation was that budget and staff limitations have an effect on the selection and placement of TCDs on horizontal curves. Many respondents pointed out that personnel in many more rural jurisdictions know the standards, but do not have the financial resources, the staff, or the equipment to perform studies and/or place signs. Similar to the focus group results, the clear picture that emerged was that rural jurisdictions and those with limited budgets have less comprehensive curve-related signing than more urban or richer jurisdictions.

When broken down into state and county jurisdictions, answers about signing consistency did not change greatly. State-level respondents tended to be more uniform and positive in their answers than were their county-level counterparts, but still had a negative view about practices across the state or at different jurisdictional levels within a state. At the state level, curve TCDs are reported to be used more often than at the county level. This is probably due to the fact that state roads tend to have higher traffic volumes and are generally held to a "higher standard" than are county roads and to the fact that state road departments have more resources available to them.

With regard to identifying curves that are difficult to sign or cause problems for average drivers, there was some disagreement. State and county-level respondents tended to agree that the five *most-difficult curves to sign* are "broken-back" curves, curves that get sharper as the driver goes through them, spiral curves, curves over the top of a hill, and back-to-back curves. However, they indicated that the five types of curves that are the *most-difficult to drive* are spiral curves, curves over the top of a hill, unexpected curves, sharp curves after a long tangent, and very sharp curves. According to the respondents, curves that are most difficult for drivers to negotiate are those that violate their expectations, that include a combination of factors, or both.

In conclusion, the state of the practice with respect to curve-related TCDs on rural two-way, two-lane roads is consistent in some aspects, but not in others. Both the focus groups and the survey yielded similar results. Standards and methods cited are relatively uniform, and variation in the standard information that is used appears to be minor. From what the practitioners have stated, the standards are generally understood and followed in their jurisdiction, although "in-house" training or practice sometimes overrides printed guidelines. Most agencies feel that they have achieved consistency within their own jurisdiction, but are less positive about what is happening elsewhere. State-level agencies were more confident than were county-level agencies that curve signing and advisory speed determination practices were the same across their jurisdiction. The biggest potential problem area appears to be in assessing and establishing advisory speeds. As a point of interest, if the 2003 version of the *MUTCD* is followed, it can be expected that there will be even more inconsistency among jurisdictions and that drivers will see some curves undergo significant changes in the advisory speeds that are posted. The practitioners surveyed in this study seemed to all be of the same mind with respect to which curves are most difficult to sign and drive. Better communication among agencies, either through state oversight or technology transfer programs, may be needed to improve consistency.

DRIVER FOCUS GROUPS

The perceptions of drivers regarding the treatment of horizontal curves were also assessed. While information from drivers is useful in its own right, it is also useful to compare their perceptions with the practitioners'. In addition to assessing driver perceptions, an attempt was made to differentiate between those who had been involved in a crash on a horizontal curve and those who had not, the idea being that a comparison between curve-crash-involved and "typical" drivers might reveal different patterns in driving habits or in how they respond either to TCDs or to the curves themselves.

The first task was to convene focus groups of crash-involved and typical drivers. Two separate focus groups were held in East Lansing, Michigan, in March and June 2004. The intent of the focus-group exercises was to discuss TCDs used on rural, two-way, two-lane horizontal curves. These sessions were spent discussing TCDs in general, identifying actual problem curve situations encountered by the participants, and then reviewing the TCDs that had been deployed and how they might be modified to make the situations less problematic. There was also discussion about responses to advisory speed signs and the general topic of TCDs for horizontal curves.

As noted above, the initial goal had been to convene one focus group of around 10 drivers evenly split between those who had been involved in crashes on rural curves and "typical" or average drivers who had not been involved in that sort of crash. Recruitment for the first exercise did not go according to plan, and a smaller group was used (five participants), only one of whom was known to have crashed. While the potential crash-involved participants were identified using crash records, the relatively limited numbers made recruitment difficult. The non-crash participants were simply identified using local and web-based telephone directories. As it turned out, the smaller group was better for the type of activities undertaken and allowed ample opportunity for discussion and interaction by all participants. A second group of six participants was convened later although it contained no pre-identified crash-involved participants. Participant ages were estimated to range from the early 20s to mid-70s with five male and six female participants. All participants were from suburban or rural areas in the three counties surrounding the urban area of Lansing/East Lansing, Michigan. The telephone recruiters who contacted potential participants concentrated on exchanges from suburban and rural areas so that there would be a good experiential base with rural roads and curves. All participants had experience with both urban and rural streets and roads in the area.

In general the participants in both focus groups were knowledgeable about the typical TCDs used for rural curves. They indicated that they have lower expectations for the number of TCDs present on low-volume facilities. At some point, both groups indicated that there needs to be better maintenance of TCDs on rural curves, whether it is by re-striping edge lines or clearing brush around signs. In addition, the participants commented that there is a need for better consistency among states and, more specifically, among counties in Michigan.

In terms of the specific TCDs that participants think would be helpful at curves, participants indicated their preference for

- Advance curve warning signs with advisory speed plates;
- Information (via signs) regarding other potential issues at the curve such as an intersection on the curve or loose gravel; and

- Seeing the curve in advance, especially through the addition of reflective visual aids for nighttime driving such as chevrons or by clearing obstruction near TCDs.

Participants indicated that they tended to drive slower and closer to the posted advisory speed when driving unfamiliar curves. When driving familiar curves, participants indicated that they routinely go at least 5 mph over the advisory and/or about 5 mph faster than they would at an unfamiliar curve (the responses were not necessarily consistent). In general, speed advisories were perceived as a warning to "slow down" but not necessarily to the advisory level. In that context, there was considerable variance in how speed advisories should be used and at what level they should be set. However, the participants indicated that they felt that changing advisory speeds at rural curves is not a high priority for change or use of financial resources. Most of the participants have their own method of relating their speed to the posted advisory speed.

CRASH-INVOLVED AND TYPICAL/ AVERAGE DRIVER SURVEY

As noted, both a focus-group exercise and a survey were undertaken to assess driver responses to different curve-related issues. The focus of the survey was also on rural two-lane, two-way roads. The topics were parallel to both those of the driver focus group and the practitioner-related exercises and included the adequacy of existing signs; perception of and response to specific TCDs, identification of what makes some curves more difficult than others, the extent to which familiarity is a factor in difficulty with curves, what types of roads present the most difficulty, how TCDs for curves could be improved, characteristics of their own "worst" curve-related experience, and whether that "worst" experience on a curve had short- or long-term effects on driving habits. The drivers were broken into two basic groups: drivers involved in a motor-vehicle crash on a horizontal curve within approximately two years; and typical or "average" drivers. The survey was done in both Michigan and North Carolina. There were actually seven different driver groups queried: typical Michigan-local, typical Michigan-statewide, typical North Carolina, two sub-groups of crash-involved Michigan-local, crash-involved Michigan-statewide, and crash-involved North Carolina. The differentiation between local and statewide Michigan drivers occurred because there was interest in identifying a "local" crash group for other phases of the project. The local group was composed of drivers in and around the greater Lansing area, which included both the urbanized Lansing/East Lansing area as well as the surrounding six counties that are largely rural agricultural areas outside the immediate urbanized area. The Michigan statewide sample was from the Lower Peninsula only. The overall response rate was ~13%.

The following summary and discussion are based on stated preferences and do not necessarily represent how respondents actually perform on the road system. The summary is provided in three separate categories: where there were no or slight differences among the respondent groups, where there were differences by state, and where there were differences by crash versus typical drivers.

The first set of summary statements contains those where there were no substantial differences among the groups of respondents:

- Except of the local Michigan crash group, respondents were generally confident that they knew the difference between advisory and regulatory signs.
- Respondents generally stated that advance curve warning signs helped them anticipate and drive through a curve.
- Respondents generally stated that large arrows and chevrons as well as pavement markings helped them anticipate and drive through a curve.
- The most prevalent comment about advisory speeds was that their use "depends" on one or more factors such as weather and visibility. Many respondents commented that they generally interpreted the advisory speed as a message to "slow down," even if not to the actual speed noted on the advisory sign. Few respondents reported actually driving at the advisory speed; conversely, numerous comments were made to the effect that advisory speeds are routinely exceeded.
- There was no consensus on how appropriate advisory speeds should be determined: fully 25% thought it should be the maximum safe speed, more than 30% thought it should be faster than most drove, and 36% thought it should be a "comfortable" speed on dry pavement.
- While speed was often mentioned in the context of problems with curves, 42% of all the respondents indicated that their worst-curve experiences occurred on roads with speed limits of 50 mph or less.
- The "top five" characteristics of problem curves include very sharp, no advance signs, over top of a hill, getting sharper as the curve is traversed, and unexpected. With minor variations, these were listed by all groups. Violation of driver expectation appears to be the common thread.
- The "top three" sign-related solutions were to lengthen the distance between the advance signs and the curves, to increase sign size, and to increase the number of advance signs. All of these are concerned with giving the driver the appropriate information earlier and appear to be consistent with the "top five" problems.
- In the context of fixing problem curves, while TCD changes were often mentioned as remedies, other factors such as geometric changes were mentioned more often. This is in spite of the clear emphasis in the survey instrument on TCDs.
- If a curve "check list" was to be made on how to "fix" curves, it would include correct the superelevation; install/ maintain good-quality center- and edgelines; ensure that appropriate advance warning signs are present; generally make sure that the road, shoulders, and right-of-way are

well-maintained; and provide special emphasis on "bad" or dangerous curves.

In some instances, there were variations in answers to questions that could be attributed to the respondent's state of residence. While these are highlighted below, it is not clear that the variation is really state- or region-related. In many instances, the variations among the various groups in Michigan were more pronounced than those between the two states. Although the majority of all respondents indicated that they used advisory speeds as "guides," Michigan respondents were more likely to use them in that manner and less likely to say that they drove at the advisory speed. It is not clear why this difference exists—it may be a function of the perception of speed-limit enforcement in general.

The variations in answers that could be attributed to respondents' state of residency are as follows:

- While all respondents thought familiarity was a significant issue in successfully negotiating curves, it was rated as more important by Michigan respondents.
- Michigan respondents were more likely to report gravel roads as a contributing factor in making curves hazardous. This may simply be a function of there being more gravel roads in rural Michigan.
- The North Carolina respondents were more likely to cite a combination of factors in describing their worst curve experiences.

Finally, there were differences between respondents who had been involved in a curve-related crash and the "typical" respondents. While some crash respondents may not have been involved in crashes on curves because of difficulties in locating actual crash locations, they had certainly been involved in some crash; likewise, while some of the typical, randomly selected respondents may have been involved in crashes, it should be much less likely. These caveats notwithstanding, differences between the two groups included the following:

- Crash groups in both states were more likely than their typical counterparts to *disagree* with a statement indicating that they were getting enough advance information about upcoming curves.
- Although all respondents were generally positive about advisory speed signs, crash groups were more likely to *disagree* with a statement indicating that advisory speed signs were helpful.
- While crash-involved respondents were not overwhelmingly honest in reporting their "worst curve" experience, they were far more likely to note involvement in a crash than were typical groups.
- Typical respondents were more likely to think that curves on gravel roads were a more serious problem than did the crash respondents.
- Typical respondents were more likely to think that curves "far away" from home were the most problematic while crash respondents indicated that "closer" curves were—that is, it is likely that those who crash on curves do so more often on roads with which they are familiar. This is in spite of an earlier assertion that familiarity with curves was a significant issue for all groups.
- While all respondents cited poor weather or pavement conditions, poor visibility, darkness, and unexpected traffic as important contributors to curve problems, the crash groups cited poor weather more often. Conversely, darkness was more often cited by typical drivers.
- While all groups cited speed-related problems when describing their "worst curve" experience, the crash groups were less likely than their counterparts to cite "going too fast" as part of the problem. Ironically, most groups thought that advisory speeds are too low while citing going "too fast" as a contributing factor in worst-curve experiences.
- Crash groups were somewhat more desirous of change in signs and markings. Overall, approximately 25% of the respondents did not think any TCD-related change was necessary.
- Crash groups were somewhat more likely to think that bad curve experiences had an effect on driving behavior although all groups stated that, not surprisingly, the effects lessened over time.

Overall, while there were some differences in responses by state, it is not clear that the differences are related to intrinsic regional behavior differences or simply differences in the roadway system such as fewer gravel roads in North Carolina. On the other hand, there were often clear differences between crash and typical respondents. Drivers who had been involved in crashes were more likely to state that their worst experiences occurred closer to home than were the typical respondents, and they were more likely to indicate the need for more or better communication. While the former confirms what is known about many crashes occurring closer to home, it is not clear what the implications are for TCDs. Improved communication would probably not help drivers in many of their familiar problem situations. On the other hand, all respondent groups stated that "fixes" that deal with geometry and other design features are more important than modifications of TCDs. In regard to changes needed for TCDs, for the most part, respondents seemed satisfied with the ones they routinely encounter. However, they were adamant in suggesting that center- and edgelines be more widely used. Interestingly, there were very few comments about the use of chevrons, large arrows, or both.

There is cause for concern with respect to speed advisory signs. While most respondents report using the advisories as a general guide and as a suggestion to "slow down," they also indicate that they typically exceed advisory speeds. At the same time, they often cite excessive speed as a reason for their problems with curves. There was also significant variance in how respondents think that speed advisories should be set, from lower than most would go (which is the case now) to a maximum safe speed on dry pavement.

FIELD STUDY OF DRIVER BEHAVIOR USING DRIVER PERFORMANCE MONITORING TECHNIQUE

The project also included a driver observation study using driver performance monitoring (DPM) techniques in which a sample of randomly selected drivers were observed as they traversed an approximately 25-mile predetermined route negotiating 43 curves. As part of the DPM data collection, detailed observations were made by trained observers at 11 curve sequences (some sequences contained more than one curve) and included assessments of a driver's "search, speed, and direction control" performance as they negotiated each sequence. The vehicle's speedometer readings at various points were also recorded as were comments on driving behavior.

As applied in this project, DPM is an observation technique in which one or more trained observers ride with a subject driver (in the subject's vehicle) over a predetermined route and make observations regarding driving behavior at specific locations. The behavior of each driver is compared with what is expected at each location. That expectation is established by observing other drivers at the same locations on the same route prior to the data collection runs. While DPM is a qualitative approach to evaluating driver behavior, it is made as quantitative as possible by scoring each subject as exhibiting satisfactory or unsatisfactory behavior on each of three dimensions: visual search, speed, and direction control. An example of satisfactory behavior would be gradually slowing down for a curve versus an abrupt speed change right at the point of curvature. The observer(s) also makes comments regarding any other occurrences such as a vehicle pulling out of a driveway on the approach to a curve or other actions that might affect driver performance. The person in the front seat is the principal observer making the judgments on behavior while the back-seat observer makes ancillary comments and observations such as speedometer readings at various points along the route. DPM has been used in several contexts including as a driver-training tool for commercial truck drivers, as a diagnostic tool to evaluate whether recovering stroke victims are safe to resume driving, and as a research tool in an earlier NCHRP project on older drivers (NCHRP Project 3-44, "Improved Traffic Control Device Design and Placement to Aid the Older Driver").

General DPM Route Description

The DPM route used in this project was an approximately 25-mile loop in a primarily rural area southeast of Lansing, Michigan. The two-way, two-lane roads that composed the route were a mixture of a state-numbered highway and county roads, although the latter predominated. There were 43 curves on the route with 11 curves or curve combinations composing the DPM observation sequences. The terrain is generally gently rolling with a few steeper sections. There were no long grades. The environment ranged from a low-density suburban area with houses set back 75 feet or more from the traveled way to wooded and agricultural areas with farms and widely scattered houses. The aerials of the DPM curve sequences also provide detail of the environment adjacent to the route. The prevailing traffic volumes were typical of rural roads, generally on the order of 1 to 2,000 vehicles per day. The state-numbered and -maintained road tended to be in better condition and to have better and slightly wider shoulders than did the county roads. Regulatory speed limits ranged from 45 to 55 mph although some were not marked. For the latter, the *de facto* limit in Michigan in rural areas is 55 mph. The curves themselves varied from very gentle with excellent visibility, requiring no speed reduction or advisory speed signs, to a sharply descending right-angle turn, just after the crest of a hill, which had a 20 mph advisory speed plate. There was one ~2-mile section of gravel road and another section that was a quarter-mile to one-half-mile long. Most paved sections had marked center- and edgelines.

DPM Subjects

The 39 DPM subjects were randomly selected from online and printed telephone books. The subject pool was constrained by telephone exchange so that they would be from the area and, hence, more likely to participate. However, there was no attempt to randomize by age or to adhere to a rigorous statistical sampling regime as the purpose was not to achieve statistically significant results. The 39 subjects were split between day (28) and night (11) conditions. In addition to the randomly identified subjects, there were four Michigan State Police (MSP) officers who drove the route and were observed as if they were regular subjects. The MSP officers were instructed to drive at the edge of what they perceived as the "safe envelope" so that an approximation of the maximum safe speed could be obtained. In spite of this direction, one of the officers drove at the posted regulatory and advisory speeds although he indicated that the "safe" speed was higher than those at which he drove—the data for this person were eliminated from all analyses.

DPM Results

As noted above, there are a number of quantifiable driver behaviors derived from the observers' comments and observations. For example, each driver either performed satisfactorily or not on each of the standard DPM measurements of search, speed, and direction control through any given curve sequence. Note that a sequence might consist of as many as three or four sections. Likewise, observer summaries contained indications of the type of errors, if any, that each driver made as he or she traversed the sequence, although these were not necessarily limited to the standard DPM measurements. *It is important to note that the words "error" and "problem," as used herein, refer to a deviation from expected driver behavior.* Declaration of an "error" or a driver having a "problem" does not necessarily imply that a patently unsafe maneuver has occurred. Errors included not looking in the appropriate direction for an oncoming or intersecting vehicle, not slowing down appropriately, an abrupt and/or late speed reduction, encroaching on or crossing the center- or edgelines or both in the case of a multiple-curve sequence, and handling difficulties such as abrupt or potentially dangerous lane changing or encroachment. While not all portions of the route were marked with edge- or centerlines, a centerline crossing was nonetheless noted when the driver crossed the approximate center of the roadway. The DPM performance assessment and other comments were quantified and displayed in a spreadsheet. In addition, the speeds collected by the back-seat observers were used to construct an approximate speed profile for the entire route. Finally, the performances of all drivers on each DPM sequence were aggregated to provide overall "scores" for the sequences.

Given this performance-based information, the sequences could be ordered in any one of several ways. For example, the sequences with the highest numbers of driver errors could be identified or they could be ordered by the frequency of a specific type of error. Likewise, the sequences could be ordered by approach speed or speed in the curve. The summaries of the subject performances can also be compared with the performance of the MSP officers or with other expectations of performance. An example of the former is a comparison of the difference between the subjects' average speed for a specific curve in a DPM sequence with the average (n=3) from the MSP officers. An example of the latter is comparison between average subject speed and the posted regulatory and advisory speeds.

Another basis for comparison of driver performance is a hierarchical ranking of "curve difficulty" or complexity based on the TCDs currently deployed. This hierarchy was developed by project personnel and is shown in Table 1. Each curve on the DPM route can be assigned a number based on this hierarchy. Note that as used here, the hierarchy is based on the TCDs currently deployed at any given curve and not, for example, on any measure of the curve itself such as degree of curvature or radius.

After all the DPM observations had been made, short subject-based reports were written and comments were aggregated for each sequence. Discussion was organized on the basis of the hierarchy of curve-related TCDs deployed—generally from the simplest curve to the most complex, based on existing signing. The hierarchy is subjective in nature but does provide a basis for ordering the discussion. The hierarchy is not without problems. For example, a curve

TABLE 1 Curve hierarchy based on TCDs deployed

Curve Ranking	Signing Conditions
0	no curve
1	curve present, no sign
2	curve w/curve sign only
3	curve w/turn sign only
4	curve w/reverse turn sign only
5	curve sign + large arrow
6	turn sign + large arrow
7	reverse curve sign + large arrow
8	curve sign w/speed advisory
9	turn sign w/speed advisory
10	reverse curve sign w/speed advisory
11	curve sign + chevrons
12	turn sign + chevrons
13	reverse curve sign + chevrons
14	curve sign w/speed advisory + large arrow
15	turn sign w/speed advisory + large arrow
16	reverse curve sign w/speed advisory + large arrow
17	curve sign w/speed advisory + chevrons
18	turn sign w/speed advisory + chevrons
19	reverse curve sign w/speed advisory + chevrons
20	curve sign + other combination
21	turn sign + other combination
22	reverse curve sign + other combination

with a curve arrow and a speed advisory plate of 45 mph is "higher ranked" than a curve with a turn arrow but no advisory speed plate.

By way of context, the values of the curve hierarchy for the DPM sequences ranged from 1—a curve with no curve-related treatments—to 17—a complex curve with curve warning signs, advisory speed plaques, and chevrons. In some instances, there are multiple curves in a DPM sequence although they are not necessarily reverse curves. The individual curves in a single DPM sequence may, and frequently do, have different values within the hierarchy. Finally, the sequences contain situations in which the worst curve was the first one encountered and other situations in which the worst curve was the second or third one encountered. In terms of observations, there were 42 drivers including the 3 MSP officers. The number of drivers having one or more errors at the various sequences ranges from 1 to 35. With one exception, all curve sequences presented problems to almost a quarter of all drivers; the "worst" sequences resulted in at least one error assigned to almost 90% of the regular (non-MSP) drivers.

Discussion of DPM Results

Given the DPM results for individual sequences, the question is whether there are overarching issues that emerge and, especially, whether there is anything that may impact the guidelines for the use of curve signs and markings. In the discussion that follows, reference is made to specific DPM or curve sequences.

Advisory Speeds

Perhaps the most interesting finding that emerges from the sequence-based results is the response of drivers to advisory speed signs and to regulatory speed limits. First, there were three different speed limits encountered by drivers on the DPM route: 45, 50, and 55 mph. In addition, there were two gravel-road sequences where the speed limit was unmarked and, thus, a *de facto* 55-mph limit was in effect (Sequences 4 and 6). Signed advisory speeds for the DPM sequences ranged from 20 to 40 mph. Speed advisories were not present at all curve sequences, and none was present on either sequence on the gravel roads. On the curve sequences, the average speeds of the regular drivers never exceeded the posted or *de facto* speed limits. On the gravel road segments, regular drivers were quite conservative, approaching curves at average speeds less than 35 mph. The MSP officers drove similarly, although faster, in all instances except on the curve sequences on gravel roads where they drove about 2 mph slower than the other drivers.

Considering those sequences marked with advisory speeds, in every instance drivers drove, on average, faster than the speed advisories that were displayed. Moreover, there is some indication that lower speed advisories did not result in proportionately lower speeds. For example, for the two sequences with the lowest speed advisories of 20 and 25 mph, the daytime average speeds were 10 to 11 mph over the advisory, nighttime averages were 7 to 8 mph over, and the MSP averages were 12 and 16 mph over. For the four sequences with 35-mph speed advisories, daytime averages were 5 to 8 mph over, nighttime averages were 5 to 7 mph over, and the MSP averages were 11 to 15 mph over. For the sequence with the 40-mph advisory, the daytime average was 1 mph over, nighttime was at the advisory, and the MSP average was 7 mph over. For Sequence 1 where the second curve in the sequence had an advisory of 40 mph, daytime drivers were ~6 mph over, nighttime drivers about 3 mph over, and MSP officers 11 mph over. Not considering the sequences on gravel roads, for the sequences with no advisory speeds and regulatory limit 50 or 55 mph, the daytime average ranged from 47 to 52 mph, nighttime from 44 to 48 mph, and the MSP from 52 to 57 mph.

Based on these results, it is noted that while drivers slow down when confronted with speed advisories and slow down even more for lower advisories, they are still more likely to exceed lower advisories by a greater amount than they do higher advisories—their speed-reduction response is somewhat limited. There are several possible explanations for this: drivers may feel that the risk of exceeding the advisory speed is lower at lower speeds; they may simply feel that they don't need to go that slowly; or they may perceive that they have slowed down the requisite amount—that is, their sense of speed may be diminished. The latter explanation is similar to the reasoning for freeway off-ramp crashes where the appropriate exit speed, sometimes as low as 25 mph, is misjudged in comparison with the mainline freeway speed, which can be 70 mph or higher—drivers are simply not going as slow as they think they are.

Assuming that speed advisories are marked using the *MUTCD* as a general guide, drivers are consistently driving faster than the curves are marked. Moreover, the MSP speeds indicate that for most situations, the maximum safe speed is even higher. However, for curves with the lowest advisory speeds, the number of drivers with *curve-related* errors is the greatest over all sequences (25 and 24 of 39 regular subjects, respectively).

Based on the results just presented, the question arises of what would happen if the existing guidelines for speed advisories were to be changed, resulting in advisories being increased. While there are different scenarios that might occur, the worst-case is that drivers maintain the difference between posted advisories and their travel speed. Under this scenario, if the curves with 20- and 25-mph advisories on the DPM route were increased 5 or 10 mph and drivers continued to exceed these lowest advisories by 10 to 11 mph in the daytime, they would be negotiating the curves at 35 and 40 mph or similar to the speeds of the MSP officers. An increase in curve-related driver errors could be expected. Under this scenario, where existing advisories were 35 mph and drivers were 5 to 8 mph above the advisory, if these advisories were raised to 40 mph, drivers could be expected to drive at 45 to 48 mph—only a little under the MSP speeds of 46 to 50 mph. It remains to be seen how drivers would respond to increasing advisory speeds, but the evidence here suggests that there could be problems, especially at those curves requiring the lowest advisories.

The findings with respect to drivers exceeding speed advisories is consistent with findings from other parts of this project where drivers reported that they consistently exceed posted advisory speeds at curves and where practitioners indicated that their expectations and perception of common practice were that drivers routinely exceeded advisories.

In terms of recommendations, what emerges from this analysis, at least in the short term, is that raising advisory speeds may well result in problems for drivers who routinely exceed advisories. Moreover, the problem could be worse on curves with the lowest advisories. Thus, the effects of driver response to raised advisories should be thoroughly studied before changes are made. Given the numbers and types of driver errors with existing treatments, it seems appropriate that signing for curves with the greatest difference between the posted speed limit and the advisory speed should be comprehensive (e.g., advance warning signs, speed advisories, chevrons, or centerline markings). While the use of comprehensive treatments did not result in lower numbers of driver errors in the study, drivers should still be given as much information as possible on curves where the desired speed reduction is the greatest.

General Speed-Related Issues

Reordering the DPM sequences by the entry speed (which is defined as the lowest of the posted speed limit and the posted advisory) for the sequence and then examining the number of drivers with *curve-related* errors revealed an interesting pattern. The two sequences (9 and 5) with the lowest advisories (20 and 25 mph) had the largest numbers of drivers (24 and 25) having errors. The four sequences (2, 3, 7, and 8) with 35-mph advisories were next with 19, 12, 8, and 7 drivers having errors; and the 40- and 50-mph sequences (5a and 1) had even lower numbers of drivers with errors (1 and 4). However, the sequences with the highest speed limits (55 mph) were mixed with three (6, 11, and 10) having a higher number of errors (19, 18, and 13) and one (4) with only one driver making an error. Sequences 10 and 11 both consist of multiple curves and are ranked "high" because in each sequence, the initial curve has no advisory but there are advisories and additional treatments for a subsequent curve. Notwithstanding that Sequences 10 and 11 have advisories within the sequence, the preponderance of drivers making errors come at "both ends" of the speed scale—at curves that have very low advisories and those where the initial speed is high. While some issues could be taken with the definition of an error or "problem" within the context of DPM, it seems clear that the problematic sequences that emerge are those that require significant speed reduction at the outset and those where the necessary reduction, although less, is within a sequence of curves.

The recommendation for the sequences where the initial speed is relatively high but decreases at a subsequent curve within a series of curves is to continue to sign the lower-speed curve aggressively in spite of the number of drivers making errors even when speed advisories and other treatments are present. This recommendation is based more on common sense and judgment than the study results *per se.*

Driver Errors

The sequences were also examined by ordering them according to the number of drivers having errors. In addition to speed-related errors at the curves with the lowest advisories, the greatest number of drivers (24 and 25) making non-intersection errors occurred for these same curves. The next highest numbers of drivers having non-intersection errors occurred for a curve with a 35-mph advisory (19) and two that had no advisory (18 and 19), one of which had a posted limit and one of which was not posted. Thus, looking at the speeds and the driver errors, for at least some curves what happens is that speeds in excess of the advisories, and especially the lower advisories, lead to greater numbers of driver errors.

Examining the driver errors in more detail, an arbitrary distinction between sequences where 10 or more drivers had curve-related errors versus those sequences where there were fewer than 10 is made. This shows that seven sequences fall into the first category while five fall into the second. Interestingly, the curves where more drivers made errors were also higher-ranked in the curve hierarchy—that is, these curves already had more extensive treatments. This was especially true with the use of chevrons where four of the seven in the first category had chevrons present versus only on one of the other group (of five). Contrarily, neither of the two worst curves had chevrons deployed. This leads to one of two conclusions: either chevrons have little impact in reducing drivers' curve-related errors or drivers would have experienced even more errors if the chevrons had not been present.

Examining the initial speeds for both groups of curve sequences reveals that while the average drivers approached the first category of curves a little faster than the other (~41 mph versus ~39 mph), the MSP officers showed the opposite (~44 mph versus ~46 mph).

Interestingly, the two sequences on gravel roads showed opposite results. For one sequence (4), there were very few errors as drivers approached and drove through the curve conservatively, negotiating them with ease. The other sequence (6), which consisted of a much more abrupt curve with less visibility through the curve, was more problematic. The conclusion, albeit based on only two sequences, is that drivers will generally perform well unless a curve is more difficult. This gives credibility to the idea that gravel roads may require less signing except at difficult curves such as those that require a turn arrow, have sight distance problems, or both. Again, the sample size of curves in this category is quite small.

Curves and Intersections

Results from other parts of this project have also indicated that more problematic types of curves are those that have additional distractions or elements—most specifically, an intersection either on or near the curve. The speed differentials notwithstanding, the problems that drivers had in several sequences were in not giving adequate attention to the intersection that was encountered in the vicinity of the curve in spite of the fact that standard intersection signs were typically present. There were six sequences (5, 11, 3, 7, 8, and 5a) that had an intersection or, in one instance, a driveway that was in essence an intersection. The two sequences that had the most intersection-related errors were 5 and 5a where the intersection was literally on the curve: 10 and 25 drivers, respectively, made errors. In these two sequences the intersecting roadway came in at close to a right angle from one side or the other. Three other sequences (11, 3, and 8) had intersections close to, but not on, the curve. These intersections were far less problematic with between one and four drivers making errors. The final sequence of interest (7) had an intersection in the curve, but drivers had an excellent view of it as the intersecting road was essentially "straight ahead" as they approached it and the road (and route) curved to the left—a significantly different "look" for the approaching driver. Notwithstanding the fact that all of these intersections were marked with Intersection Ahead signs, it is clear that intersections in the curve caused the most difficulties for drivers. None of the signs "combined" the curve and intersection warning. Given the problems experienced, even with signs deployed, it seems clear that the combination is indeed problematic and that drivers should be provided with advance warning whenever possible.

Overall Summary and Recommendations

Based on the discussion above, overall findings are reiterated and some recommendations made.

Advisory Speeds

Findings and recommendations regarding advisory speeds are as follows:

- The DPM subjects routinely exceeded posted advisory speeds. These findings are consistent with findings from other parts of this project where surveyed drivers reported that they consistently exceed posted advisory speeds at curves and where practitioners indicated that their expectations and perception of common practice were that drivers routinely exceeded advisories. This phenomenon is also noted in the literature review.
- Raising advisory speeds may well result in drivers who routinely exceed advisories and approach the maximum safe speeds, at least in the short term. Moreover, the problem will likely be worse on curves with the lowest advisories. Thus, the effects of driver response to raised advisories should be thoroughly studied before changes are made.
- It is not clear that comprehensive signing for curves needing the lowest speed advisories will reduce the number of drivers with errors. However, the number of problems with such curves suggests that drivers either need additional information or need to better process and/or respond to the information that is made available. Thus, it is argued that signing should be comprehensive for the situations where the lowest advisory speeds are appropriate.

General Speed-Related Issues

A recommendation regarding speed-related issues is as follows:

- The recommendation for the sequences where the initial speed is relatively high but decreases at a subsequent curve within a series of relatively close curves is to continue to sign the lower-speed curve aggressively in spite of the number of drivers making errors even when speed advisories and other treatments are present. This is consistent with current practice of independent signing for sequential curves unless the tangent is <600 feet long.

Driver Errors

Findings and recommendations regarding driver errors are as follows:

- When sequences were divided into two groups (≥10 drivers made errors versus <10), seven fall into the first category while five fall into the second. The curves where more drivers made errors already had more extensive treatments. This was especially true with the use of chevrons where four of the seven more problematic sequences had chevrons present versus only on one of the other group (of five). Contrarily, neither of the two worst curves had chevrons deployed.
- The two sequences on gravel roads showed opposite results. For one sequence, there were very few errors as drivers approached and drove through the curves conser-

vatively, negotiating them with ease. The other sequence was more problematic with a much more abrupt curve with lower visibility through it. The conclusion, albeit based on only two sequences, is that drivers will generally "take it easy" on gravel roads and will perform well unless a curve is more difficult or unexpected. This gives credence to the idea that gravel roads may require less signing except for "difficult" curves such as those where a turn arrow would be used when they should be signed more aggressively.

Curves and Intersections

Findings and recommendations regarding curves and intersections are as follows:

- Notwithstanding the fact that all intersections were marked with Intersection Ahead signs, intersections in the curve caused difficulties for drivers. None of the signs "combined" the curve and intersection warning. It is not clear what more could or should be done, but it is clear that the combination is indeed problematic and should be signed whenever it occurs—that is, drivers should always be told when there is an intersection on or near a curve.

Anecdotal Observations Based on DPM Subject Performance

In addition to the more quantified results just recapitulated, a summary of more qualitative comments has also been prepared. The point of this exercise was to use the perspective of the DPM observer in assessing how drivers responded to curve-related TCDs and to the physical situations that they encountered in the field.

The drivers were observed to operate their vehicles "mechanically" in an incremental rather than continuous process and did not respond to TCDs as if they were messages about what was on the road ahead. The immediate responses were often "tokens" of response—for example, drivers would take their foot off the pedal although they would not actively slow down, in spite of a speed advisory being present. While in some instances this response was "good enough," in others it was not. This is borne out by the quantifiable responses at several of the curves. If the curve was reasonably gentle and did not violate basic expectations, the drivers were in good shape. If the curve was a more serious undertaking, token responses then led to driver errors. The types of curves or situations where more drivers had errors included the following:

- Curves where the drivers had limited or no visibility of the curves when the TCDs were first visible;
- Curves where there were vertical curves, primarily hill crests that obscured the curve; and
- When the curve was combined with another element, especially intersections.

In general, although the curves were well-marked, the nominal responses to the TCDs (such as easing up on the gas pedal) were simply not enough when the situations were more complex. Consequently, a more positive or assertive response was delayed until the drivers actually saw the extent of the curve or other feature. In some instances, modest responses caused later driver errors. There was also a general "dilution" of the driver's attention—that is, in addition to tending to the driving task, they also looked at the scenery, asked general questions, talked on a cell-phone, or asked specific questions. This performance can be compared with the three trained MSP officers—they were highly focused on the task at hand and not easily distracted.

CHAPTER **3**

INITIAL GUIDELINES AND RECOMMENDATIONS FOR CHANGES TO THE *MUTCD*

INTRODUCTION

The focus of this project was to address the issue of consistency in the use of TCDs to communicate information on changes in horizontal alignment to the driver. As noted earlier in this report, there was a question as to whether the millennium edition (ME) of the *MUTCD* or the 2003 edition should be the "base condition." Early work on the project was actually done before the 2003 edition was in wide use, and it was also clear that some practitioners did not even use the ME. When it came time to propose guidelines and changes, it was decided to be consistent with the early work and to use the millennium edition as the base version of the *MUTCD;* differences would be resolved post hoc. Thus, the guidelines that are discussed in the rest of this chapter use the millennium edition as a base. This is also true for the final practitioner survey discussed in the next chapter. Resolution of differences between the millennium edition and the 2003 edition is done in the final chapter wherein final guidelines are presented and discussed.

The *MUTCD* provides surprisingly little guidance on the use of individual TCDs for communicating with the driver and no guidance on combinations of TCDs for this purpose. The millennium edition of the *MUTCD* states the following:

- The horizontal alignment turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5) sign *may* be used in advance of situations where the roadway alignment changes.
- A Large Arrow (W1-6) sign *may* be used on the outside of the turn or curve.
- An advisory speed plaque (W13-1) *may* be used to indicate the speed for the change in horizontal alignment.
- The Turn (W1-1) sign or the Curve (W1-2) sign *may* be combined with the Advisory Speed (W13-1) plaque to create a combination Horizontal Alignment/Advisory Speed (W1-9) sign.
- The (W1-1) or (W1-2) sign *may* be combined with the Cross Road (W2-1) or the Side Road (W2-2 or W2-3) sign to create a combination Horizontal Alignment/Intersection (W1-10) sign that depicts the condition where an intersection occurs within a turn or curve.
- The Chevron Alignment (W1-8) sign *may* be used to provide additional emphasis and guidance for a change in horizontal alignment.
- On roadways without continuous centerline markings, short sections *may* be marked with centerline pavement markings to control the position of traffic at specific locations, such as around curves. . . .
- Delineators *may* be used on long continuous sections of highway or through short stretches where there are changes in horizontal alignment.

The word "*may,*" while used extensively, is not defined *per se* in the millennium edition of the *MUTCD,* but is defined in the 1988 edition as "a permissive condition, NO requirement for design or application is intended." "May" is typically used in the context of defining "options." In the ME, it is noted (Introduction, p. I-3) in the definition of the term "option" that

> [An option is] a statement of practice that is a permissive condition and carries no requirement or recommendation. . . . The verb may is typically used.

Necessary uniformity in the use of devices is defined in §1A.06:

> Uniformity of devices simplifies the task of drivers because it aids in recognition and understanding, thereby reducing the perception/reaction time. . . . Uniformity means treating similar situations in a similar way.

In order to achieve this uniformity, the *MUTCD* relies on the application of engineering judgment by setting the standard that "when engineering judgment determines the need for a horizontal alignment sign, one of the W1-1 through W1-5 signs *shall* be used."

However, the *MUTCD* provides little guidance that would result in the use of engineering judgment leading to uniform application of TCDs to communicate information on the change in horizontal alignment. The definition of engineering judgment in the *MUTCD* is as follows:

> The evaluation of available pertinent information, and the application of appropriate principles, standards, guidance and practices as contained in this Manual and other sources for

> the purpose of deciding upon the applicability, design, operation, or installation of a traffic control device. Engineering judgment shall be exercised by an engineer, or by an individual working under the supervision of an engineer, through the application of procedures and criteria established by the engineer. Documentation of engineering judgment is not required.

It is not surprising that there are inconsistencies in the use of TCDs to communicate information on changes in horizontal alignment to the driver because the *MUTCD* does not specify or even suggest factors to be considered when applying engineering judgment in this instance.

FINDINGS FROM THIS STUDY RELATED TO UNIFORMITY

The driver survey respondents and the driver focus group participants in this study both reported a perception of non-uniform treatment of horizontal alignment changes across different jurisdictions. The practitioner survey results included the finding that in many jurisdictions the decisions on which, if any, TCDs to use to inform the driver of a change in horizontal alignment are made by non-engineers. The participants in the practitioner focus groups identified the need for better guidance on when to use supplemental TCDs at horizontal curves.

The practitioner survey revealed a wide variation in the use of chevrons: from using them on all curves when an advisory speed plaque is used to only using them when there is a 6° or greater degree of curvature. The DPM study was inconclusive with respect to using chevrons because they did not seem to change driver performance when negotiating curves.

The practitioner survey also revealed a wide variation about the decision of when to use advisory speed plaques: some jurisdictions use them on all curves when the advisory speed is equal to or less than the posted speed limit but other jurisdictions use them on curves where the advisory speed is 20 mph or more below the posted speed limit. This variation could be problematic because the driver survey respondents and the driver focus-group participants both stated that they use the advisory speed as a guideline in selecting the speed when entering a horizontal curve. The latter is in spite of the fact that they do not necessarily slow to the posted advisory speed.

Overall, the TCD options provided in the *MUTCD* are perceived to be adequate—there does not appear to be an unmet demand among practitioners for a range of new and different options. Likewise, drivers seem reasonably satisfied with the TCDs that they encounter and, in fact, place TCD changes relatively far down a list of changes they would like to see at horizontal curves. In a similar vein, most practitioners stated that *they* use TCDs consistently although they are not so sure about their counterparts in other jurisdictions.

Practitioners were likely to attribute inconsistency in the use of TCDs to differences in operating budget and other resources and not to interpretation of the manual. Drivers also perceive some inconsistency from one jurisdiction to another although, not surprisingly, there is no attribution of the reasons for the inconsistencies.

Practitioners were generally in favor of the concept of better guidelines for using TCDs that would lead to more consistent use, but there was an even stronger sentiment for maintaining sufficient flexibility for rendering judgments regarding which devices should be used when. However, practitioners expressed concern about prescriptive guidelines that could be interpreted as what "must" be done.

In this context of varying views of what the content of guidelines could or should consist of, a set of recommendations was developed. In the paragraphs that follow several relatively modest changes to the *MUTCD* (the millennium edition version) are recommended based on the results of the research presented here. These changes were then presented to practitioners in a survey. The response to the survey is contained in the following section of this report.

RECOMMENDED CHANGES TO THE *MUTCD*

First Change

Recommended Change

The first recommended change is as follows (changes to the language of the *MUTCD* are in **bold**):

1. The first option in §2C.06 of the *MUTCD* should be changed to read horizontal alignment signs *may* be used in advance of situations where the roadway alignment changes

> **and *should* be used when the alignment change would result in an advisory speed equal to or lower than the posted speed limit.**
>
> **The Winding Road (W1-5) sign should be used where there is a series of turns or curves that requires driving caution and where curve or turn signs would be too numerous to be effective. Where any of the curves has an advisory speed that is (*X*) mph or more below that of the first curve, then a curve or turn warning sign and an advisory speed plaque *should* be used.**

Bases for the Recommendation

The bases for the first recommendation are as follows:

- The state *MUTCD* review showed that at least 10 states have already adopted this language.
- The practitioner survey indicated that horizontal alignment signs are already widely used except on winding roads and low-volume roads, which are covered in separate sections of the *MUTCD.*
- This change would increase uniformity at a relatively low cost because most agencies already sign those curves

when the advisory speed would be lower than the posted speed limit.
- The use of "should" (as opposed to "shall") allows for engineering judgment to be used when there is a good reason to not place a sign at a curve or a set of curves.

Second Change

Recommended Change

The second recommended change is as follows.

2. §2C.42 of the *MUTCD* should be changed to read:

An Advisory Speed (W13-1) plaque *should* be used to indicate the advisory speed for a change in horizontal alignment when the advisory speed is *X* mph or more below the applicable speed limit.

Bases for the Recommendation

The bases for the second recommendation are as follows:

- The practitioner survey showed a wide variation in determining when to use advisory speed plaques, with *X* ranging from 0 to 20 mph. Selecting a single value of *X* could lead to more uniform signing.
- The driver survey respondents and the driver focus-group participants both stated that they use the advisory speed as a guide in selecting the speed they choose when entering a horizontal curve. With the wide variance in practice, this guidance is obviously inconsistent across jurisdictions.
- The DPM analysis showed that drivers routinely exceed the advisory speed on curves. This phenomenon was determined to be independent of the use of other TCDs at the curves. While drivers do slow down more for lower advisories, they exceed those lower advisories by an increasingly greater amount—that is, the lower the advisory, the lower the observed speed, and the greater the differential between the observed and posted advisory speeds. This indicates that drivers use the advisory speed plaque as their primary basis for selecting an approach speed to a change in horizontal alignment.

Third Change

Recommended Change

The third recommended change is as follows.

3. Add a section to the *MUTCD* (similar to §2B.11 for setting speed limits in speed zones) to define the factors to be considered when conducting an engineering study to establish the appropriate TCDs when there is a change in the horizontal alignment of the highway. The language should read:

Standard:

After an engineering study has been made in accordance with established traffic engineering practice or where engineering judgment determines the need for horizontal alignment signs, advisory speed plaques, and/or supplemental guidance, these TCDs *shall* be used.

Guidance:

The factors that *should* be considered in determining the system of TCDs to be displayed when there is a change in the horizontal alignment of the highway include the following:

- **The difference in the posted speed limit and the 85th-percentile speed of free-flowing traffic;**
- **The approach sight distance to the beginning of the curve;**
- **The visibility around the curve;**
- **Unexpected geometric features within the curve, such as an intersection or a change in the curve radius; and**
- **The position of the most critical curve in a sequence of relatively closely spaced curves.**

Bases for the Recommendation

The bases for the third recommendation are as follows:

- The *MUTCD* provides no guidance on the use of supplemental TCDs.
- The practitioner survey respondents identified many of these factors as characteristic of curves that are difficult to sign appropriately. They expressed the need for additional guidance on when to use supplemental TCDs.
- The practitioner focus group defined the use of supplemental TCDs as the major inconsistency in communicating with the driver at horizontal curves.
- Ninety-five percent of the respondents to the driver survey said arrows and chevrons helped them to successfully negotiate horizontal curves.
- The driver survey respondents identified visibility and unexpected events as factors that cause them problems and where additional guidance would be beneficial.
- The driver focus group participants identified edgelines, delineation, and chevrons as devices that assist them in negotiating curves.
- The DPM results showed that curves with complicating factors such as intersections in the curves were more problematic for drivers.

This recommendation concerns the definition of the term "engineering study," principally, the addition of an explicit list of seven factors to be considered. Regarding the explicit language in the 2003 *MUTCD,* the following language is from §1A.13, Item 26:

> Engineering Study—the comprehensive analysis and evaluation of available pertinent information, and the application of appropriate principles, Standards, Guidance, and practices as contained in this Manual and other sources, for the pur-

> pose of deciding upon the applicability, design, operation, or installation of a traffic control device. An engineering study shall be performed by an engineer, or by an individual working under the supervision of an engineer, through the application of procedures and criteria established by the engineer. An engineering study shall be documented.

It is argued here that the definition is too general for the purposes of placing TCDs on horizontal curves; it is thus recommended that a more explicit list of factors to be considered be included in the definition. The definition cited does little to help practicing engineers know what to look at when undertaking such a study. Indeed, there are other instances in the *MUTCD* where additional factors to be considered in other situations are explicitly listed. For example, in §2B.13 regarding speed limit signs on p. 2B-11, six factors are listed including road characteristics, pace speed, roadside development and environment, parking practices and pedestrian activity, and crash experience. Signal and other warrants are also, in essence, lists of factors to be considered in engineering studies.

OTHER RECOMMENDATION

In addition to the changes to the *MUTCD* noted above, a fourth related recommendation is provided:

The NCHRP should consider funding a project to incorporate these factors in an expert system similar to the U.S. Limits system being developed to provide guidance on the speed limit to be posted in speed zones.

The bases for this last recommendation are as follows:

- The practitioner focus-group participants indicated a need for guidance in the use of supplemental TCDs.
- The literature review demonstrates that no single variable is effective in defining "problem" curves, but a combination of factors can be associated with problem curves. This is a scenario where expert systems are most useful.

In the next chapters, practitioner responses to these proposals are outlined and final recommendations are presented.

CHAPTER **4**

PRACTITIONER OPINION ON PROPOSED *MUTCD* CHANGES

INTRODUCTION

The final task was to query practitioners regarding their views on the proposed changes to the *MUTCD* presented in the previous chapter. The same mailing lists used for the initial practitioner survey were used again with the addition of the members of a subcommittee of the National Committee on Uniform Traffic Control Devices (the national committee). As was the procedure for the first practitioner survey, this survey was distributed by regular mail and by e-mail.

Overall, approximately 1,100 surveys were distributed although some copies were circulated and forwarded within an agency, so a total *n* is unknown. From these, 144 usable responses were obtained. There were 66 responses from state-level agencies, 61 from the county level, and 11 from other jurisdictions. The latter are typically not included in results presented here. There were also 9 responses from members of the national committee. While the input from the national committee is important, the sample size regarding any given question is quite small (9 or fewer). For example, a shift in one respondent results in a "percentage change" of 11%—a 5-to-4 response that changes to 4-to-5 results in a change from 55.5% favoring to 44.4%. Thus, in the discussion that follows, more weight is given to the practitioners' opinions.

FINAL PRACTITIONER SURVEY RESULTS

The responses to the key questions are provided in tables below along with a discussion and any comments that were made.

First Recommendation (Changing "May" to "Should" Regarding Use of Basic Curve Signs)

The text of the first recommendation and the results regarding "adoption" are shown in Table 2. This recommendation is intended to increase uniformity in the application of the basic horizontal alignment signs by changing "may" to "should." As can be seen, support is fairly strong for adopting this change (about 2/3 to 1/3) although it is less so from the national committee members. Note, however, that the sample size for the latter is small. At the same time, there is very little support for making the condition even stronger by moving to a "shall" condition.

The support for the stronger but not strongest language is consistent with what practitioners indicated in the focus groups and earlier survey. They are interested in more consistency and stronger guidelines but within limits as they do not want "guidance" to result in mandatory changes.

It is also interesting to note that support is strong regardless of whether it is measured at the state or local (county) level although support from the state-level respondents was stronger. This may be because the signs are more likely to already be deployed on the state-level portions of the system and because the change is more a reflection of what is already being used in the field.

Respondents were also asked about significant problems associated with the adoption of the first recommendation, specifically related to cost and liability. Overall, only about one-quarter of the respondents thought that cost would be a problem—less than 20% of state-level respondents and about a third of county-level practitioners. Liability was perceived to be more problematic with ~35% of all respondents indicating that it would be an issue. Again, there was some difference between state and county-level practitioners with 29% of the former and ~38% of the latter thinking that liability would be an issue.

The comments from the respondents were also interesting. Of those responding, ~25% thought cost would be problem with about 42% making additional comments about cost. These figures increased to ~35% and ~42%, respectively, when liability was the question. Regarding comments on "cost," there was a significant range of issues mentioned. On the "positive" side, several indicated that the "may" is already effectively interpreted as "should" in their jurisdiction and, thus, there would be no cost impact. On the "negative" side, other respondents indicated that it would mean more signs and additional cost unless lower-volume roads were exempted. One respondent indicated that this was akin to "another unfunded federal mandate." However, since the *MUTCD* has a separate section for low-volume roads, these comments may have resulted from the respondent's taking the recommendation out of the intended context. In the comments, there seemed to be general agreement that cost impacts would more likely be felt at the local level rather than state level. Several respon-

TABLE 2 Support for the first recommendation

First recommendation: The first option in §2C.06 of the millennium edition of the *MUTCD* should be changed to read that horizontal alignment signs *may* be used in advance of situations where the roadway alignment changes and *should* be used when the alignment change would result in an advisory speed equal to or lower than the posted speed limit.

The Winding Road (W1-5) sign should be used where there is a series of turns or curves that requires driving caution and where curve or turn signs would be too numerous to be effective. Where any of the curves has an advisory speed that is (*x*) mph or more below that of the first curve, then a curve or turn warning sign and an advisory speed plaque *should* be used.

Overall Guideline Questions	**Answer**	**Employer**		
		county road commission (*n*=61)	state highway department (*n*=66)	national committee members (*n*=9)
Do you believe the changes from *may* to *should* in the first recommendation should be adopted?	yes	60.7*	74.2	55.6
	no	39.3	25.8	44.4
		(*n*=33)	(*n*=45)	(*n*=5)
Should the changes be even more emphatic, to *shall*? (i.e., be *shall* rather than *should*?)	yes	12.1	6.7	0
	no	87.9	93.3	100

*All entries are percentages of total respondents.

dents were concerned about how this would impact mountainous states or mountainous areas within a state—the implication being that the change would have a greater impact in those situations.

Concerns about liability, in addition to being more numerous, were also more extensive. Some respondents essentially argued that "may" and "should" are both recommendations and that liability increases only when a sign is required, but not used. Another respondent noted that "should" had already been interpreted by the state attorney general's office as a "standard" that could result in "unlimited liability" for the DOT. There were essentially two perspectives on liability issues: while many thought that the changes were appropriate and the "right" thing to do, many others commented that liability would almost assuredly be increased. It was also clear that liability varied significantly from one state to another: one respondent noted that courts were currently very protective of the jurisdictions' actions with respect to TCD placement while another, as noted earlier, interpreted the word "should" as a rule with deviation being grounds for liability. So, while the majority of respondents thought the change should be made (if it had not operationally been made already) and did not see severe problems with it, a minority believe they could suffer significantly increased liability.

Comments regarding making the language even more stringent ("may" to "shall") were more emphatically negative. Typical comments included more problems with cost, far more problems with liability, and the elimination of engineering judgment. One respondent indicated that "it would take the 'engineering' out of the traffic engineering business."

Second Recommendation (Use of Advisory Speed Plaques)

With reference to Table 3 for text and results, support for the second recommendation—which is intended to increase uniformity in the application of advisory speed plaques—is also supported by respondents at about the same levels as the first recommendation. Just under half of all respondents thought that the criterion for using speed advisories should be when the advisory speed would be ~10 mph under the speed limit. Approximately two-thirds of all respondents thought that the threshold speed should be 10 mph or less under the speed limit. Although the sample size was small, the national committee members were about twice as likely to favor a lower threshold of 5 mph. Somewhat surprisingly, there were only a few comments, and they were mixed—for example, define *X* or options should always use "may."

Third Recommendation (Engineering Study)

Although the requirement for the use of an "engineering study" is cited in the *MUTCD,* the term is not adequately

TABLE 3 Support for the second recommendation

Second recommendation: *MUTCD* §2C.42 should be changed to read as follows: **An Advisory Speed (W13-1) plaque *should* be used to indicate the advisory speed for a change in horizontal alignment when the advisory speed is *X* mph or more below the applicable speed limit.**				
Overall Guideline Questions	**Answer**	**Employer**		
		county road commission (*n*=61)	state highway department (*n*=66)	national committee members (*n*=9)
Do you believe the change from *may* to *should* in the second recommendation should be adopted?	yes	63.9*	77.3	55.6
	no	36.1	22.7	44.4
		(*n*=57)	(*n*=61)	(*n*=5)
If the second recommendation is adopted, what value of *X* should be specified?	0	1.8	3.3	0.0
	5	21.1	34.4	50.0
	10	45.6	45.9	37.5
	>10	26.3	14.8	12.5
	other	5.2	1.6	0.0

*All entries are percentages of total respondents.

defined in the specific context of horizontal curves. This is in contrast to the provisions in other sections of the *MUTCD,* which are explicit. One example is §2B.13 of the 2003 *MUTCD,* which provides factors to consider when setting speed limits. To that end, the third recommendation was intended to increase uniformity in the use of an engineering study by defining the term, at least in the context of horizontal curves. Basic results are shown in Table 4.

Both state and local practitioners supported this recommendation (just greater than 60% of the respondents) although not quite as strongly as they did the first two recommendations. A majority of the respondents from the national committee did *not* support the third recommendation, although the sample size is small. Respondents were also asked to indicate which factors should be added or eliminated, if any.

While comments *per se* were not solicited on the basic question, about 10% of the respondents made one anyway. The comments were generally negative: "too cumbersome, confusing, and nebulous"; "engineers [already] know what to consider"; "not appropriate for *MUTCD* but perhaps the TCD Handbook"; and "didn't like the list presented."

Table 5 is an overview of what the respondents thought about the adequacy of the list of study factors. Just less than half thought that the list was adequate "as is" with the rest desiring to modify the list in some way—primarily by adding factors.

Table 6 is the distribution of responses to a follow-up question regarding the factors that should be included in an engineering study to determine the appropriate TCDs for horizontal curves. As noted in Table 6, there is some disagreement in terms of what an appropriate study might include. The factors listed are interesting from several perspectives. While some such as consideration of the accident history make sense, the relative number of respondents who single out 85th-percentile speeds to be disregarded or at least discounted is somewhat alarming, especially in conjunction with the number who believe that continued emphasis should be placed on the ball-bank indicator. The latter was without any reference to interpreting the readings. Several respondents also mentioned the need for research in using the ball-bank indicator.

Fourth Recommendation (Expert System)

The fourth (or "other") recommendation was to develop an "expert system" that could be used to provide guidance on

TABLE 4 Support for the third recommendation

Third recommendation: Add a section to the *MUTCD* (similar to §2B.11 for setting speed limits in speed zones) to define the factors to be considered when conducting an engineering study to establish the appropriate TCDs when there is a change in the horizontal alignment of the highway. The language should read as follows:

Standard:

After an engineering study has been made in accordance with established traffic engineering practice or where engineering judgment determines the need for horizontal alignment signs, advisory speed plaques, and/or supplemental guidance, these TCDs *shall* be used.

Guidance:

The factors that *should* be considered in determining the system of TCDs to be displayed when there is a change in the horizontal alignment of the highway include

- **The difference in the posted speed limit and the 85th-percentile speed of free-flowing traffic;**
- **The approach sight distance to the beginning of the curve;**
- **The visibility around the curve;**
- **Unexpected geometric features within the curve, such as an intersection or a change in the curve radius; and**
- **The position of the most critical curve in a sequence of relatively closely spaced curves.**

Overall Guideline Question	**Answer**	**Employer**		national committee members (*n*=8)
		county road commission (*n*=60)	state highway department (*n*=65)	
Do you believe the third recommendation defining elements to be included in an engineering study for TCD application at horizontal curves should be adopted?	yes	61.7*	61.5	37.5
	no	38.3	38.5	62.5

*All entries are percentages of total respondents.

TABLE 5 Adequacy of study factors listed in the third recommendation

If answered "yes" regarding adoption of a recommendation for an engineering study for TCD applications at horizontal curves, is the list of factors sufficient?

Possible Responses	**Employer**		national committee members (*n*=4)
	county road commission (*n*=37)	state highway department (*n*=42)	
list in recommendation is sufficient	51.4*	42.9	25.0
add factors	32.4	38.1	50.0
eliminate factors	5.4	7.1	25.0
both add and eliminate factors	10.8	11.9	0.0

*All entries are percentages of total respondents answering "yes" or providing suggestions.

TABLE 6 Factors suggested for inclusion in horizontal curve study

Factors	Number of Respondents Concurring		
	5 factors in Guideline 3 sufficient	add to 5 factors	eliminate from 5 factors
the difference in the posted speed limit and the 85th-percentile speed of free-flowing traffic	37*	—	2
85th-percentile (part of above, but listed separately as several wanted to eliminate reference to this speed)	—	—	5
the approach sight distance to the beginning of the curve	37	—	3
the visibility around the curve	37	—	3
unexpected geometric features within the curve, such as an intersection or a change in the curve radius	37	—	1
the position of the most critical curve in a sequence of relatively closely spaced curves	37	—	2
shoulder width	—	2	—
shoulder type	—	1	—
obstruction close to pavement	—	1	—
gradient	—	2	—
ball-bank study	—	5	—
ball-bank study using 10°	—	1	—
electronic ball-bank study	—	1	—
85th-percentile speed of vehicles in curve	—	1	—
accident history	—	7	—
superelevation	—	1	—
roadway volume or average daily traffic	—	3	—
signing practices in area	—	1	—
degree of curvature	—	1	—

advisory speeds. As shown in Table 7, support for this recommendation fell below a majority for all respondents. There may be some clues for the lack of support in the (12) comments that respondents offered. First, some respondents are not aware of the capabilities of an expert system or how one works. This is clear from comments such as "do not understand what an 'expert system' would be or what it would achieve" and "ball-bank indicators are already available and have been used extensively for this purpose." Otherwise, some respondents worried that use of such a system becomes too prescriptive or that the discretion encompassed in the term "engineering judgment" is compromised. A typical comment was that "engineers should determine sign installations." Still others, who made comments such as "not as part of *MUTCD,*" did not understand its relationship to the *MUTCD.* Obviously, if such a system is developed, it will have to be accompanied by extensive "marketing" so that end users know what it is and how to use it. However, the danger exists for such systems to be used as a "black box" by unsophisticated users.

TABLE 6 (Continued)

length of curve	—	1	—
correlation to no-passing zone	—	1	—
vertical alignment	—	2	—
curve advisory speed	—	1	—
overall alignment characteristics of segment	—	1	—
surface conditions	—	2	—
road/lane width	—	2	—
guardrail	—	1	—
curve widening	—	1	—
roadside hazards	—	1	—
number of respondents not supportive of the third recommendation	48		

[*]Note that 77 respondents were in favor of Guideline 3. Of those, 37 responded that the list of factors was sufficient; the rest suggested one or more additions and/or deletions from the list.

TABLE 7 Support for the fourth recommendation

Fourth Recommendation: NCHRP should consider funding a project to incorporate these factors in an expert system similar to the U.S. Limits system being developed to provide guidance on the speed limit to be posted in speed zones.

Overall Guideline Questions	Answer	Employer		national committee members (*n*=9)
		county road commission (*n*=58)	state highway department (*n*=62)	
Do you believe the fourth recommendation regarding the development of an expert system should be pursued?	yes	44.8[*]	46.8	22.2
	no	55.2	53.2	77.8

[*]All entries are percentages of total respondents.

CHAPTER 5

REVISED RECOMMENDATIONS FOR THE *MUTCD* AND RELATED CHANGES

INTRODUCTION

In this chapter, revised recommendations are presented. The revisions are prompted by two things: (1) the responses of practitioners to the originally proposed recommendations and (2) the reconciliation of the changes to the *MUTCD* that are needed because of the differences between the millennium and 2003 editions of the *MUTCD*.

It is again noted that the proposed changes to the *MUTCD* are modest in scope. This is due to several reasons: the results from the study indicated that the basic guidelines for using curve-related TCDs are not seriously "broken" and do not need major revision; results from this project, as well as more specific results from previous work, are sometimes inconsistent; it is virtually impossible to develop guidelines that would apply to all situations and still be explicit (e.g., if a speed reduction of *X* is desired, use sign *Y* with chevrons and centerline markings); and, perhaps most importantly, most practitioners have mixed feelings regarding more explicit guidelines. Concerning the latter, there was some resistance to even listing elements of what should be considered in an engineering study, let alone providing guidelines regarding how the results of such a study would be interpreted to determine the appropriate TCDs for a given horizontal curve.

In the paragraphs that follow, the three basic recommendations are reiterated and discussed individually. In each instance, the original recommendation is presented and then discussed.

FIRST RECOMMENDATION

Initial Proposed Statement

The initial proposed statement is as follows:

> The first option in §2C.06 of the millennium edition of the *MUTCD* should be changed to read that horizontal alignment signs *may* be used in advance of situations where the roadway alignment changes, and *should* be used when the alignment change would result in an advisory speed equal to or lower than the posted speed limit.
>
> The Winding Road (WI-5) sign should be used where there is a series of turns or curves that requires driving caution and where curve or turn signs would be too numerous to be effective. Where any of the curves has an advisory speed that is (*x*) mph or more below that of the first curve then a curve or turn warning sign and an advisory speed plaque *should* be used.

This recommendation had good support from the practitioners in the follow-up survey. Exceptions to this came from practitioners who interpreted the "may to should" as a rule that must be followed with at least one state indicating that this is the way that a state attorney general had interpreted it. Given that states have the option of adopting the *MUTCD* in a wholesale manner or with exceptions, states that have significant problems with the language can make an exception. These problems notwithstanding, most respondents indicated that they were supportive of the change.

Existing Statements in the *MUTCD*

The precise wording of the first option in §2C.06 of the millennium edition (ME) and 2003 edition are shown below with additions in the 2003 version shown in *italic:*

- **ME:** The horizontal alignment Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5) signs may be used in advance of situations where the horizontal roadway alignment changes. A Large Arrow. . . .
- **2003:** The horizontal alignment Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5) signs *(see Figure 2C-1)* may be used in advance of situations where the horizontal roadway alignment changes. A *One-Direction* Large Arrow. . . .

The messages regarding use of the noted signs are basically the same in both of these versions with only clarifying comments added.

Final Proposed Statement

The proposed revised version that results from implementing the first part of the first recommendation, using the 2003 version as the base and showing changes in **bold,** is as follows:

> The horizontal alignment Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5)

signs (see Figure 2C-1) may be used in advance of situations where the horizontal roadway alignment changes, **and should be used when the alignment change would result in an advisory speed equal to or lower than the posted speed limit.** A One-Direction Large Arrow. . . .

The Winding Road (W1-5) sign should be used where there is a series of turns or curves that requires driving caution and where curve or turn signs would be too numerous to be effective. Where any of the curves has an advisory speed that is 10 mph or more below that of the first curve, then a curve or turn warning sign and an advisory speed plaque should be used.

The speed of 10 mph is inserted in the second paragraph above based on the responses to other questions in the final survey. This is also discussed below. An additional question, changing the "should" condition to "shall" had very little support because as it was apparently interpreted as potentially causing too many liability or litigation-related problems and being too prescriptive. Thus, the more emphatic language is not recommended.

SECOND RECOMMENDATION

Initial Proposed Statement

Section 2C.42 of the *MUTCD* should be changed to read:

An Advisory Speed (W13-1) plaque *should* be used to indicate the advisory speed for a change in horizontal alignment when the advisory speed is *X* mph or more below the applicable speed limit.

This recommendation also garnered good support although the objections from some respondents were basically the same as reported for the first recommendation.

Existing Statements in the *MUTCD*

In the ME, the discussion of advisory speed plaques was in §2C.42. In the 2003 edition, this discussion was in section §2C.46. The precise wordings of these two versions are given below with changes in the 2003 edition shown in *italic:*

- **ME (§2C.42):** The Advisory Speed (W13-1) plaque may be used to indicate the recommended speed for a condition.
- **2003 (§2C.46):** The Advisory Speed (W13-1) plaque *(see Figure 2C-5)* may be used to *supplement any warning sign* to indicate the recommended speed for a condition.

While one of the changes between the ME and 2003 edition is merely a clarifying comment, the other change is potentially more sweeping—referring to all instances where the plaque is used to supplement a warning sign. The earlier version also had general application but it was placed in the section with the horizontal curve signs. The wording that had been proposed here and reviewed by the practitioners referred explicitly to horizontal curves and not all instances where advisory speed plaques might be used.

Final Proposed Statement

The final proposed revision is for a new section that would be applicable only to horizontal curves and based, in part, on the 2003 wording is as follows:

An Advisory Speed (W13-1) plaque should be used to indicate the advisory speed for a change in horizontal alignment when the advisory speed is 10 mph or more below the applicable speed limit.

Another option is to replace §2C.46 in the 2003 edition with a variation on the wording given above—that is, to eliminate the words "for a change in horizontal alignment" thus making the proposed revision more generic.

As was the case for the first recommendation, the speed of 10 mph is inserted in the proposed revision above based on the responses to other questions in the final survey. The selection of "10" as the speed increment to be used is based on the final survey responses and consistent with general comments from drivers and practitioners during the focus group and earlier survey exercises.

The possibly more significant addition to the section on advisory speed plaques in 2003 was the "option" section where the advisory speed was defined:

The advisory speed may be the 85th percentile speed of free-flowing traffic, the speed corresponding to a 16-degree ball bank indicator reading, or the speed otherwise determined by an engineering study because of unusual circumstances.

It is also noted that the first two conditions are thought to be approximately equal for horizontal curves. This definition for determining appropriate advisory speeds has the potential to significantly increase existing advisory speeds and to have adverse impacts on motorist speeds through horizontal curves. The latter occurs if motorists continue to assume that they can travel at speeds that are typically as high as "+10 mph" over the posted advisory speed. If the advisory speed is "set" at a speed approximating the 85th-percentile speed, the average motorist may actually exceed what would be the normal 85th-percentile speed by 5 to 10 mph or more. That is, they might maintain what they perceive to be a safe increment over the posted advisory. While the higher advisories may be "more realistic," motorist reaction is not clear and it is likewise not clear how the revised guidelines might be phased in within and between jurisdictions. At least in the short term, the lack of consistency among speed advisory applications may be exacerbated rather than ameliorated by exercising the new option. Based on responses to the survey questions, it seems likely that practitioners would be critical of this option in terms of it costing a considerable amount of money to re-check all existing curves within a jurisdiction and in terms of increased liability, at least during a transition period. Some jurisdictions may also selectively not adopt this definition, resulting in long-term differences between jurisdictions—that is, less consistency, not more.

THIRD RECOMMENDATION

Initial Proposed Statement

Add a section to the *MUTCD* (similar to section §2B.11 for setting speed limits in speed zones) to define the factors to be considered when conducting an engineering study to establish the appropriate TCDs when there is a change in the horizontal alignment of the highway. The language should read as follows:

Standard:

After an engineering study has been made in accordance with established traffic engineering practice or where engineering judgment determines the need for horizontal alignment signs, advisory speed plaques, and/or supplemental guidance, these TCDs *shall* be used.

Guidance:

The factors that *should* be considered in determining the system of TCDs to be displayed when there is a change in the horizontal alignment of the highway include the following:

- **The difference in the posted speed limit and the 85th-percentile speed of free-flowing traffic;**
- **The approach sight distance to the beginning of the curve;**
- **The visibility around the curve;**
- **Unexpected geometric features within the curve, such as an intersection or a change in the curve radius; and**
- **The position of the most critical curve in a sequence of relatively closely spaced curves.**

In the 2003 edition, the section on speed limit signs was renumbered (from §2B.11 in the ME to §2B.13 in the 2003 edition) although the content remained basically the same. As noted, the factors to be considered in an engineering study are not explicitly defined in either the ME or 2003 edition. However, in both editions, there are factors implied in the guidance section on the use of the advisory speed plaque (ME §2C.42; 2003 edition §2C.46):

> Because of changes in conditions, such as roadway geometrics, surface characteristics, or sight distance, might affect the recommended speed, each location should be periodically evaluated and the Advisory Speed plaque changed if necessary.

In this context, defining the factors that should be considered in an engineering study doesn't really increase the level of obligation for a jurisdiction doing studies or periodic evaluations but rather provides a list of the factors to be considered. However, based on the results from the final practitioner survey, the list of factors initially proposed has been modified in the final proposed statement given below.

Final Proposed Statement

Changes from the initial statement are shown in *italic:*

Standard:

After an engineering study has been made in accordance with established traffic engineering practice or where engineering judgment determines the need for horizontal alignment signs, advisory speed plaques, and/or supplemental guidance, these TCDs shall be used.

Guidance:

The factors that should be considered in determining the system of TCDs to be displayed when there is a change in the horizontal alignment of the highway include

- **The difference in the posted speed limit and the 85th-percentile speed of free-flowing traffic (*or a 16° ball-bank reading*);**
- **The approach sight distance to the beginning of the curve;**
- **The visibility around the curve;**
- **Unexpected geometric features within the curve, such as an intersection or a change in the curve radius;**
- ***Curve and roadway geometry;***
- ***Accident history;* and**
- ***As appropriate,* the position of the most critical curve in a sequence of relatively closely spaced curves.**

It is also recommended that further definition of the factors to be included in engineering studies related to horizontal curves be included in appropriate sections of the *Traffic Control Device Handbook.*

It has been argued here that the existing definition of an "engineering study" is too general for the purposes of placing TCDs on horizontal curves; it is thus recommended that the inclusion of a more explicit list of factors to be considered be included in the definition. The current definition does little to help practicing engineers know what to look at when undertaking such a study. Indeed, there are other instances in the *MUTCD* where additional factors to be considered in other situations are explicitly listed. For example, in §2B.13 regarding speed limit signs, six factors are listed including road characteristics, pace speed, roadside development and environment, parking practices and pedestrian activity, and crash experience. Signal and other warrants are also, in essence, lists of factors to be considered in engineering studies. In addition, just under two-thirds of county road and DOT respondents to the final survey regarding the efficacy of the suggested recommendations thought this recommendation should be adopted.

It has also been recommended that these changes should be in the *MUTCD* as recommended because not all engineers and other persons determining which TCDs to use at a horizontal curve necessarily have ready and immediate access to other references such as the TCD Handbook. Nonetheless, the expanded list of factors to be included should also be included in the TCD Handbook along with a recommended procedure for collecting the various data.

FOURTH RECOMMENDATION

Initial Proposed Statement

The initial proposed statement is as follows:

> NCHRP should consider funding a project to incorporate these factors in an expert system similar to the U.S. Limits system being developed to provide guidance on the speed limit to be posted in speed zones.

The response of the practitioners to the proposed expert system was not as positive as had been expected. However, based on some respondent comments, at least some of the opposition can be attributed to the respondents not knowing enough about such a system. Moreover, it is neither intended that development of such a system nor use of it be linked directly to the *MUTCD.* A problem for which there is variation among the opinions of different professionals and for which there is no precise set of rules or algorithm that can be used to produce a "right" answer is a problem for which an expert system is expected to have application.

There is also value in linking development of an expert system to outcomes and experience gained through implementation of the third recommendation—that is, if studies for horizontal curves become more the norm, valuable information should be obtained by practitioners that ultimately assists them in making more informed decisions regarding TCD treatments and specifying speed advisories for those locations. This experience will also be helpful in developing and refining expert systems.

Final Proposed Statement

The recommendation for development of such an expert system is still advanced although the proposed statement is modified:

> NCHRP should consider funding a project to develop an expert system that would incorporate the factors listed in the third recommendation and that would be used for guidance for traffic control device deployments (including advisory speeds) for horizontal curves. Information and experience obtained as a result of the implementation of the third recommendation should also be incorporated into the system. This system should be similar in concept to the U.S. Limits system being developed to provide guidance on the speed limit to be posted in speed zones.

CONCLUDING REMARKS

Initially, the outcomes of this project had been envisioned to include a comprehensive set of guidelines for using various TCDs, including advisory speed plaques, for changes in horizontal alignment on different components of the road system. Over time, the emphasis changed to two-lane, two-way rural roads. Moreover, as the literature was reviewed and practitioners consulted, it became clear that it would be impossible with limited resources to develop comprehensive guidelines for use of different TCDs in the myriad combinations of circumstances that exist in the field, for example: Under what explicit circumstances should chevrons be used? What would the expected result be? Finally, most practitioners felt that existing guidelines and engineering judgment were adequate for determining when different devices should be used.

An interesting conundrum was presented by the responses from road users, from practitioners, and even from the NCHRP panel. While there is general agreement that improving consistency in the application of the various TCDs available to provide information and guidance to drivers encountering a change in horizontal alignment is desirable, there is significant reluctance to support language or guidelines that would result in this improved consistency. Moreover, as just noted, it is not clear that specific guidelines applicable to each of the myriad combinations of factors related to horizontal curves could ever be realized.

The *MUTCD* already contains language recognizing that there may be an exception to any standard, guidance, or option when engineering judgment determines that the situation can be made safer or can operate more efficiently if an exception is used (i.e., §1A.09 in the 2003 edition). However, the formulation of standards and guidance can be effective tools in achieving uniform application of TCDs. Since horizontal curves are so numerous and varied, some guidance can nonetheless be an effective means of reducing the inconsistent use of these devices, an inconsistency that is recognized by the engineering community.

If more explicit standards or guidance are not acceptable to many practitioners and/or if it is impossible to develop an exhaustive set of guidelines, the alternative should be to improve consistency in the exercise of engineering judgment by identifying the factors that should be considered in determining the appropriate treatment. If all engineers consider the same factors in making a decision, there is an increased probability that they will reach the same decision for a given set of conditions, thus leading to greater uniformity. Conversely, uniformity will not be achieved by allowing engineers and non-engineers to continue to select the TCDs to be used on horizontal curves without guidance or even the identification of factors that should be used in making these decisions.

Thus, the suggested changes in guidelines became more general, and even those were subject to debate. For example, while something as straightforward as changing from "may" to "should" for the use of warning signs was supported by a significant majority of practitioners, there was still substantial opposition. It is unlikely that widespread support for more explicit sign-specific guidelines would be well received. Thus, the suggested changes to the *MUTCD* were modest in some respects. However, they were all directed to providing more consistent information to the motorist. Nonetheless, from other perspectives even these changes were cause for consternation.

Finally, there was a comment regarding whether the existing arsenal of TCDs available for horizontal curves is "working." The United States has a crash rate that is among the lowest in the world, and the crash rate has decreased substantially over time. This decrease is due to good traffic engineering practice, among other things, and points to how well the system does work, not that it couldn't improve. If anything, this research project demonstrated that the TCD arsenal readily available to practitioners is actually working well. In addition, most of the practitioners that participated in the project were satisfied with the array of available TCDs and the "instructions" for using them. For the most part, and including recommendations made here, changes that are required are "tinkering at the margin." If the expectation was for radical changes to the *MUTCD,* then the outcomes here are disappointing. However, if the desire was to obtain a reasonable assessment of whether things needed to be changed, then that has been achieved—and the required changes are minimal.

The recommendations for additional research come in two areas. The first area is the need for the investigation of development of an expert system. Because of the combinations of conditions encountered in the field, an expert system would seem to represent a viable tool to be used by engineers in assessing the need for different TCDs at specific locations. Used properly, it would help engineers identify the options that "best practices" might indicate for TCDs at an explicit site.

The second area is further research into motorist reaction to wholesale changes in determining the appropriateness of advisory speeds using a ball-bank reading of 16°. Based on feedback from both motorists and practitioners, it is important to ascertain how motorists will respond to what will generally be higher advisory speed values on many curves. If motorists, and especially "unfamiliar" ones, continue to routinely exceed the new speed advisories by the same margins as they do now, dangerous situations could easily exist. Moreover, it is expected that "conversion" to a new method would lead to considerable inconsistency in the use of advisory speed plaques for several years. This would occur, if for no other reason, because of the apparent disparities in budgets of different county road commissions, resulting in some counties, states, or parts of states "converting" their advisory speed plaques immediately while others lag for several years until the advisory speed plaque and other curve-related TCDs might otherwise be updated as a part of normal maintenance.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation