Equal Severity Curve (ESC) Update

Requested by
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The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Executive Summary

Background

Caltrans uses the Equal Severity Curve to determine appropriate locations for the placement of guardrail on embankments. The ESC assists designers in determining the relative severity of encroachments on embankments versus impacts with roadside barriers. The line, or curve, shown on the ESC design chart represents combinations of embankment height and slope that result in a crash's severity being generally equal to the severity of the average impact with a roadside barrier. Overall, crash severity will be lessened if guardrail is used on embankments that plot above the line of the ESC.

Chapter 7 of Caltrans' Traffic Manual, "Traffic Safety Systems," describes the department's use of the ESC (see page 9 of the PDF at http://www.dot.ca.gov/hq/traffops/signtech/signdel/pdf/TMChapter7.pdf for a discussion of the ESC; the ESC design chart appears on page 15 of the PDF).

Given the changes in guardrail and vehicle design since the ESC was adopted, Caltrans staff proposed a research project aimed at identifying whether the ESC requires updating and, if it does, how to approach the necessary research. To support this proposed research project, we reviewed national guidance, state guidelines with regard to guardrail placement, and related research, and contacted state departments of transportation (DOTs) to determine:

- If there is research available that will facilitate updating the ESC.
- The best approach to new research that may be required in order to update the ESC.
- How other states determine appropriate locations for the placement of guardrail.
- How other states have updated the ESC.
- Best practices for determining guardrail placement.

Summary of Findings

We gathered information in five topic areas related to guardrail placement:

- National Guidance.
- Tools and Procedures.
- Survey of State Practice.
- Related Research.
- Research in Progress.

Following is a summary of findings by topic area.

National Guidance

- NCHRP's guidance in connection with guardrail implementation includes newly released guidelines developed with the use of a benefit-cost analysis procedure. One of the adjustments made in the benefit-cost analysis reported in the 2009 publication *NCHRP Report 638: Guidelines for Guardrail Implementation* assumes that 26 percent of guardrail impacts go unreported. This adjustment assumes that all unreported crashes involved property damage only.
- AASHTO's *Roadside Design Guide* (RDG) is a key document used by state transportation agencies in determining guardrail placement. The 2006 edition is in the process of being revised, with a new edition expected in early 2011.
- The 2005 publication *NCHRP Report 537: Recommended Guidelines for Curb and Curb-Barrier Installations* provides recommendations for location of guardrail with respect to curbs for various operating speeds.
- NCHRP has issued a series of reports relating to roadside barrier selection, including reports addressing vehicle compatibility with roadside hardware. Perhaps one of the most critical NCHRP documents related to barrier selection is *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*, first published in 1993. An update to *NCHRP Report 350* was recently approved by AASHTO. The new document, titled *Manual on Assessment of Safety Hardware* (MASH), is being prepared for publication and is expected to be available soon.

Tools and Procedures

- The Roadside Safety Analysis Program (RSAP) applies a benefit-cost analysis to compare a safety treatment with an existing condition or alternative safety treatments using the encroachment probability approach. A project is in process that will update the software, its manuals and user interface. An updated RSAP is expected in 2010.

Survey of State Practice

- Relevant excerpts from guidelines or specifications related to guardrail location for 12 state DOTs indicate a fairly broad application of the barrier warrant guidelines contained in the RDG.
- More than half of the state guidelines reviewed for this Preliminary Investigation include the same height and slope factors associated with embankment barrier warrants as those included in the current edition of the RDG and in the ESC design chart that appears in Caltrans' Traffic Manual.
- None of the five states we contacted have current plans to update their embankment barrier warrants. Some states indicated an interest in seeing the updated RDG, expected in early 2011, before considering changes to barrier warrants.
- Two states—Indiana and Washington—have established site-specific barrier warrants that consider factors beyond the height and slope considerations contained in the RDG.
- References to the use of the RSAP, or its precursor, ROADSIDE, appear in the design guidelines of Illinois and Indiana DOTs. Oregon is among the states electing to use an in-house program or procedure rather than employing the RSAP to determine the cost-effectiveness of guardrail placement.
- Two states we contacted—Illinois and Oregon—noted an ongoing discussion within the roadside safety community about the appropriateness of the length of barrier procedures included in the current version of the RDG.

Related Research

- Tools to aid in making guardrail placement decisions are documented in reports by Minnesota (bridge-approach guardrail), Ohio and Florida (crash reduction factors), and Virginia (development of a decision aid).

- Studies related to guardrail design include a 2007 report that assesses the compliance of Texas' current roadside safety hardware with the proposed update to *NCHRP Report 350* and a 2006 paper that addresses issues raised about the design procedures included in the RDG to determine guardrail run-out length.
- Recent research addressing vehicle-guardrail collisions considers the effects of changes in the U.S. vehicle fleet and the greatest opportunities to reduce fatalities.
- A 2007 study examines the influence of roadside infrastructure on driver behavior using a driving simulator, finding that the type and size of a safety barrier appears to be less important than its presence.

Research in Progress

- Two recently concluded research studies aimed to develop guidelines for guardrail placement. An Iowa study focused on placement of bridge rails on low-volume roads, while a Kentucky Transportation Center study took a broader approach and sought to develop a guardrail location and prioritization program.

Gaps in Findings

Two critical national projects are under way to update documents often used by state DOTs in determining guardrail placement—the RDG and the RSAP. Updates of both documents are expected in 2010 or early 2011.While the RSAP appears to play a lesser role in state DOT decision making with regard to guardrail placement, provisions of the RDG underlie the barrier warrant guidelines of many states. Some states have indicated an interest in seeing how the updated RDG addresses barrier warrants before considering any changes to state guidelines. It is not known if the 2011 edition of the RDG will include a revised design chart for embankment barrier warrants.

Next Steps

Caltrans might consider the following related to updating the ESC for California:

- As mentioned above, updated national guidance through AASHTO's *Roadside Design Guide* and the Roadside Safety Analysis Program is expected in 2010 or early 2011. Caltrans may wish to review the updated guidance before undertaking an update of its ESC.
- Most of the state guidelines we reviewed include embankment barrier warrant guidance that is similar to the ESC design chart that appears in Caltrans' Traffic Manual. It may be helpful to initiate contacts with states using similar embankment barrier warrants after the 2010/2011 release of updated national guidance to assess how other states plan to apply that guidance.
- Some states have developed barrier warrants that build upon the guidance contained in the RDG (see the **Survey of State Practice** section of this Preliminary Investigation for references to site-specific barrier warrants used by Indiana and Washington DOTs). Caltrans may wish to contact these states to discuss the process used to develop site-specific barrier warrants.
- When published, the final report of recently completed research by the Kentucky Transportation Center that proposes to develop a prioritization program for locating guardrail may be of interest to Caltrans.

Contacts

During the course of this Preliminary Investigation, we spoke with the following individuals:

National contacts

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National Guidance

Below we highlight reports issued by NCHRP and AASHTO that address guardrail installation and selection. Among these reports is a recently released NCHRP report that provides guidelines for determining when guardrail use is cost-effective. AASHTO's *Roadside Design Guide*, a document used by state transportation agencies to aid in decision making when determining guardrail placement, is referenced throughout this Preliminary Investigation. A new edition of this important publication is expected in early 2011.

Roadside Barrier Implementation Guidelines

Guidelines for Guardrail Implementation, *NCHRP Report 638*, 2009.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_638.pdf
The research documented in this report used a benefit-cost analysis procedure to develop general guidelines for guardrail implementation. The Roadside Safety Analysis Program (RSAP), an encroachment probability model software package, was used to identify specific locations where guardrails should be implemented and to produce guidelines on appropriate guardrail performance levels. (See page 8 of this Preliminary Investigation for more information about the RSAP.)

First, researchers identified the safety treatment options to be evaluated and the parameters needed to describe each alternative, including safety treatment layout, construction costs and crash severities. Next, they identified roadway, roadside and traffic characteristics of highway functional classes, along with the type and severity of hazards commonly found along each type of roadway. Functional classes included in the analysis were freeway, urban arterial, urban collector/local, rural arterial, and rural collector/local. Finally, roadway, roadside and hazard conditions were assigned to a set of detailed hazard scenarios, and the RSAP was used to analyze each hazard scenario under various roadway and traffic characteristics.

Highlights from the report include:

- Table 12 on page 19 of the PDF provides barrier crash severities and costs. The table reflects one of the adjustments made in the analysis, which assumes that 26 percent of guardrail impacts go unreported. This adjustment assumes that all unreported crashes involved property damage only.

- Table 13 on page 20 of the PDF provides preliminary guidelines for guardrail selection for various combinations of highway class, hazard offset, curvature, grade and offset to slope.

- Supplemental analysis procedures that begin on page 25 of the PDF address unusual hazards, such as deep vertical drops, bodies of water, or a severe slope along relatively flat terrain.

See the following appendices for additional detail:

Appendix A, Guardrail Use Guidelines for Benefit/Cost = 2
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_638appendixA.pdf

Appendix B, Guardrail Use Guidelines for Benefit/Cost = 3
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_638appendixB.pdf

Appendix C, Guardrail Use Guidelines for Benefit/Cost = 4
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_638appendixC.pdf

Appendix D, Guardrail Use Guidelines for Benefit/Cost = 1
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_638appendixD.pdf

Roadside Design Guide, 3rd edition, AASHTO, 2006.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01042488.html
This synthesis of current information and operating practices related to roadside safety focuses on safety treatments that can minimize the likelihood of serious injuries when a motorist leaves the roadway.
Chapter 5 of the current edition of the *Roadside Design Guide* (RDG) offers the following guidance with regard to the placement of roadside barriers:

> Barrier warrants are based on the premise that a traffic barrier should be installed only if it reduces the severity of potential crashes. It is important to note that the probability or frequency of run-off-the-road crashes is not directly related to the severity of potential crashes. The mere installation of barriers could lead to higher incident rates due to the proximity of the barriers to the traveled way.

Figure 5.1a of the RDG provides comparative risk warrants for embankments that reflect the same embankment height and side slope factors reflected in the Equal Severity Curve used by Caltrans. The RDG's Figure 5.1a is referenced throughout the **Survey of State Practice** section of this Preliminary Investigation.

The RDG notes that Figure 5.1a does not take into account the probability of an encroachment occurring or the relative cost of installing a traffic barrier as opposed to leaving the slope unshielded. Figures 5.2 and 5.3 provide examples of modified warrant charts that consider the cost-effectiveness of barrier installation given site-specific conditions.

NCHRP Project 20-7, Task 240, "Update of AASHTO Roadside Design Guide," will update the RDG based on research that has been conducted over the past four to five years. The tentative schedule for implementing the RDG update is:

- September 2009: AASHTO Technical Committee on Roadside Safety meets to review revisions.
- October 2009: Draft submitted for review and balloting by AASHTO Technical Committee on Roadside Safety.
- October/November 2009: Draft submitted for review and balloting by AASHTO Subcommittee on Design.
- Spring 2010: AASHTO Technical Committee on Roadside Safety addresses comments resulting from balloting by AASHTO Subcommittee on Design.
- September 2010: Draft submitted for review and balloting by AASHTO Standing Committee on Highways.
- Winter 2010: Ballot approval.
- Spring 2011: Publication of the RDG update.

Recommended Guidelines for Curb and Curb-Barrier Installations, *NCHRP Report 537*, 2005.
http://trb.org/publications/nchrp/nchrp_rpt_537.pdf
This report presents the findings of a research project to develop guidelines for the use of curbs and curb-guardrail combinations on high-speed roadways. Researchers' recommendations concerning the location of curbs with respect to guardrails for various operating speeds include:

- Guardrails installed behind curbs should not be located closer than 2.5 meters for any operating speed in excess of 60 km/h.
- For roadways with operating speeds of 70 km/h or less, guardrails may be used with 150-millimeter-high or shorter sloping-face curbs as long as the face of the guardrail is located at least 2.5 meters behind the curb.
- Guardrails may be used with 100-millimeter-high or shorter sloping-face curbs as long as the face of the guardrail is located at least 4 meters behind the curb.
- Above operating speeds of 85 km/h, guardrails should only be used with 100-millimeter-high or shorter sloping-faced curbs, and they should be placed with the curb flush with the face of the guardrail.
- Above operating speeds of 90 km/h, the sloping face of the curb must be 1:3 or flatter and must be 100 millimeters high or shorter.

Roadside Barrier Selection

Improving the Compatibility of Vehicles and Roadside Safety Hardware, *NCHRP Web Document 61*, February 2004.
http://gulliver.trb.org/publications/nchrp/nchrp_w61.pdf
The objectives of this study were to:

- Identify current and future vehicle characteristics that are potentially incompatible with existing roadside safety hardware.
- Assess opportunities for and barriers to improved compatibility.
- Increase vehicle and hardware manufacturers' awareness of compatibility problems.

A one-day workshop conducted in connection with the study included representatives from the automotive industry, roadside hardware manufacturers and a variety of government agencies. Workshop findings include:

- The automotive industry's current vehicle design strategies do not specifically address the magnitude and frequency of incompatibilities between roadside hardware and vehicles.
- Future roadside hardware testing criteria must take emerging vehicle platforms and design trends into account. Vehicles chosen for testing must be representative of the current vehicle population.
- Vehicle finite element models can be used by automotive manufacturers to evaluate emerging vehicle designs by simulating a series of impact conditions with prominent roadside devices.
- Improved data collection and analysis techniques are necessary to evaluate on-the-road systems and aid in identifying vehicle to roadside hardware incompatibilities.

Evaluation of Roadside Features to Accommodate Vans, Minivans, Pickup Trucks, and 4-Wheel Drive Vehicles, *NCHRP Report 471*, 2002.
http://gulliver.trb.org/publications/nchrp/nchrp_rpt_471.pdf
This study was intended to address the dearth of available research on the safety performance of light trucks at the time the study was conducted. Computer simulation, crash data and crash testing studies were used to expand the knowledge base of light truck performance for impacts with roadside features. Researchers found:

- With few exceptions, widely used roadside safety hardware, or modified versions, can be expected to perform in a satisfactory manner for most expected impacts by the light truck subclasses.
- For encroachments on an embankment, light trucks require greater lateral distances (i.e., clear zones) to recover than automobiles do.
- Light trucks are more likely to overturn when encroaching on a roadside geometric feature than automobiles are. Roadside geometric features include embankments and ditches, and driveway and median crossover slopes.

Recommended Procedures for the Safety Performance Evaluation of Highway Features, *NCHRP Report 350*, 1993.
http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_350-a.pdf; appendices to the report are found at http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_350-b.pdf
This key 1993 publication used a comprehensive literature review, an analysis of performance evaluations, and expert advice to develop recommended procedures for evaluating the safety performance of highway safety features, including guardrails, end treatments, crash cushions and breakaway devices.

NCHRP Project 22-14(2) was initiated to begin the process of updating *NCHRP Report 350*; that process is now complete. Advance copies of the electronic draft document were provided to each state's representative on AASHTO's Standing Committee on Highways for review during the ballot session to approve the updated manual. AASHTO has officially approved the updated manual, now titled *Manual on Assessment of Safety Hardware* (MASH), and the document is currently being prepared for printing.

In February 2009, Federal Highway Administration (FHWA) staff gave a presentation at the American Traffic Safety Services Association Traffic Expo Workshop entitled "MASH-08 Manual for Assessing Safety Hardware:

Update of NCHRP Report 350" (see slides 8 through 37 of the PowerPoint at http://www.atssa.com/galleries/default-file/Emerging%20Issues-HYWY_Barriers.pdf). The presentation includes information about FHWA and state DOT implementation of MASH:

FHWA Implementation Issues

- Immediately upon publication, any new devices—including modifications to NCHRP 350-compliant devices—will have to be tested using the MASH criteria.
- There will be a grace period for acceptance of NCHRP 350 devices if the test program was started before the MASH publication date. The FHWA deadline for reviewing Report 350 tests is January 1, 2011.

State DOT Implementation Issues

- It is expected that each DOT can set its own implementation dates and implementation criteria.
- States may choose to continue to use NCHRP 350-compliant hardware and permit NCHRP 350-compliant devices to be installed indefinitely.
- States may choose to establish a state-specific deadline for MASH compliance.

FHWA/State DOT Implementation Issues

- NCHRP 350 devices will not be grandfathered as meeting MASH requirements but will remain identified as NCHRP 350 devices unless retested and passed under MASH.
- Existing generic devices will not be subject to testing under MASH unless they are used by a state that has converted to the new criteria.

Tools and Procedures

The Roadside Safety Analysis Program (RSAP) is used by transportation agencies to aid in decision making when selecting locations for and types of roadside safety treatments. The software's benefit-cost analysis compares a safety treatment with the existing condition or alternative safety treatments using the encroachment probability approach.

Roadside Safety Analysis Program (RSAP)—Engineer's Manual, *NCHRP Report 492*, 2003.
http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_492.pdf
RSAP's encroachment probability approach incorporates two integrated programs: the Main Analysis Program, which contains the cost-effectiveness procedure and algorithms, and the User Interface Program, which provides a user-friendly environment for data input and review of program results.

The Engineer's Manual describes the cost-effectiveness analysis procedure and the various algorithms and data sources built into the procedure. The RSAP software and a separate User's Manual, which describes the User Interface Program, are provided on the CD included with the print edition of the 2006 edition of the RDG. Detailed information about the RSAP is included in Appendix A of the RDG.

RSAP developers acknowledge in the 2003 report that, while the RSAP is an improvement over existing procedures, it has drawbacks and limitations. RSAP users have expressed concern that the default relationships and data tables embedded in the program do not reflect current knowledge about the probability of roadside encroachments, severity of crashes, and properties of roadside features. A research project to update the RSAP is under way and expected to conclude in July 2010 (see http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2517 for additional information). The objectives of this project are to rewrite the software, update the manuals, improve the user interface, and update the embedded default data tables—for example, the severity indices—of the RSAP.

An interim report was expected in July 2009. Charles Niessner, TRB Senior Program Officer, indicated that the interim report was pending at the time of publication of this Preliminary Investigation; it is not known if the interim report will be made public.

Survey of State Practice

State guidelines, standards and specifications with regard to guardrail placement are highlighted below. Most of the state guidelines refer to the RDG in some regard. Seven of the 12 state guidelines we reviewed include the same height and slope factors associated with embankment barrier warrants as those represented in Figure 5.1a in the RDG; the same design chart appears in Caltrans' Traffic Manual as the ESC. We also contacted five states to inquire about possible changes to the states' current barrier warrants. Our informal survey included Illinois, Florida, Minnesota, Oregon and Texas.

Colorado
CDOT Design Guide, Chapter 4: Cross Section Elements, 2005
http://www.dot.state.co.us/DesignSupport/Design%20Guide%2005/DG05%20Ch%2004%20Cross%20Sec.pdf
See pages 19 to 23 of the PDF for a discussion of traffic barriers. Additional information is available in CDOT's *Safety Selection Guide* at http://www.dot.state.co.us/DesignSupport/SafetySelection%20Guide/Index.htm.

CDOT uses the **RDG's barrier warrants**; see page 21 of the PDF:

> Height and slope of the embankment are the basic factors in determining the barrier need through fill section. The designer should refer to the AASHTO *Roadside Design Guide* (6) determination of barrier needs.

Florida
Plans Preparation Manual, Volume 1, Chapter 4: Roadside Safety, January 2009
http://www.dot.state.fl.us/rddesign/PPMManual/2009/Volume1/zChap04.pdf

FDOT's **description of barrier warrants** appears on page 11 of the PDF:

> Roadside barriers are warranted when hazards exist within the clear zone, hazards cannot be cost effectively eliminated or corrected, and collisions with the hazards will be more serious than collisions with the barriers.
>
> The length of advancement and length of need necessary to properly shield the hazard must be determined on an installation by installation basis as indicated in the *Design Standards*. [See *Design Standards Booklet* below for details.]
>
> The following conditions within the clear zone are normally considered more hazardous than a roadside barrier:
>
> 1. Fill slopes steeper than 1:3.
> 2. Bridge piers, abutments and railing ends.
> 3. Non-traversable culverts, pipes and headwalls.
> 4. Non-traversable parallel or perpendicular ditches and canals.
> 5. Bodies of water other than parallel ditches and canals that the engineer determines to be hazardous.
> 6. Parallel retaining walls with protrusions or other potential snagging features.
> 7. Retaining walls at an approach angle with the edge of pavement larger than 7 degrees (1:8).
> 8. Non-breakaway sign or luminaire supports.
> 9. Trees greater than 4 inches in diameter measured 6 inches above the ground at maturity.
> 10. Utility poles.
> 11. Rigid protrusions above the ground in excess of 4 inches in height.
>
> In addition to the above hazards, there may be other situations that warrant barrier consideration, such as nearby pedestrian or bicycle facilities, schools, residences or businesses.

Design Standards Booklet, 400: Guardrail, 2010 (effective July 2010)
http://www.dot.state.fl.us/rddesign/rd/rtds/10/400.pdf

Details about **guardrail placement** appear on page 1 of the PDF:

8. In addition to use at roadside areas or other areas where the Engineer has deemed guardrail necessary, guardrail should be considered on flush shoulder sections where fill slopes are steeper than 1:3 within the clear zone and fill heights are 6' or greater. Curbed sections where fill slopes are steeper than 1:3 and fill heights are 6' or greater within 22' of the traveled way should be evaluated for installation of guardrail. Additional guidance for evaluating the need for guardrail can be found in the Plans Preparations Manual.

See page 26 for **design standards for placement of guardrail** on slopes.

Andy Keel manages design standards documentation for FDOT. Andy indicated that the guardrail specification for slopes, which was an interim standard in 2008, was expanded upon in the 2010 edition of the *Design Standards Booklet*. The text and guardrail design standards appearing in the *Design Standards Booklet* take the place of the height-and-slope design chart used by many agencies.

Illinois
Bureau of Design & Environment Manual, Chapter 38: Roadside Safety, 2002
http://www.dot.state.il.us/desenv/BDE%20Manual/BDE/pdf/chap38.pdf
See Section 38-4: Roadside Barrier Warrants, which begins on page 29 of the PDF.

RSAP is used to determine roadside barrier warrants, as described on page 30 of the PDF:

> Where practical, the designer should use an approved cost-effectiveness methodology to determine roadside barrier warrants. This will provide an objective means to analyze the myriad factors which impact roadside safety, and it will, in theory, allow the Department to allocate its resources to maximize the safety benefit to the traveling public. It will also promote uniformity of decision-making for roadside safety throughout the Department. The designer must use a cost-effectiveness methodology which has been approved by the Bureau of Design and Environment. Currently, IDOT generally uses the cost-effectiveness methodology Roadside Safety Analysis Program (RSAP) presented in Appendix A of the AASHTO *Roadside Design Guide*.

Engineering judgment is discussed on page 31 of the PDF:

> It is acceptable to use engineering judgment to determine the warrants for roadside barriers for two conditions:
>
> 1. If the decision is obvious for a specific site, the designer may forego the use of a cost-effectiveness method and use his/her judgment to install or not install a roadside barrier.
> 2. If extenuating circumstances exist, the designer may override Department policies for barrier warrants or the results of a cost-effectiveness method, either to install or not install a roadside barrier. In this case, the designer must document the reasons for his/her decision. This documentation should include crash histories for the section of roadway, traffic volumes, posted speed, and roadway geometry.

IDOT's **barrier warrants for embankments**, which reflect the same height and slope factors represented in Figure 5.1a of the RDG, appear on page 32 of the PDF.

Dave Piper, IDOT's Safety Design Engineer, indicated that IDOT has no immediate plans to update its roadside barrier warrants. Dave commented that the length of need, or guardrail run-out length, specified in the RDG has prompted discussion in connection with recent studies that indicate the guardrail lengths recommended by the RDG are conservative. (See "Guardrail Run-Out Length Design Procedures Revisited" on page 16 of this Preliminary Investigation for more information.)

Indiana
The Indiana Design Manual, Chapter 49: Roadside Safety, 2005
http://www.in.gov/dot/div/contracts/standards/dm-Archived/05%20Metric/program%20files/Part%205%20Vol.%202/Ch%2049/ch49.htm

Page 37 of the PDF includes a discussion of **guardrail warrants for embankments**:

> 49-4.04 Guardrail Warrants for Embankments
>
> Figures 49-4B, 49-4C, 49-4D, 49-4E, 49-4F, 49-4G, and 49-4G(1) present the Department's criteria for placement of traffic barriers on embankments for design speeds of 60, 70, 80, 90, 100, and 110 km/h, and multi-lane divided and undivided roadways, respectively. Although these figures were developed using 3.6-m lanes and 3.0 to 3.6-m shoulders, they can be used for any lane and shoulder widths. Guardrail for embankments is generally not warranted on facilities with design speeds of 50 km/h or less. Slope-height combinations which fall on or below the curve do not warrant shielding. To adjust for horizontal curvature and grade, use the factors shown in Figure 49-9D, Grade Traffic Adjustment Factor (Kg) and Curvature Traffic Adjustment (Factor (Kc).

Design charts presented as Figures 49-4B, 49-4C, 49-4D, 49-4E, 49-4F and 49-4G provide site-specific warrants for embankment barriers based on design speeds. Figure 49-4G(1), which presents criteria for placement of traffic barriers on multilane divided and undivided highways, reflects the same height and slope factors that appear in the RDG's Figure 5.1a. See the left navigation bar for links to these design charts.

Examples of applying barrier warrants appear on pages 37 and 38 of the PDF:

Example 49-4.1

Given: 2-lane, 2-way highway
Design Speed = 90 km/h
Design Year ADT = 3000
Tangent Section
Grade = 2%
Foreslope = 2.0:1
Fill Height = 3.0 m

Problem: Determine if guardrail is warranted for the embankment.

Solution: Using Figure 49-4E, it can be determined that guardrail is not warranted based on the embankment. However, the designer should consider the need for guardrail based on other factors (e.g., nearby hazards, accident history).

Example 49-4.2

Given: Same highway section as discussed in Example 49-4.1, but with a horizontal radius of 250 m, the embankment of concern on the outside of the curve and a fill height of 3.0 m.

Problem: Determine if guardrail is warranted for the embankment.

Solution:

1. The Design Year ADT first needs to be adjusted by horizontal curvature factor:

   Kc = 4.0 from Figure 49-9D

   Corrected Design Year ADT = 3,000 x 4.0 = 12,000

2. Using Figure 49-4E, it can be determined that guardrail is now warranted based on the embankment height. Section 49-5.0 discusses the appropriate location for installing guardrail.

Pages 96 to 99 of the PDF provide the **assumptions used to develop embankment warrant figures**. Figures 49-4B through 49-4G were developed using the computer program ROADSIDE, the precursor to the RSAP. From page 99:

> Figure 5.1, on page 5-3 of the AASHTO *Roadside Design Guide*, was also imposed on the charts as a lower boundary for when guardrail would be required.

Kentucky
KYTC Highway Design, Roadside Design: Design Elements, January 2006
http://transportation.ky.gov/design/designmanual/chapters/11Chapter%200800%20AS%20PRINTED%202006.pdf

Page 1 of the PDF notes KYTC's **use of the RDG**:

> AASHTO's *Roadside Design Guide* and engineering judgment should be used for roadside safety design.

Michigan
Michigan Road Design Manual, Volume 3, Chapter 7: Appurtenances, 2002 (interim updates October 20, 2008)
http://mdotwas1.mdot.state.mi.us/public/design/files/englishroadmanual/erdm07.pdf

The RDG is among the sources used to **determine guardrail location**; see page 15 of the PDF:

> Basic Concepts for Roadside Control
>
> The following are basic concepts and design options for the use or non-use of roadside barriers. The primary sources of information for roadside control are found in the AASHTO documents listed in Section 7.01.01, "References." [See below.]
>
> References (from page 13 of the PDF):
>
> A. *Guide for Selecting, Locating, and Designing Traffic Barriers*, AASHTO, 1977
> B. *A Guide to Standardized Highway Barrier Rail Hardware*, AASHTO-AGC-ARTBA Joint Committee, 1995
> C. *A Supplement to A Guide for Selecting, Designing and Locating Traffic Barriers,* Texas Transportation Institute and FHWA, March 1980
> D. *Roadside Design Guide,* AASHTO, 2006

Page 36 of the PDF includes a discussion of **guardrail at embankments**:

> As a general rule, a barrier should be placed to protect a vehicle from going down an embankment only if the barrier itself is the lesser of the two hazards. Such a comparison must of necessity be very subjective because of the many variables involved. (Note: The 1996 AASHTO *Roadside Design Guide* attempts to quantify this comparison by assigning severity index numbers; the higher the number the more severe a crash may be expected to be. See Table A.13.1 page A-39, and the discussion that begins on page A-17 of the Guide.) The Department generally follows the criterion that, if the fill slope is 1:3 or flatter, no barrier is required. For slopes of 1:3 or flatter, the height of fill does not increase severity.
>
> The economics of earthwork obviously dictate that all slopes cannot be 1:6, regardless of fill height. As the fill becomes higher, more consideration must be given to steepening the slopes, which in turn may call for a decision relative to placing a barrier.
>
> Slopes intended to be traversable, i.e., one flat enough that a barrier can be omitted but still perhaps 1:3, should be relatively free of discontinuities that might "trip up" a vehicle. Plans should note that half-buried boulders and large rocks should be removed as part of the final trimming operation.

Page 36 of the PDF also provides **height-slope guidelines** in chart form. The chart uses the same height and slope factors as those reflected in Figure 5.1a of the RDG.

Minnesota
Road Design Manual, Chapter 10: Traffic Control Devices and Traffic Barriers, January 2001
http://www.dot.state.mn.us/design/rdm/metric/10m.pdf

Page 12 of the PDF includes a **reference to the RDG**:

> 10.7.0 Traffic Barriers
>
> The following is a discussion of the Mn/DOT design for roadside and median barriers. For further information, the designer is referred to the AASHTO *Roadside Design Guide* published in 1996 and the users handbook

Design, Construction and Maintenance of Highway Safety Features and Appurtenances, Publication No. FHWA-HI-97-026, June 1997 or subsequent editions of these publications.

Mn/DOT's **equal severity curve** appears on page 14 of the PDF. The design chart, which uses the same height and slope factors as the RDG's Figure 5.1a, is discussed on page 13 of the PDF:

> 10-7.01.03 Adverse Geometrics
>
> Height of embankments, steepness of side slopes and sharpness and direction of curvature are all elements contributing to the consequences of accidents involving vehicles inadvertently leaving the roadway. The need for guardrail depends on the extent to which these factors contribute to accident severity. The need for shoulder guardrail along embankments must be rationalized by evaluating whether the chance of "riding out" an over-the-embankment path would be less damaging than striking the guardrail. As a guideline, the equal severity curve shown in Figure 10-7.01A should be used for embankment slopes. Combinations of embankment height and slope plotting above and to the right of the curve indicate a need for guardrail. Combinations plotting below and to the left of the curve indicate conditions are less likely to be severe without guardrail. However, other factors contributing to accident severity, such as hazards located either on or at the toe of the slope, should be taken into consideration.

Mike Elle, Mn/DOT's Design Standards Engineer, indicates that Mn/DOT is in the process of updating Chapter 10 to reflect the current provisions of the RDG and other changes. At this time, updates to embankment barrier warrants are not in process, though median barrier warrants are under review. It is not known whether Mn/DOT's embankment barrier warrants will be revised.

Missouri

Engineering Policy Guide, Category: 606.1 Guardrail, undated (last modified July 2009)
http://epg.modot.org/index.php?title=606.1_Guardrail

The **RDG's Figure 5.1** is used to warrant guardrail; see http://epg.modot.org/index.php?title=606.1_Guardrail#606.1.3.6_High_Fills of the web page:

> 606.1.3.6 High Fills
>
> Guardrail for embankments is specified on plans for roads with 400 AADT [annual average daily traffic] or more. For roads under 400 AADT, guardrail is optional, however, good design judgment requires guardrail when conditions warrant. Guardrail is not normally warranted for embankment height on projects where clear zones are utilized. However, guardrail may be warranted as shown on Figure 5.1 in the *AASHTO Roadside Design Guide*. Combinations of embankment height and slope that plot above the curve indicate a need for guardrail. Combinations plotting below the curve indicate conditions are less severe without guardrail. However, other factors contributing to accident severity such as hazards located either on or at the toe of the slope are to be taken into consideration.

Ohio

Location and Design Manual, Section 600: Roadside Design, January 2007
http://www.dot.state.oh.us/Divisions/ProdMgt/Roadway/roadwaystandards/Location%20and%20Design%20Manual/600_jan07.pdf

Page 8 of the PDF discusses **barrier warrants**:

> 601.1.2 Slopes
>
> Embankment height and steepness of foreslopes are the basic factors to be considered in determining the need for barrier slope protection. Figure 601-1 should be used to determine roadside barrier warrants for embankments.

Page 37 of the PDF presents Figure 601.1, **Barrier Warrants for Embankments**, which uses the same height and slope factors as the RDG's Figure 5.1a.

Page 8 of the PDF also addresses **low-speed** and **very low-volume roadways**:

601.1.4 Protection on Low Speed Roadways

Barrier protection on city streets and urban type facilities with design speeds less than 50 mph [80 km/h] is not normally required. However, the designer should specify protection at locations where geometric conditions, accident experience or other circumstances indicate that protection should be considered.

601.1.5 Protection on Very Low-Volume Local Roads (ADT less than or equal to 400)

The guidelines presented elsewhere in this section were developed using the AASHTO Roadside Design Guide. Guidelines contained in the AASHTO Guidelines for the Geometric Design of Very Low-Volume Local Roads (less than or equal to 400 ADT) may be used in lieu of those presented here.

On roads with very low traffic volumes, research has found that roadside clear zones provide very little benefit, and that traffic barriers are not generally cost-effective. With no criteria to identify appropriate locations where a clear zone or barrier may be warranted, the very low-volume guidelines provide great flexibility to the designer in exercising engineering judgement to decide when it is appropriate to provide improved roadsides. These guidelines apply to both new construction and existing roads.

Oregon

Highway Design Manual, Chapter 5: General Design Standards and Design Elements, 2003 (relevant portions of the chapter were revised June 1, 2005)
ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/HDM/Rev_E_2003Chp05.pdf

ODOT uses the **RDG to determine guardrail locations**, as described on page 52 of the PDF:

This section provides information to the designer concerning guardrail and concrete barrier. Information on offsets, single slope barrier, cast in place, and slip form barrier is provided. The 2002 AASHTO "Roadside Design Guide" shall be used to determine guardrail and concrete barrier locations. Exceptions to this guide are to be approved by the Roadway Engineering Manager.

Dan MacDonald, ODOT's Senior Roadside Design Engineer, indicates that ODOT has no immediate plans to update its guardrail warrants given the pending update of the RDG and *NCHRP Report 350*. ODOT is not using the RSAP, opting to use its own benefit-cost analysis program.

While ODOT has no plans to update guardrail warrants, Dan mentioned the length of need, or guardrail run-out length, specified in the RDG as being a point of contention. This issue was also noted by Illinois DOT's safety design engineer. Current guardrail run-out length design procedures included in the RDG were developed on the basis of encroachment data collected in the 1960s. More recent studies indicate that optimum guardrail lengths should be shorter than those recommended by the RDG. (See "Guardrail Run-Out Length Design Procedures Revisited" on page 16 of this Preliminary Investigation for more information.)

Texas

Roadway Design Manual, October 2006
ftp://ftp.dot.state.tx.us/pub/txdot-info/gsd/manuals/rdw.pdf

Items of interest in the TxDOT manual include:

- A brief discussion of guardrail appears on page 234 of the PDF.
- A discussion of guardrail warrants appears in Section 2 of Appendix A, which begins on page 287 of the PDF.
- Table A-1 on page 288 of the PDF provides general applications of conditions for roadside barriers.
- Page 289 of the PDF includes the guide for use of guardrail for embankment heights and slopes. This design chart reflects the same height and slope factors as those represented in the RDG's Figure 5.1a.
- Example problems appear in Section 7 of Appendix A, which begins on page 300 of the PDF.

Rory Meza, director of TxDOT's Roadway Design Section, indicates that TxDOT has incorporated portions of the RDG into TxDOT's *Roadway Design Manual*. Internal research has allowed for some state-specific modifications, though specific research is not cited. TxDOT is not currently using the RSAP but continues to consider its use. No changes to barrier warrants are planned while TxDOT waits to see what results from the updates in process for the RSAP and the RDG.

Washington
Design Manual, Chapter 1600: Roadside Safety, June 2009
http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/1600.pdf

Page 5 of the PDF provides direction on the **placement of guardrail** on side slopes:

> (a) Fill Slopes
>
> Fill slopes can present a risk to an errant vehicle with the degree of severity dependent upon the slope and height of the fill. Providing fill slopes that are 4H:1V or flatter can mitigate this condition. If flattening the slope is not feasible or cost-effective, the installation of a barrier might be appropriate. Exhibit 1600-5 represents a selection procedure used to determine whether a fill side slope constitutes a condition for which a barrier is a cost-effective mitigation. The curves are based on the severity indexes and represent the points where total costs associated with a traffic barrier are equal to the predicted collision cost associated with selected slope heights without traffic barrier. If the ADT and height of fill intersect on the "Barrier Recommended" side of the embankment slope curve, then provide a barrier if flattening the slope is not feasible or cost-effective.
>
> Do not use Exhibit 1600-5 for slope design. Design guidance for slopes is in Chapters 1130 and 1230. Also, if the exhibit indicates that barrier is not recommended at an existing slope, that result is not justification for a deviation. For example, if the ADT is 4000 and the embankment height is 10 feet, barrier might be cost-effective for a 2H:1V slope, but not for a 2.5H:1V slope. This process only addresses the potential risk of exposure to the slope. Obstacles on the slope can compound the condition. Where barrier is not cost-effective, use the recovery area formula to evaluate fixed objects on critical fill slopes less than 10 feet high.

Page 18 of the PDF includes Exhibit 1600-5, **Guidelines for Embankment Barrier**, which provides guidelines used to determine whether a barrier is a cost-effective mitigation based on embankment height, slope and average daily traffic.

Related Research

The reports and articles highlighted below address guardrail placement decision aids developed in Minnesota, Ohio, Florida and Virginia; the effects of proposed changes to *NCHRP Report 350* on existing Texas roadside hardware; the appropriateness of guardrail length of design procedures contained in the RDG; and research with regard to vehicle-guardrail collisions and the influence of roadside safety hardware on driver behavior.

Guardrail Placement Decision Aids

The Safety and Cost-Effectiveness of Bridge-Approach Guardrail for County State-Aid (CSAH) Bridges in Minnesota, Minnesota DOT Research Services Section, October 2005.
http://www.lrrb.org/PDF/200539.pdf
This research sought to determine the average daily traffic (ADT) at which the benefit-cost (B/C) ratio for the installation of approach guardrail at county-state-aid (CSAH) bridges in Minnesota becomes greater than 1.0. Findings include:

- Fatalities and A-injury crashes accounted for only 6 percent of the crashes occurring at bridges with approach guardrail compared to 28.5 percent at bridges without approach guardrail.
- The subsequent benefit-cost analysis showed that bridge-approach guardrail is cost-effective (i.e., B/C > 1) for CSAH bridges with ADT greater than or equal to 300 vehicles per day (vpd).
- Overall, approach guardrail has a benefit-cost ratio of approximately 3.5 to 5.5.

- Researchers recommended that the ADT threshold for approach guardrail on CSAH bridges be set at 400 vpd, which is consistent with previous Mn/DOT standards and AASHTO low-volume local road guidelines.
- Approach guardrail should be considered on a case-by-case basis for bridges with ADT between 150 and 400 vpd, especially those between 300 and 400 vpd.
- Placement of approach guardrail at bridges with ADT less than 150 vpd is not cost-effective in most cases.

Development of Crash Reduction Factors, Ohio DOT Office of Research and Development, September 2005.
http://www2.dot.state.oh.us/research/2005/Safety/14801-FR.pdf
Crash reduction factors (CRFs) are used to identify and prioritize the most effective safety improvement measures, and prioritize and allocate available resources for a highway safety improvement project. Traffic, geometric and crash data for both the treatment and comparison sites were collected from Ohio in developing a series of CRFs. Appendix D, which begins on page 53 of the PDF, provides analysis results for flattening a slope and removing guardrail. The estimated CRF for total crashes after flattening slopes and removing guardrail is 0.424, with a standard error of estimate of 0.575.

Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects, Florida DOT, April 2005.
http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_SF/FDOT_BD015_04_rpt.pdf
This report describes FDOT's efforts to update existing CRFs. A summary of state-developed crash reduction factors includes CRFs specific to guardrails (see page 41 of the PDF.)

"Decision Aid for Allocation of Transportation Funds to Guardrails," J. H. Lambert, J. A. Baker, K. D. Peterson, *Accident Analysis & Prevention*, Vol. 35, No. 1 (2003): 47-57.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/00937972.html
This paper addresses the allocation of resources to run-off-road and fixed objects hazards on Virginia's secondary road systems. Researchers developed a decision aid to assist in guardrail resource allocation by accounting for potential crash severities, traffic exposure, costs of treatment, and other factors. The decision aid allows for interpretation of benefits and costs, emphasizing the needs and preferences of individual localities. The paper describes archiving and comparison of protected and unprotected hazards; regional screening of hazardous corridors; and multicriteria benefit-cost analyses of guardrail sites. A case study of guardrail selection is also presented.

See the December 2001 final contract report, *Risk-Based Management of Guardrails: Site Selection and Upgrade*, at http://www.virginiadot.org/vtrc/main/online_reports/pdf/02-cr1.pdf.

Guardrail Design

Initial Assessment of Compliance of Texas Roadside Safety Hardware with Proposed Update to NCHRP Report 350, Texas Transportation Institute, September 2007.
http://tti.tamu.edu/documents/0-5526-1.pdf
Researchers familiar with the proposed update to *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features* indicate that the changes in design vehicles and impact conditions proposed in the update will place more structural demand on barrier systems and may aggravate stability problems associated with some existing barriers. In this project, researchers performed an initial assessment of the ability of Texas roadside safety hardware to comply with the update to *NCHRP Report 350*. The impact performance assessment was based on crash test results, engineering analyses, and engineering judgment. Results of the performance assessment were used to prioritize additional testing and evaluation.

"Guardrail Run-Out Length Design Procedures Revisited," Brian A. Coon, Dean L. Sicking, King K. Mak, *Transportation Research Record*, 1984 (2006): 14-20.
Abstract: http://dx.doi.org/10.3141/1984-04
Current guardrail run-out length design procedures included in the RDG were developed on the basis of encroachment data collected by Hutchinson and Kennedy in the 1960s. In the late 1970s, Cooper undertook a study of roadside encroachments across Canada that found much shorter encroachment distances than were observed by

Hutchinson and Kennedy. Wolford and Sicking used the Cooper data and a benefit-cost analysis to develop new design procedures, which indicated that optimum guardrail lengths should be significantly shorter than those recommended by the RDG. Some agencies have adopted the Wolford and Sicking recommendations, while others continue to use the RDG procedures.

This paper addresses issues raised about guardrail run-out length design procedures. Differences between the Hutchinson and Kennedy and Cooper encroachment data are reviewed and explained, and the two encroachment data sets are compared with real-world impact conditions and new crash data collected under NCHRP Project 17-22 (9). Findings include:

- The Cooper encroachment data were found to compare well with real-world crash data, whereas the Hutchinson and Kennedy encroachment data indicated a complete lack of correlation with accident databases.
- Wolford and Sicking's benefit-cost-based guidelines produced guardrail run-out lengths very similar to those generated by Cooper's data.
- Because guardrail crashes produce serious injuries and fatalities, adopting the guardrail run-out length recommendations from Wolford and Sicking can be expected to improve the overall level of safety along the nation's highways.
- Reduced guardrail length recommendations would produce significant construction cost savings.
- Although the Cooper encroachment data are currently the most appropriate source of guardrail length design guidelines, real-world crash data ultimately offer the best possible source of data for making the length of need determination. The Wolford and Sicking length recommendations should be revisited if sufficient real-world crash data become available.

Crash Injury Testing and Data

"Comparison of Roadside and Vehicle Crash Test Injury Criteria in Frontal Crash Tests," Douglas J. Gabauer, Hampton C. Gabler, *International Journal of Vehicle Safety*, Vol. 3, No. 1 (2008): 1-13.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01113291.html
Early full-scale roadside safety hardware crash tests to assess occupant injury risk potential used the flail space model, which assumed that the occupant is not airbag-restrained or belted. These assumptions are questionable given the U.S. vehicle fleet of today. This study contrasted dummy-based injury criteria and flail space model injury risk in frontal crashes in which airbag-restrained, belted, or unbelted occupants are involved. The flail space model was unable to account for occupant risk variations due to seat belt and airbag presence and performance in an analysis of 39 front crash tests in which speeds ranged between 40 and 97 km/hr.

"Opportunities for Reduction of Fatalities in Vehicle-Guardrail Collisions," Hampton C. Gabler, *Annals of Advances in Automotive Medicine*, Vol. 51 (2007): 31-48.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01080727.html
Using U.S. crash statistics from 2000 to 2005 to determine opportunities for fatality reduction in vehicle collisions with guardrails, this analysis suggests four targets for fatality reduction: motorcycle crashes, light truck and van rollover collisions, side impacts of cars into barriers, and collisions with guardrail ends. The greatest opportunity for fatality reduction is the protection of motorcyclists and side impact protection of passenger vehicle occupants in guardrail collisions. Together, motorcyclists and side impacts of passenger vehicles with guardrails account for nearly half of all vehicle-guardrail fatalities.

Influence of Driver Behavior

"Influence of Roadside Infrastructure on Driving Behavior: Driving Simulator Study," Richard van der Horst, Selma deRidder, *Transportation Research Record 2018* (2007): 36-44.
Abstract: http://dx.doi.org/10.3141/2018-06
This paper describes the results of a driving simulator study that focused on the influence of roadside infrastructure on drivers' speed choice and the lateral placement of their vehicles. Roadside features studied included trees, guardrails, barriers, panels and emergency lanes. It was found that drivers tended to move away laterally from safety barriers when they first approached them and slightly slowed down. Only the safety barrier's presence had an effect; the type and size of a safety barrier appeared to be less important. Trees were not found to affect the speed of a driver unless the driver was close to the road edge on a rural road with an 80 km/h (approximately 50 mph) speed limit, and this effect quickly faded.

Research in Progress

Two projects in Iowa and Kentucky, both scheduled for completion this summer, are addressing guardrail placement using benefit-cost analysis.

"Bridge Rails and Approach Railing for Low-Volume Roads in Iowa," Iowa State University, Institute for Transportation, expected completion date July 31, 2009.
http://rip.trb.org/browse/dproject.asp?n=22966
Co-sponsored by the Iowa Department of Transportation and the Iowa Highway Research Board, this project is intended to provide guidance to county engineers for replacement or upgrading of bridge and bridge approach guardrails by:

- Determining the criteria and guidelines used by other states for bridge and approach guardrail implementation for low- and very low-volume roads.
- Performing benefit-cost analysis using bridge and approach guardrails based on traffic levels and road classifications.
- Investigating the use of nonstandard and innovative bridge and approach guardrails for low-volume roads.

See the Institute for Transportation's project web page at http://www.intrans.iastate.edu/research/detail.cfm?projectID=751248467.

"Development of a Guardrail Location and Prioritization Program," University of Kentucky, Lexington, Kentucky Transportation Center, expected completion date June 30, 2009.
http://rip.trb.org/browse/dproject.asp?n=14957
The objectives of this research study were to identify locations in need of guardrail installations and develop a prioritization program for those locations using a benefit-cost analysis. The final report is not yet available.