TRANSPORTATION
RESEARCH
CIRCULAR

Number 396, May 1992

International Harmonization of Testing and Evaluation Procedures for Roadside Safety Features

TRANSPORTATION RESEARCH BOARD / NATIONAL RESEARCH COUNCIL

PREFACE

This circular contains the proceedings of a workshop sponsored by the Transportation Research Board (TRB) Committee A2A04 on Roadside Safety Features and the Federal Highway Administration. The workshop was held January 13-14, 1991, at the Sheraton-Washington Hotel in Washington, D.C., U.S.A. This circular includes invited presentations and findings from workshop groups which discussed many issues related to the international harmonization of test and evaluation procedures for roadside safety appurtenances.

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PART 1 INTRODUCTION

For many decades, the United States has developed roadside safety devices (furniture) to protect occupants of errant vehicles that, for whatever reason, leave the road and strike a roadside obstruction. The United States began crash testing of these devices in the 1930s. However, guidelines were first developed for the testing of guardrails in 1962. The latest set of guidelines is contained in National Cooperative Highway Research Program (NCHRP) Report 230, *Recommended Procedures for Safety Performance Evaluation of Highway Appurtenances* published in 1981. A committee of federal, state, and university experts in this field is now in the process of updating these guidelines under the sponsorship of the Transportation Research Board, NCHRP.

The European Committee for Standardization (CEN) is also preparing European standards for performance requirements and test methods for various safety road products including safety fences and barriers, road signs, traffic signals, road and street lighting (performance requirements), and other traffic control devices. This effort is to provide for a unification of standards, regulations, certification, and testing to allow for the free flow of products and services among all European Community (EC) and European Free Trade Association (EFTA) countries.

Because of the concurrent development in procedures, and to help advance international harmonization, FHWA proposed to the international highway community to hold an international conference (later changed to workshop) in the United States in 1991.

The objective of the workshop was to initiate the development of a technical framework for the harmonization of test and evaluation procedures and standards for roadside safety hardware such as guardrails, sign supports, and crash cushions. It aimed to provide a forum to explore and identify common measurement procedures that may accommodate differences in philosophies among the countries involved. The program was structured to explain the evolution of existing testing procedures and standards, identify and discuss proposed procedures and standards, and identify significant differences in conditions and philosophies.

Agenda

Figure 1 presents the agenda for the workshop. The structure of the workshop included two major components:

- **Formal Presentations.** Experts in test and evaluation procedures for roadside safety appurtenances such as guardrail, bridgerail, and crash cushions from the United States, Europe, and Australia were invited to make presentations at the workshop.

- **Workshop Groups.** Breakthrough groups were formed to provide a forum for informal discussion on international harmonization. Part 3, Table 18 presents the composition of the breakout groups. Appendix A presents a list of all the attendees at the workshop with their affiliations. The attendees worked from prepared discussion topics (Part 3) that addressed many issues related to achieving harmonization of test and evaluation procedures.

Sunday, January 13, 1991

8:30 AM	**Registration** Lobby outside of the Nathan Hale Room
9:00 AM	**Welcome** TRB Committee on Roadside Safety Features Chairman — Mr. William Hunter, University of North Carolina, Highway Safety Research Center (U.S.A.)
9:10 AM	**Purpose of the Workshop** Harry W. Taylor, Federal Highway Administration (U.S.A.)
9:20 AM	**Rationale for Existing U.S.A. National Barrier Testing Procedures** John Viner, Federal Highway Administration (U.S.A.)
9:45 AM	**Rationale for Existing U.S.A. Sign Luminaire Support Testing Procedure Rail Testing Procedure** James Hatton, Federal Highway Administration (U.S.A.)
10:00 AM	**Update of NCHRP Report 230** Hayes Ross, Texas Transportation Institute (U.S.A.)
10:30 AM	**Break**
10:45 AM	**Affect of Differences Between European and American Automobiles on Testing Procedures** Tom Turbell, VTI-Swedish Road and Traffic Research Institute (Sweden)
11:05 AM	**French Testing Procedures and Status of EC 92 Standards Setting (CEN TC 226, WG1)** Robert Quincy, INRETS-National Institute for Research on Transport Means and Their Safety (France)
11:30 AM	**Affect of Differences in Truck Size and Weights on Testing Procedures** Francesco M. La Camera and Alessandro Ranzo, University of Rome, La Sapenzia, (Italy)
12:00 PM	**Lunch—Atrium 1** Welcoming Remarks by E. Dean Carlson, Executive Director FHWA (U.S.A)
1:10 PM	**German Testing Procedures** B. Wolfgang Wink, Volkmann and Rossbach (Germany)
1:30 PM	**Affect of Differences in Australian Vehicle Size and Weight on Testing Procedures** Rod Troutbeck, Queensland University of Technology (Australia)
1:50 PM	**A Determination of Occupant Risk (THIV, Speed, and Angle)** Ivor Laker (United Kingdom)
2:10 PM	**Instructions to Breakout Groups** Harry W. Taylor, Federal Highway Administration (U.S.A.)
2:25 PM	**Break**
2:40 PM	**Begin Breakout Group Meetings**

Chairman	**Group**	**Location**
Charles McDevitt	1	Thomas Paine Room
Ken Opiela	2	Ethan Allen Room
Maurice Bronstad	3	Embassy Room
Malcolm Ray	4	Nathan Hale Room

4:45 PM	**End Breakout Groups**
Jan. 14	**Report of Breakout Groups Chairman at Regular Scheduled Meeting of A2A04(2) at 8:00 PM in the International Ballroom** (All participants are invited)

FIGURE 1 Agenda.

PART 2 PRESENTATIONS: BACKGROUND ISSUES

A. Opening Remarks

By: William W. Hunter, University of North Carolina

On behalf of the Roadside Safety Features Committee of the Transportation Research Board (TRB), a cosponsor of this workshop, it is with pleasure that I welcome you to this meeting, especially those of you who are here from far-away places. The Roadside Safety Features Committee has been an active participant in this arena through efforts of its International Research Subcommittee, presently cochaired by Hayes Ross of the Texas Transportation Institute and Thomas Turbell of the National Swedish Road and Traffic Research Institute. Thomas Turbell is also the Swedish representative to the current European meetings dealing with international harmonization.

Our committee is also well represented in the update of NCHRP Report 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*. This document could turn out to be important for international harmonization.

It is literally true that the world has shrunk when you think of the relative ease with which we travel and rapidly communicate. This shrinking also has a bearing on why it is important that we have a meeting concerned with international harmonization issues that relate to roadside safety hardware. Not only are we close in time and space, but even in regard to vehicle types and designs, and roadside hardware designs. There is much we can learn from each other and apply to our separate, and yet corporate problems.

B. Purpose of the Workshop

By: Harry W. Taylor, Federal Highway Administration

This is an invitation-only workshop, and all of you were invited because you are experts on roadside safety hardware, researchers, manufacturers, or users. Many of you are also members of standards and regulations-setting groups in your respective countries. As such, you have a strong influence on the use of roadside safety hardware.

We in the United States believe that international harmonization of test and evaluation procedures is worthwhile, and other countries do also. The FHWA has written to 54 different countries asking about their interest and support of international harmonization. Most of their replies have been supportive. We believe international harmonization will lead to increased safety by encouraging introduction of products such as crash cushions, end treatments, new traffic barriers, new sign and luminaire supports, and other types of roadside safety hardware. We also believe it will promote increased trade.

What is harmonization? Harmonization is not standardization. Standardization deals primarily with defining physical details of hardware; while on the other hand, harmonization implies identifying general performance characteristics of a device so that acceptable comparisons can be made. It also implies common measurement procedures, or acceptable surrogates.

Why are we holding this workshop now? We felt that this was an opportune time to have a workshop to continue the discussion that was begun at a workshop entitled "Strategic Highway Research Program and Traffic Safety on Two Continents," held in September 1989, and initiated by Thomas Turbell. A second reason is that the highway community in the United States was updating its test and evaluation procedures, (NCHRP Report 230); U.S. bridge rail specifications are also being updated. The final reason is that the European Community is scheduled to develop its test and evaluation procedures by the close of 1992. Some of the registrants are members of the EC organization, CEN, Technical Committee 226, Working Group 1, which is charged with developing those procedures. Registrants from other countries also are interested in updating standards. While they may not primarily be developers of safety hardware, they are users of hardware, and therefore are interested in criteria for comparing different safety features.

The immediate goal of this workshop is to progress toward a general measurement framework; to do that we are going to discuss specific test and evaluation procedures and philosophies. We are going to discuss various existing national conditions, including traffic and size and weight of vehicles. We are also going to address possible impediments to international harmonization. We believe it is possible to develop a framework to compare roadside safety devices while still meeting various national conditions, and while still providing necessary safety. The intent of international harmonization is not to develop one individual test and evaluation procedure, but to develop a method of comparison.

During this workshop, we will have presentations by various experts on test and evaluation procedures. The first set of presentations will be from the United States on the philosophy behind development of the U.S. standards and our proposed new standards. Then, we will have a set of presentations on test and evaluation procedures being addressed by the EC in developing their new standard. These presentations will include one by a representative from Australia to show how Australian sizes and weights of vehicles affect the kinds of devices they would like to use. We will then go into four breakout groups for discussion on issues that were raised by the individual presenters.

C. Rationale for Existing U.S. National Barrier Testing Procedures

By: John G. Viner, Federal Highway Administration

The large number of people who have chosen to spend their Sunday morning at this workshop attests to the importance of this topic as seen by us in the United States and those of you in the European Community, and other parts of the world. I wish you success in your efforts.

I would like to review with you a portion of the U.S. procedures for testing and evaluation of roadside hardware. Most of you are aware that there are two bases for the barrier test and evaluation criteria in the United States. One is centered on this document, the NCHRP Report 230, *Recommended Procedures for Safety Performance Evaluation of Highway Appurtenances*. I would like to talk to you about my perceptions about the background of this document—what it contains, and what people were thinking about. The other source of testing and evaluation criteria here in the United States, at the national level, is the standards and guidelines policies of the American Association of State Highway and Transportation Officials (AASHTO). Jim Hatton, who has been secretary to those efforts, will follow me and speak to that.

Purpose

Let's start off by asking the question, "What does this document say of itself? What is its purpose?" If you look at the Introduction and Commentary, it's pretty simple. The purpose is to compare the safety performance of two or more designs. We are concerned about absolute measures of safety evaluation, but the purpose is comparison—we need to keep that in mind.

Approach

The approach that was chosen in this document is that of the "practical worst case." By this, it means severe impact conditions are used, not typical ones. In other words, we cannot use the results of these tests to say "on the average, 'X' percent of injuries would be expected in the real world with this device under these conditions." It is not intended for such purposes. Roadside barriers and safety devices, etc., tend to "fall apart," i.e, show major performance differences at the practical extremes. That is where, for the purpose of crash tests, we tend to look, and that is the focus of this document.

Other occurrences in the real world were recognized but simply were felt to be too complex for this purpose and for this kind of document. For example, traffic rails are curved in the real world, but the criteria calls for testing straight rails. Typically, we're dealing with uneven roadsides, but we test on flat grades. Further, to the degree that soils are important, idealized soils are specified. These are the approaches that this document takes.

The document includes a cautioning note about the use of these procedures: "Specific questions concerning a device or specific site conditions may require crash tests or in-service evaluation conditions other than those recommended in this document. This document is not intended to supersede or override the direct addressing of such needs." In other words, in the view of the writers of this document, neither it nor any other document can cover all the conditions that can exist in the real world. A professional engineer is going to have to think about specific sites and specific problems that may be peculiar to his country, state, or specific application.

Method

This report was developed in an iterative fashion in 1981; it is deliberative in its approach; and it is a consensus document. It is iterative in the sense that the first document that preceded it was prepared by a committee of the (then) Highway Research Board in 1962 as a one-page circular, Number 482, suggesting common ways to test guardrails so that people could compare the safety performance of these devices.

Nothing has changed since that time—that is still the purpose of this document. In 1974, under a contract with Southwest Research Institute, NCHRP Report 153 was written, which practically is the predecessor of NCHRP Report 230. All of the elements of NCHRP Report 230 are in Report 153: longitudinal barriers, impact attenuators, poles, signs, and luminaires. Transportation Research Circular 191, written in 1978, was an interim update of this document written by a task force of TRB Committee A2A04. Finally, in 1981, NCHRP Report 230, which is currently operative, was written.

So NCHRP Report 230 is iterative. It builds on earlier work; it did not start from "whole cloth" to develop these complex procedures.

It is a deliberative document. Even after these preceding rounds, comments from 50 individuals or agencies were received, and analyzed. The contractor prepared written responses to all comments received, which were reviewed in turn by an appointed ad hoc committee. This committee discussed both the comments of the individual submitters and the responses of the contractors. Southwest Research Institute, was represented by Jarvis Michie and Maurice Bronstad. This process occurred through several draft cycles and resulted in a consensus document.

Test Components

The document describes vehicles, impact conditions, and performance evaluation measures for each test, and also gives test report guidelines. That is, we must describe the vehicles to be used, specific impact conditions, and test outcome; together with guidelines to assist other people in evaluating what the test agency has seen. Finally, we have to document everything, because the purpose is to compare. We must preserve the results, so people can look at them later and form their own judgments. Let us look at these test components one at a time.

Vehicles

NCHRP Report 230 suggests two things: a minimum matrix of automobile tests, and a supplementary matrix of heavy-vehicle tests. Three vehicles are in the minimum matrix of cars by weight: 4,500, 2,250, and 1,800 lb. The supplementary vehicles suggested are buses (three different types); and the heaviest vehicle is a tractor-trailer of 80,000 lb.

Let us look at the background that led to the selection of the cars. In the 1960s, at the time the first circular was written, basically, cars, for practical purposes, were one size in this country. They weighed around 4,000 lb, and 4,500 lb was on the upper side. So, the first documents were written for these cars, and this weight of vehicle has carried through to the publication of NCHRP Report 230.

In the early 1970s, when NCHRP Report 153 was written, we went through a period in this country in which a large number of foreign cars (particularly the VW Beetle) that weighed under 2,000 lb were imported. Also, the United States began to manufacture compact-sized automobiles: namely, the Pinto and the Vega. The 2,250-lb Vega became a critical vehicle in determining the overturn of shaped concrete barriers in ongoing work at that time, and this weight of car was adopted into the procedures in NCHRP Report 153 in 1974.

At the time of writing NCHRP Report 230, something new happened. We could see a definite change in the vehicle fleet in the future—we knew it was coming because, after the oil embargo of 1974, all of the manufacturers in this country had committed themselves to increasing the fuel economy of their fleets. Interestingly enough, in 1979 we had insight in how they were going to do this, because a study done by NHTSA of the plans of domestic automobile manufacturers revealed this information. This study predicted the shift in weights of domestic automobiles manufactured in 1978 and in 1986. We are reviewing the background of a document that considers a range of vehicle weights. (The reason we are dealing with a range of vehicles will be discussed later.) In 1978, the upper tail of this range, above 4,500 lb, contained only 5 percent of all cars. The lower tail of the range, below 2,250 lb, also contained about 5 percent of all cars. So, 2,250 to 4,500 lb encompassed 90 percent of the weights of the domestically produced vehicles.

However, the comparable projection for 1986 said that the 4,500-lb car would no longer be produced. The 95-percentile car in 1986 was predicted to weigh 3,300 lb. It also indicated that to get that same distribution at the lower tail end of the curve, we needed to look at cars that were as light as 1,800 lb.

This issue was a serious one for those of us deliberating NCHRP Report 230, because we knew from our work that a number of devices behaved poorly in general when vehicle weight decreased. It was thus a safety issue to consider the lower end of that curve. On the other hand, the central issue of comparison with crash tests that had gone on in the past seemed to require that the 4,500-lb vehicle be retained in this document. As the heavy (4,500-lb) cars are used for strength tests, lighter cars would produce less demanding tests at the same speed and angle. In other words, we lessen safety standards by going from a 4,500- to a 3,300-lb car. However, we would also lessen safety standards by ignoring the fact that we were expecting vehicles to be downsized.

In order to be practical about this situation, we had to have cars to test. There were cars that were sold in this country in the low-weight range. The 1976 Honda Civic was one. In fact, we had to ballast these cars to get them up to 1,800 lb. They also had other attributes that met what the American manufacturer said was going to happen to the fleet in 1986. Front-wheel drive was to come in, getting rid of the heavy transmission. So we began testing with this car, and we wrote a document around vehicles that were as light as 1,800 lb.

Impact Conditions

A practical worst-case speed of 60 mph was selected for all devices. We knew that poles can behave more poorly at low speeds, so 20 mph was set for poles. Practical angles of 0 to 25 degrees were selected. Impact points were selected depending on whether we were talking about impacting the end of the device or the side of the device. On the ends, there are even more choices. The crash can be centered or off-centered. This discussion is in the commentary of the document.

Speed, angle, and impact conditions are specified for three general types of devices: traffic rails, impact attenuators, and poles. I'm going to cover the first two only, because the last one in this document has been completely superseded by the work of AASHTO, as covered by Jim Hatton.

For traffic rails, the combination selected for this document was our old friend, the 4,500-lb, 60-mph, 25-degree test. This strength test was retained because way back in 1962 it was selected as the basis of comparison—the purpose of this document. The 2,250-lb test was included because at the time NCHRP Report 230 was written, we knew that we needed to consider the 1,800-lb vehicle, but no one had conducted any tests with it. Thus, the document had to say that desirably for performance and safety evaluation, traffic rails should meet desired performance with an 1,800-lb vehicle at 60 mph and 15 degrees. However, if that was found to be impractical, satisfactory results with this intermediate 2,250-lb vehicle would be acceptable.

Subsequent to NCHRP Report 230, practical experience told us that we did not see any differences between most hardware types when we test at 15 degrees with 1,800-lb cars at 60 mph. Thus, despite the language in the document, practical conditions led to testing 1,800-lb cars at impact angles of 20 degrees in order to see differences.

Let us look at terminals and impact attenuators. First, when we are talking about terminals, guardrails, median barriers, and impact attenuators, we must consider two different impact areas—on the end, and on the side. There are two things that we look for in tests in general: structural strength and safety performance. NCHRP Report 230 examines structural strength using the 4,500-lb car and safety performance with the light car.

What other factors were present in 1981? In 1981, when we wrote this document, most of the impact attenuator applications were at elevated exit ramps and gores. The focus of attention for impact attenuators was thus on impact conditions that were predominantly head-on. Three of the four selected impact attenuator crash tests are on the device ends. Two tests with the heavy vehicle were suggested (or ordered, if you will, depending on whether you are going to treat this document as a guideline or a specification, respectively), to look at end head-on impact performance—the structural performance of the rail. Only one end-on test is for the safety performance with the lighter vehicle.

Tests of the side impact attenuators are with the 4,500-lb vehicle test at 60 mph at 20 degrees, where typically we had tested for traffic rails at 25 degrees, as is recommended for terminals. Why? The reason is the document's art-of-the- possible approach. The document is intended to be practical. At that time, all impact attenuators except the sand-filled devices performed very marginally at 20 degrees. In other words, it was not then thought possible to obtain satisfactory performance at 25 degrees. The document states, that when and if we got to the point where such devices could meet performance criteria in tests at 25 degrees, then a 25-degree criteria should be used.

These are the main reasons for the differences in impact conditions between these devices. Things have changed since that time. We now have impact attenuators that are used in situations that are called "terminals," and vice versa. This has been the subject of discussion, and my perception of thinking at the time this document was written.

Performance Evaluation

I have already mentioned that the evaluation criteria were recommended in Report 230 in three parts: structural strength, occupant risk, and vehicle trajectories. Structural strength says, for example, that a traffic rail intended to keep vehicles on the roadway side of a facility, should do that—the test vehicle should not penetrate through or go over the rail. That is the philosophy of how a device is designed to perform. Thus, traffic rails should redirect. Impact attenuators should result in controlled stopping. Breakaway signs or yielding signs need to behave in that manner, and no fragments should be left beneath the devices. These are qualitative judgments.

For occupant risk, a key assumption was made, that "design" occupants are unbelted. This is not true in today's world, but that was the assumption that was made. A flail space model was developed as a simple two-dimensional model to estimate the impact change of velocity at the time when the occupant first contacts the interior of a vehicle. A value was developed from the ratio of a limit velocity divided by a factor of safety. This model for the first occupant interior contact has been the primary measure, in my view, for evaluating devices under NCHRP Report 230.

Concern as to what happens after this theoretical first contact between the occupant and the vehicle was discussed in some detail during NCHRP Report 230 deliberations. Thus, measures of the ridedown acceleration were proposed. This measure is expressed as a limit acceleration that occurs after the time that the occupant first contacts, divided by a factor of safety. This measure derived from the NHTSA Standard 208 Occupant Protection proposals at that time, which were direct measures of occupants.

The NCHRP Report 230 measurements are made on vehicles and used to infer occupant response. It was recognized that this is a poor-quality link from which to measure safety, but at the time, given the limits proposed, the results were not likely to govern or control in many cases. So the ridedown model is in the document, and has not proven to be much of a problem.

The longitudinal limit velocity of 40 ft/sec of the flail space model for vehicle-occupant contact was derived from the work of Patrick in the late 1950s. In impacts of cadavers against rigid surfaces, the velocity represented the threshold for skull fracture. For the lateral limit velocity change, researchers from Southwest Research Institute brought to our attention French research that, at the time, suggested that a limit lateral velocity of 30 ft/sec might be the threshold of serious injury—the so-called AIS-3 injuries.

The factors of safety are not intended to have a consistent likelihood of injury between different device types out in the real world, between impact attenuators and breakaway signs, but again are intended to be art-of-the-possible numbers. In other words, were there several devices, or concepts, judged to be practical and reasonable that could meet the criteria? So factors of safety differ for different types of devices.

Consider for example, longitudinal pole impacts. For sign and luminaire supports, a factor of safety of 2.67 is recommended. This produces, when you divide 40 ft/sec by 2.67, a recommended change in velocity when the occupant hits the interior compartment of 15 ft/sec. By contrast, it was thought that when and if we ever got to the point where we could develop breakaway utility poles, that owing to their larger mass, these criteria would be very difficult to meet. Thus for utility poles a factor of safety of 1.33, which produces a change in speed of 30 ft/sec, is specified. Again, art-of-the-possible philosophy.

For vehicle trajectory, again some qualitative and some quantitative judgments were made. Overturns are not allowed because we know overturns tend to be very harmful. For redirection impacts, the thought was (after much debate) to compare the results of previous crash tests that were judged otherwise successful, to select the limit of the change in speed during barrier contact in an attempt to limit the impact forces during collision with the traffic rail. The suggestion was to keep it less than 15 mph, and owing to the concern of rebound back into the traffic or across the roadway, to limit the exit angle to less than 60 percent of the impact angle. Those were the vehicle trajectory requirements.

Test Report

Finally, test information has to be documented in a way that people at a later time can make comparisons. If you look in the back of NCHRP Report 230, there is a very, very important page, the report page. It calls for a strip of photographs and measurements of the initial test conditions, and certain test outcomes. This enables people to make a decision quickly and at a glance as to whether or not they want to know more about that device or consider it for their application.

Summary

I have tried to lead you through my impressions of key background relating to the development of the NCHRP 230 crash testing procedures. It is important to realize that this document is dated 1981. Its purpose is to compare safety devices; its philosophy is practical worst-case testing conditions; and its approach is to use the art-of-the-possible.

D. Rationale for Existing U.S. Sign and Luminaire Support Testing Procedures and Suggested Bridge Rail Testing Procedures

By: James H. Hatton, Jr., Federal Highway Administration

Appendix B contains the breakaway requirements from the 1985 *AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals*. Because the 1985 requirements are approximately the same as those in the 1975 specifications, we've had about 15 years of experience with these requirements. The changes that were made between the 1975 and 1985 requirements were as follows:

1. The design vehicle weight was reduced from 2,250 lb (1020 kg) to 1,800 lb (816 kg).
2. The description of the principal breakaway criterion was changed from being specified in terms of a change of momentum to being specified in terms of a change in velocity. The old criterion for breakaway was a momentum change of 1,100 lb-sec (4893 N-sec), which implied a change in velocity of 15.7 ft/sec (4.8 m/sec). The new criterion for breakaway is 15 ft/sec (4.6 m/sec). (FHWA accepts 16 ft/sec (4.9 m/sec).)
3. A limit was set on the height of the substantial remains following breakaway (the stub height) of 4 in. (0.1 m).
4. The test requirements and acceptance criteria vary only slightly from requirements in NCHRP Report 230, e.g., center-on crash testing is accepted where NCHRP Report 230 recommends off-center testing.

Some philosophy behind both editions of the AASHTO specification included the following points:

1. Design for the low end of the vehicle fleet weight range, but not the absolute bottom.
2. Expect breakaway hardware to break away when impacted at 20 mph (32 km/hr) by those vehicles in the fleet that weigh less than the design vehicle, motorcycles excluded.
3. Set the acceptance level at a point where injuries are expected to start to occur.
4. Expect practice to prevent life-threatening injuries for all impacts except those, primarily side-on impacts, in which an occupant might strike the breakaway structure. The objective is to account for fragile and out-of-position occupants.
5. Believe resulting impulse associated with a design vehicle striking a breakaway structure off-center will not cause the vehicle to yaw enough that it is likely to roll over.
6. Design to the state of the practicable.
7. There remains some hope that required breakaway structures can be retrofitted for side-on impact safety.

Appendix C contains the basic sections of the 1989 AASHTO Guide Specifications for Bridge Railings. The principal features of the specifications are as follows:

1. Designs are to be confirmed through crash testing.
2. Three levels of railing performance are recognized.
3. Railing performance levels are defined by crash tests.
4. Performance level selection procedures are included.

The philosophy behind the guide specifications includes the following points:

1. All bridge sites do not require the same level of railing capability.
2. Railing performance capability (performance level), and thus cost, should match the site requirements.
3. Crash testing is likely to reveal flaws in railing designs that might otherwise go undetected before placing a railing in service.
4. A performance level continuum or many closely spaced performance levels would be unmanageable.
5. Performance levels and selection procedures should be based partially on a rational analysis, but influenced extensively by AASHTO Subcommittee on Bridges and Structures perception of adequate design, with considerable weight given to current practice.
6. Test vehicles and test conditions should be selected to ensure good railing performance over a wide range of service impacts. (The 18,000-lb (8165 kg) single-unit truck is a surrogate for many vehicles but was not selected because it was a particularly bad actor in our accident experience.)
7. Test requirements and acceptance criteria vary considerably from requirements in NCHRP Report 230. Nevertheless, there is strong reliance on NCHRP Report 230 for guidance in conducting and reporting crash tests.

E. Update of NCHRP Report 230

By: Hayes Ross, Texas Transportation Institute

I appreciate the opportunity to tell you a little bit about the effort we are undertaking to update the NCHRP Report 230. I want to thank John Viner for doing a great job in giving you the background for NCHRP Report 230 because that leads directly to the things I am going to talk about. When Harry said that I am going to talk about the future contents of the update, I'm not sure if that is the right word because what I am going to talk about are proposals that have been put forward, but by and large are certainly not firm at this stage. We are still going through the process of trying to reach a consensus on all of these real tough issues that we are trying to address in the update. So, I want you to keep in mind that what I am going to show you are primarily proposed changes that have been put forward. There is some basis for them. We have had a meeting of the panel that is advising the researchers on the project. We had a meeting 6 months ago to review some of these issues and try to reach a consensus on how we are to address them.

Project Scheduling

NCHRP Project 22-7 (update of *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*) is being conducted by the Texas Transportation Institute (TTI) with Dynatech Engineering as a subcontractor. Jarvis Michie, who had worked on the development of NCHRP Report 230 and its predecessor, will be working with us on the project.

The scheduled duration of the project is from June 1, 1989, to November 30, 1991, though it appears that it might take a little longer. The objective of this study is to update the recommended procedures for the safety performance evaluation of both temporary and permanent highway appurtenances in such a manner as to reflect advances in technology and to accommodate current and anticipated roadway and vehicle characteristics.

The project consists of six tasks to be performed in two phases. Phase I is to develop a comprehensive list of topics to be examined, evaluate the relative importance of each topic, and prepare an interim report; Phase II consists of writing various drafts and producing the final report.

The first phase is complete; we have developed the comprehensive list of topics to be examined. We have evaluated those, and we have prepared an interim report that was presented to the NCHRP panel in June, 1990. We are now into Phase II and we are almost finished with Task 4, which is the preparation of the first and second drafts of the update. We are scheduled to present the first draft to the panel within the next couple of months. After that, we will make whatever revisions are necessary and then prepare a second draft shortly thereafter; this second draft will be submitted to the highway safety community in general. We anticipate sending it out to upwards of 100 people for comments and review. I don't look forward to that because I am sure each person will have his or her own ideas as to how this update should be formulated; but nonetheless, we do want to make a sincere effort to try to develop a document that truly represents the consensus of the highway safety community.

In an effort to involve the international community, Mr. Thomas Turbell has been included as a panel member. We in the United States are making a conscious effort to try to harmonize our efforts with those of other countries.

Major Changes

There are some major changes that are proposed for the update. The first involves test vehicles. Next, as planned, the update will incorporate three features that were not covered in NCHRP Report 230. The contents and number of test matrices have changed drastically. Finally, the other change that we are considering involves the evaluation criteria. You have heard about NCHRP Report 230 from John's talk; I will try to tell you what we are proposing for the update.

Longitudinal Barriers

We will, of course, maintain guidelines for testing longitudinal barriers. I will talk later about test matrices and test conditions that are categorized in terms of severity levels. For longitudinal barriers, it is being proposed that we have six severity levels and six test matrices. Within the longitudinal barrier area, it is planned that the update will be applicable to all types of longitudinal barriers, including bridge railings, median barriers, and roadside barriers. Now, as you will see, there are some differences between what has been proposed for the update and what Jim Hatton assumed with regard to bridge railings. So, even within this country we have problems harmonizing. By no means are we firm with all of these recommendations; we are still in the review and evaluation process. As a matter of fact, we are having a meeting in the morning to explore common ground between what has been proposed for bridge railings and what we are proposing for barriers in general.

Within the longitudinal barrier area, guidelines will be given for testing the "length of need" or the "standard portion of the barrier." Then, the other part of the longitudinal barrier problem deals with where you connect it to another barrier with a different stiffness, going through a transition region. There are other parts of longitudinal barriers, but they are addressed in other areas.

Terminals and Crash Cushions

Of course, you have to terminate a longitudinal barrier, and the treatment of those terminals is of the utmost importance. Up to now, we have tested terminals differently from any other feature; one of the recommendations for the update was that we try to incorporate guidelines on evaluating terminals with crash cushions.

Within the terminal and crash cushion area, there are two subdivisions—although this is not without controversy either. We have terminals and crash cushions with what we call "redirective" capability. That is, if you hit them anywhere along the side, they are expected to redirect the vehicle; we also have inertial crash cushions that have no redirectional capability. We cannot expect those to perform as redirective devices. The big question is, "Are we ready to basically prohibit the use of anything other than redirective crash cushion devices?" This is the big question we are trying to address within the NCHRP Report 230 update.

Support Structures

The next area is support structures, traffic control devices, and breakaway utility poles. These have all been lumped together. I guess I didn't mention that under terminals and crash cushions, we are basically talking about three severity levels, which I will talk more about. Support structures have two severity levels (levels 2 and 3)—again, I will define what these are.

Truck-Mounted Attenuators

Truck-mounted attenuators (TMAs) are something new, at least to the detail that is planned for the update. TMAs are crash cushion devices placed behind trucks. They are used as shadow vehicles in moving operations primarily on the construction or maintenance activity. Two severity levels are proposed for TMAs.

Geometrical Features

Finally, the update will address, in a general fashion, testing of geometrical features such as driveway slopes or safety treatment of drainage structures, such as ditches or embankments.

Test Vehicles

Within the test matrices we have proposed, we identify two basic test matrices; the lower would involve test speeds of 45 mph, and the upper would involve test speeds of 60 mph. Two basic types of test vehicles are proposed, as shown in Table 1. The first one is a small automobile, with a minimal weight of 1,900 lb (about 863 kg).

TABLE 1 PROPOSED TEST VEHICLES

BASIC

V1—1,900 ± 100 lb (863 kg) car
V1—4,500 ± 200 lb (2,043 kg) pickup truck

SUPPLEMENTARY

SV1—1,600 ± 100 lb (726 kg)
SV2—18,000 lb (8,172 kg) single-unit truck (weight tolerances TBD)
SV3—80,000 lb (36,320 kg) tractor-van trailer (weight tolerances TBD)
SV4—80,000 lb (36,320 kg) tractor-tank trailer (weight tolerances TBD)

There is some debate over whether to maintain the current 1,800-lb vehicle or go to a 1,900-lb vehicle. The rationale for choosing the 1,900-lb vehicle is that it will be much easier to purchase. There are few sub-1,800-lb cars. The breakdown, as far as the percentage goes for automobiles weighing less than 2,000 lb, is about 3 percent of the automobile population. Cars weighing less than 1,800 lb represent less than 1½ percent of the automobile population. So, it has been proposed that the 1,800- to 2,000-lb range be considered for the small-car test vehicle.

Cars that are within the 1,800- to 2,000-lb category include the Yugo, the Toyota Tercel, the Honda CRX, and the Dodge Colt. The trend in small-car design in the United States is to start out small and then grow with succeeding model years. This trend was followed by the Honda Civic, widely used in small-car tests, which now weighs in excess of 2,000 lb. The Honda CRX is growing; it weighs almost 2,000 lb now. So, this is a problem in standardization.

As far as cars weighing less than 1,800 lb, currently in the United States, there is the GEO Metro (it has been out 2 years), Ford Festiva (which is the most popular of all the sub-1,800-lb cars here in the United States), and the Suzuki Swift (which was the Chevrolet Sprint until Chevrolet quit making it and Suzuki started selling it). I think that Suzuki was making the Sprint all along, but when Chevrolet started making the GEO and got out of the Sprint business, Suzuki picked it up.

A major change is proposed for the SV2 vehicle—not in weight, but in type. Sales data in the United States for the last 10 years shows an increasing use of what are termed "light-duty" vehicles. These are pickup trucks, vans, recreational vehicles, and vehicles like Blazers and Broncos. As a matter of fact, the statistics indicate that these vehicles represent between 15 and 20 percent of the population of the car and light-duty truck category. It was felt that this amount was significant, and that we could no longer overlook these vehicles. Furthermore, the 4,500-lb automobile sedan no longer exists in this country, except for the luxury car, which the testing agencies cannot afford to buy.

So, these two factors suggest selecting something other than a 4,500-lb test car. What has been proposed is a pickup truck. For most of the pickup trucks that are in use, this weight would be representative of a 3/4-ton pickup truck. However, there may be a trend for the 1/2-ton pickups to become larger.

Now, as we will see with the test matrices, we have two basic tests and then four supplementary tests, and the supplementary vehicles are as indicated. As far as very small automobiles, it is being proposed that something be done like NCHRP Report 230 did; that is, include a very small vehicle in the recommendation, but tests with it would be optional. That's the SV1 vehicle, and it would weigh 1,600 ± 100 lb. The SV2, SV3, and SV4 vehicles are all trucks, heavy-duty, and high-performance vehicles.

The SV2 is an 18-kip single-unit truck that we have gained some experience with through bridge rail testing. The SV3 is an 80,000-lb tractor-trailer, a fully loaded van trailer that we have also tested and learned its properties. Finally, if you want the ultimate in barrier design, you would use an 80,000-lb tractor tank-trailer truck.

Crash Severity Levels

As shown in Table 2, six severity levels have been proposed for the update. The first one would be a low-speed, low-service-level requirement. It would have potential application in some urban areas, low-speed streets, and perhaps some very low-speed work zone operations. The test speeds would be 20 and 30 mph.

TABLE 2 PROPOSED SEVERITY LEVELS

SL-1	Supplementary or optional Severity level for special minimal service requirements
SL-2 SL-3	Basic severity levels for most service requirements
SL-4 SL-5 SL-6	Supplementary or optional severity levels for special higher-service requirements

Levels SL-2 and SL-3 are referred to as the basic severity levels, and would be applicable for most service requirements at test speed of 45 and 60 mph, respectively. The final three levels are again supplementary; they lead to the high-service-level requirements.

Most features to be addressed in the update will be tested at one, two, or three severity levels. The only feature that all six severity levels would apply to is the longitudinal barrier.

Matrix Format

In NCHRP Report 230, all features were combined into one test matrix table. It is being proposed here that we separate these out and that we have test matrices that are feature dependent. Table 3 presents the proposed test matrices for longitudinal barriers. In the left column are the six severity levels; in the next column is the barrier section; the next would be the test designation, and then the impact point and evaluation criteria.

TABLE 3 TEST MATRIX FOR LONGITUDINAL BARRIERS

Severity Level	Barrier Section	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[e] (See Table V-1)
			Vehicle	Nominal Speed (km/hr)	Nominal Angle, θ (deg)		
1 (Supplementary)	Length of Need	1-10	V1	48	20	(b)	A,D,F,H,I,(J),K,M
		S1-10[a]	SV1	48	20	(b)	A,D,F,H,I,(J),K,M
		1-11	V2	48	25	(b)	A,D,F,K,L,M
	Transition	1-20	V1	48	20	(b)	A,D,F,H,I,(J),K,M
		S1-20[a]	SV1	48	20	(b)	A,D,F,H,I,(J),K,M
		1-21	V2	48	25	(b)	A,D,F,K,L,M
2 (Basic - Lower Speed)	Length of Need	2-10	V1	72	20	(b)	A,D,F,H,I,(J),K,M
		S2-10[a]	SV1	72	20	(b)	A,D,F,H,I,(J),K,M
		2-11	V2	72	25	(b)	A,D,F,K,L,M
	Transition	2-20	V1	72	20	(b)	A,D,F,H,I,(J),K,M
		S2-20[a]	SV1	72	20	(b)	A,D,F,H,I,(J),K,M
		2-21	V2	72	25	(b)	A,D,F,K,L,M
3 (Basic - High Speed	Length of Need	3-10	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S3-10[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		3-11	V2	97	25	(b)	A,D,F,K,L,M
	Transition	3-20	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S3-20[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		3-21	V2	97	25	(b)	A,D,F,K,L,M
4 (Supplementary)	Length of Need	4-10	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S4-10[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		4-11[d]	V2	97	25	(b)	A,D,F,K,L,M
		4-12	SV2	81	15	(b)	A,D,G,K,M
	Transition	4-20	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S4-20[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		4-21[d]	V2	97	25	(b)	A,D,F,K,L,M
		4-22	SV2	81	15	(b)	A,D,G,K,M
5 (Supplementary)	Length of Need	5-10	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S5-10[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		5-11[d]	V2	97	15	(b)	A,D,F,K,L,M
		5-12	SV3	81	15	(b)	A,D,G,K,M
	Transition	5-20	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S5-20[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		5-21[d]	V2	97	15	(b)	A,D,F,K,L,M
		5-22	SV3	81	15	(b)	A,D,G,K,M
6 (Supplementary)	Length of Need	6-10	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S6-10[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		6-11[d]	V2	97	25	(b)	A,D,F,K,L,M
		6-12	SV4	81	15	(b)	A,D,G,K,M
	Transition	6-20	V1	97	20	(b)	A,D,F,H,I,(J),K,M
		S6-20[a]	SV1	97	20	(b)	A,D,F,H,I,(J),K,M
		6-21[d]	V2	97	25	(b)	A,D,F,K,L,M
		6-22	SV4	81	15	(b)	A,D,G,K,M

[a] Test is optional. See Section III-A.

[b] See Figure III-1 for impact point.

[c] See Section III-C for tolerences on impact conditions.

[d] Test may be optional. See Section III-B-1.

[e] Criteria in parenthesis are optional.

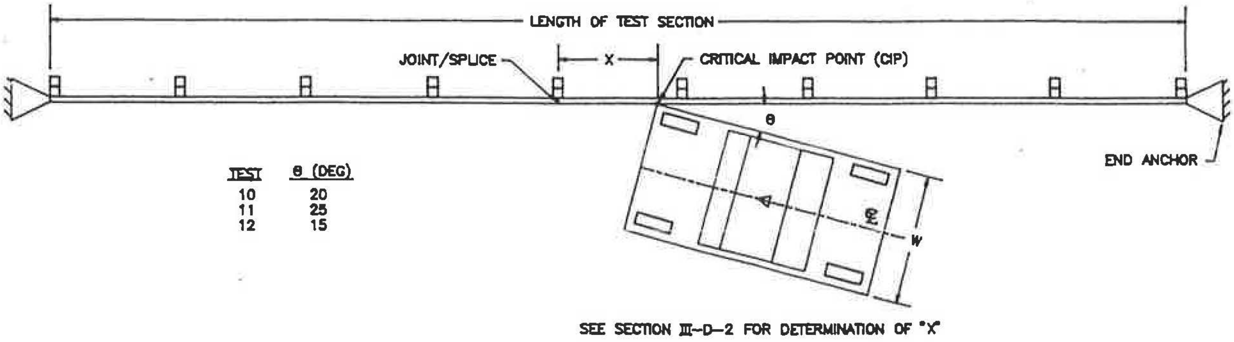
Impact Point

For the impact point, a change is being incorporated. In NCHRP Report 230, recommendations on impact point are specific. For a longitudinal barrier, an impact point midway between posts on the length of need, and at a specific distance upstream from the rigid barrier in a transition are specified. We have, during the course of testing at TTI, shown in most cases that this is certainly not the critical impact point in terms of the potential for wheel snag or for vehicular pocketing. That's one of the basic reasons for running these tests, to try to determine what the weaknesses are in these systems. We are making an effort to provide guidelines on where you should impact a longitudinal barrier as a function of its stiffness, geometric properties, and the type of test vehicle. So, we will refer to Figure 2 for the impact location, which in turn, refers to another section of the update on how you actually determine where the impact point should be.

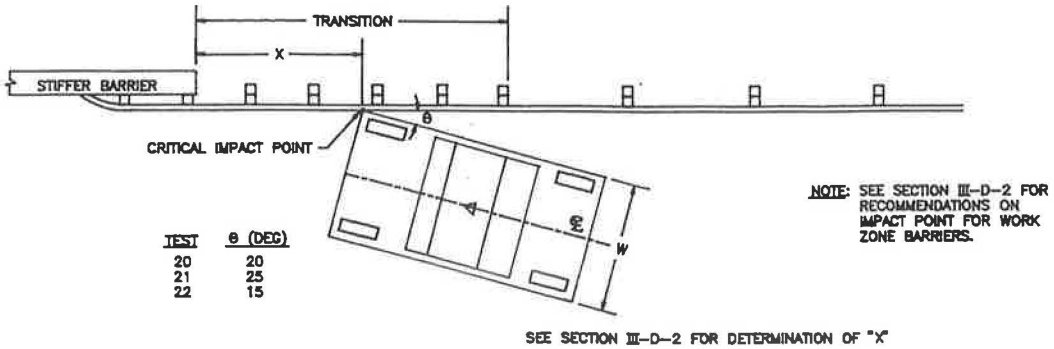
Longitudinal Barrier Strength Tests

I think the interest of the international community here today is primarily in longitudinal barriers, and I will emphasize that in my presentation. If I have time, I'll talk briefly about the proposals for crash cushions and other devices, but I did want to spend a little bit more time on the implications our proposal has on longitudinal barriers.

The proposed strength test for longitudinal barriers for these six severity levels is shown in Table 4. The vehicle for the first three levels would be the 4,500-lb pickup truck. For the last three levels, it would be in increasing order for the larger trucks. The SV2 is the 18-kip truck; the SV3 is the 80,000-lb tractor-trailer van; and the SV4 is the tanker. The first three SLs would be at 25-degree approaches at speeds from 30 to 60 mph. Remember, levels 2 and 3 are what we are recommending as the basic test matrices for all features, longitudinal barriers included. Level 3 corresponds approximately to what we have now in NCHRP Report 230 for the minimum test matrix.



TEST 10,11, AND 12



TEST 20,21, AND 22

FIGURE 2 Geometry for longitudinal barrier crash tests 10-12 and 20-22.

TABLE 4 PROPOSED STRENGTH TESTS FOR LONGITUDINAL BARRIERS

		Impact Conditions		
Severity Level	Vehicle	Nominal Speed (mph)	Nominal Speed (km/hr)	Nominal Angle (deg)
1	V2	30	48	25
2	V2	45	72	25
3	V2	60	97	25
4	SV2	50	81	15
5	SV3	50	81	15
6	SV4	50	81	15

Table 5 presents approximate barrier heights required for each of the six severity levels. These numbers were obtained from Dr. Hirsch. They are primarily for rigid barriers, bridge-rail-type, and do not take flexibility into account. If you look at SL1, which was 30 mph, 25 degrees, with the pickup truck, a barrier about 20 in. (51 cm) high is indicated. For SL6, a barrier 90 in. (229 cm) tall is indicated. So, you can see up through SL5 there is a fairly uniform differential between the requirements. A big jump occurs from SL5 to SL6 because of the unstable nature of the tanker truck.

TABLE 5 APPROXIMATE BARRIER HEIGHTS NEEDED FOR LONGITUDINAL BARRIERS FOR PROPOSED SEVERITY LEVELS (HIRSCH)

Severity Level	Minimum Height (in.)	Minimum Height (cm)
1	20	51
2	24	61
3	27	69
4	32	81
5	42	107
6	90	229

Test Matrix for Terminals and Crash Cushions

Table 6 presents one of the three tables for the crash cushion test matrices. Again, we are proposing Severity Levels 1, 2, and 3 for these devices. Table 6 deals with 45-mph impacts. Terminals and redirective crash cushions are broken out from nonredirective crash cushions, as shown at the bottom of Table 6. Furthermore, in relation to NCHRP Report 230 we are adding additional tests.

Figure 3 shows some of the impact conditions proposed for terminals and redirective crash cushions. Test 30 would an off-center small car test, the off-set being one-fourth of the width of the vehicle. The second test would be the pickup truck, head-on. The next two tests, which are new tests, are angled hits on the end of the treatment with both the small car and the pickup.

Within the terminal category, we also have further subcategories. Some of our devices are designed so that if you hit them on or near the end, the vehicle is allowed to penetrate and go behind the longitudinal barrier. Other end treatments do not do this; they have redirective capabilities right up to the end of the terminal. So, this creates complications as far as additional testing we have to consider. For a gating device there are two tests that would be performed, as shown in Figure 4, and they are a little different from what was in NCHRP Report 230. The first test is at the beginning of what we call the "length of need," where direction is expected and another test with the small car midway between that point and the end of the terminal.

The tests shown in the lower part of Figure 4 are for nongating devices. I know a lot of you are thinking that you could never afford to develop terminals or crash cushions anymore if you have to run all these tests. I am sympathetic to that notion. I am just not sure how we are going to resolve it. For now, we are proposing two tests at the beginning of the length of need for nongating terminals with both the small and large car, and another test at the critical impact point along the cushion.

If the terminal device or crash cushion will be used in a median area where it can be impacted from both sides, it is proposed that a "reverse-hit" test be conducted with the pickup as indicated at the top of Figure 5. If it is used as a roadside device, but again could be hit from the reversed direction—not the reverse side—then the lower test would be conducted.

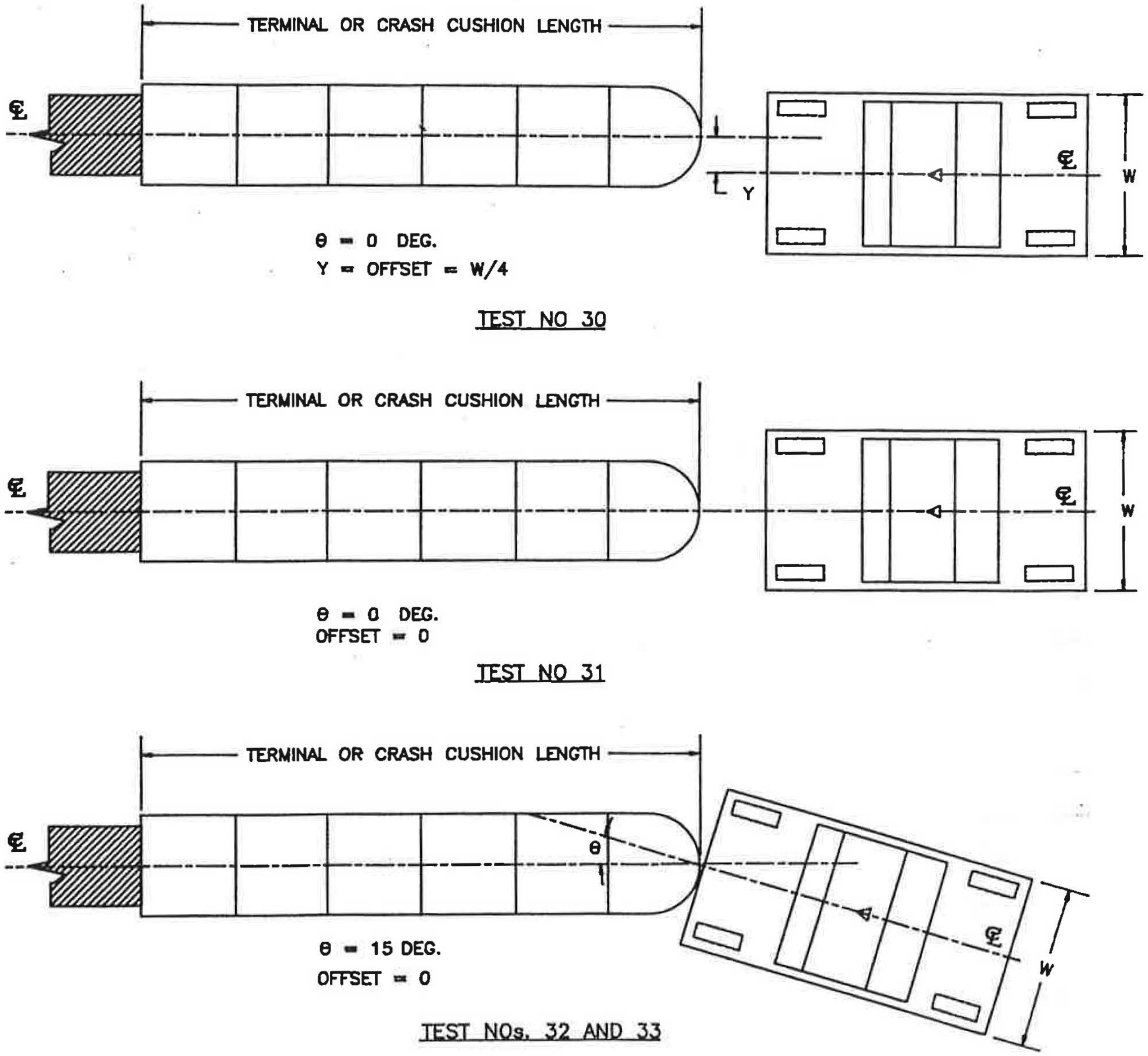
Test Matrix for Support Structures

Table 7 shows the proposed test matrices for support structures, traffic control devices, and breakaway utility poles. Traffic control devices are a new set of features that are being considered. All of these tests are with the small automobile.

TABLE 6 TEST MATRIX FOR TERMINALS AND CRASH CUSHIONS

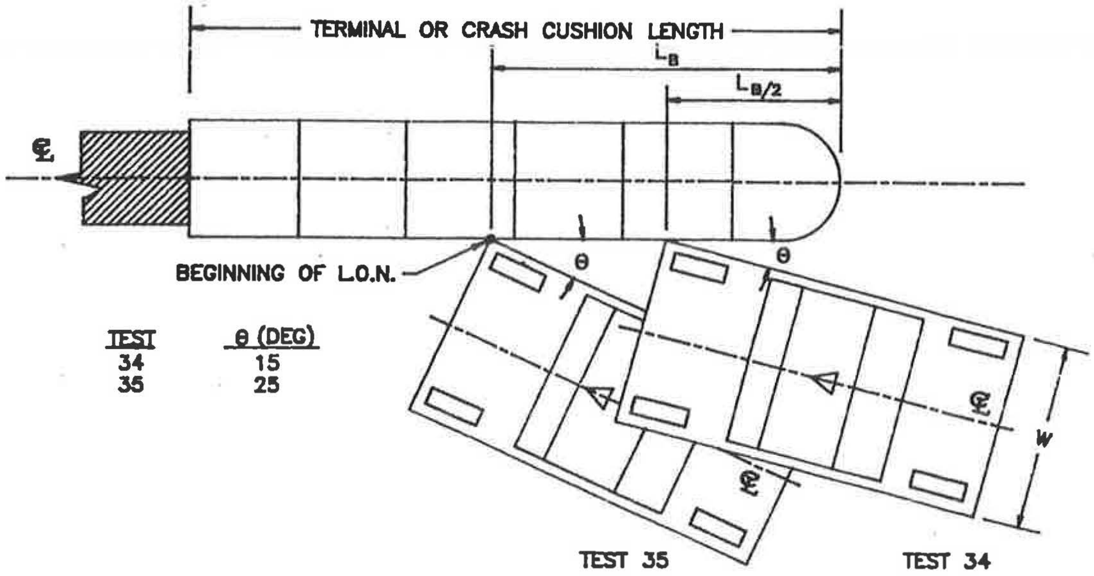
Severity Level	Feature	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[g] (See Table V-1)
			Vehicle	Nominal Speed (km/hr)	Nominal Angle, θ (deg)		
2 (Basic - Lower Speed)	Terminals and Redirective Crash Cushions	2-30[e]	V1	72	0	(b)	C,D,F,H,I,(J),K,N
		S2-30[a,e]	SV1	72	0	(b)	C,D,F,H,I,(J),K,N
		2-31	V2	72	0	(b)	C,D,F,H,I,(J),K,N
		2-32[d]	V1	72	15	(b)	C,D,F,H,I,(J),K,N
		S2-32[a,d]	SV1	72	15	(b)	C,D,F,H,I,(J),K,N
		2-33[d]	V2	72	15	(b)	C,D,F,H,I,(J),K,N
		2-34	V1	72	20	(b)	A,C,D,F,H,I,(J),K,N
		S2-34[a]	SV1	72	20	(b)	A,C,D,F,H,I,(J),K,N
		2-35	V2	72	25	(b)	A,D,F,K,L
		2-36	V2	72	25	(b)	A,D,F,K,L
		2-37[d]	V2	72	20	(b)	A,D,F,H,I,(J),K,N
	Nonredirective Crash Cushions[f]	2-40[e]	V1	72	0	(h)	C,D,F,H,I,(J),K
		S2-40[a,e]	SV1	72	0	(h)	C,D,F,H,I,(J),K
		2-41	V2	72	0	(h)	C,D,F,H,I,(J),K
		2-42	V1	72	15	(h)	C,D,F,H,I,(J),K,N
		S2-42[a]	SV1	72	15	(h)	C,D,F,H,I,(J),K,N
		2-43	V2	72	15	(h)	C,D,F,H,I,(J),K,N
		2-44	V2	72	20	(h)	C,D,F,K,L

[a] Test is optional. See Section III-A.
[b] See Figure III-2 for impact point.
[c] See Section III-C for tolerances on impact conditions.
[d] Test may be optional. See Section III-B-2.
[e] See discussion in Section III-B-2 relative to tests 30 and 40.
[f] See discussion in Section III-B-2 relative to nonredirective crash cushions.
[g] Criteria in parenthesis are optional.
[h] See Figure III-3 for impact point.

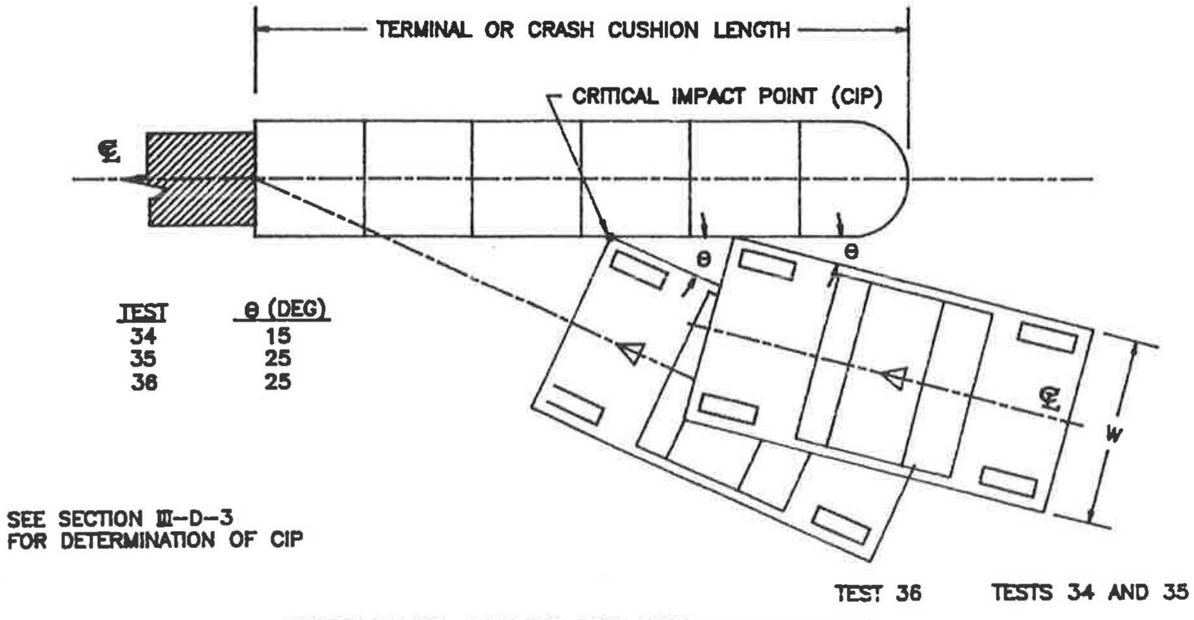


NOTE: OFFSET TOLERANCE FOR ALL TESTS = ±0.05(W)

FIGURE 3 Geometry of terminal or crash cushion Tests 32-33.

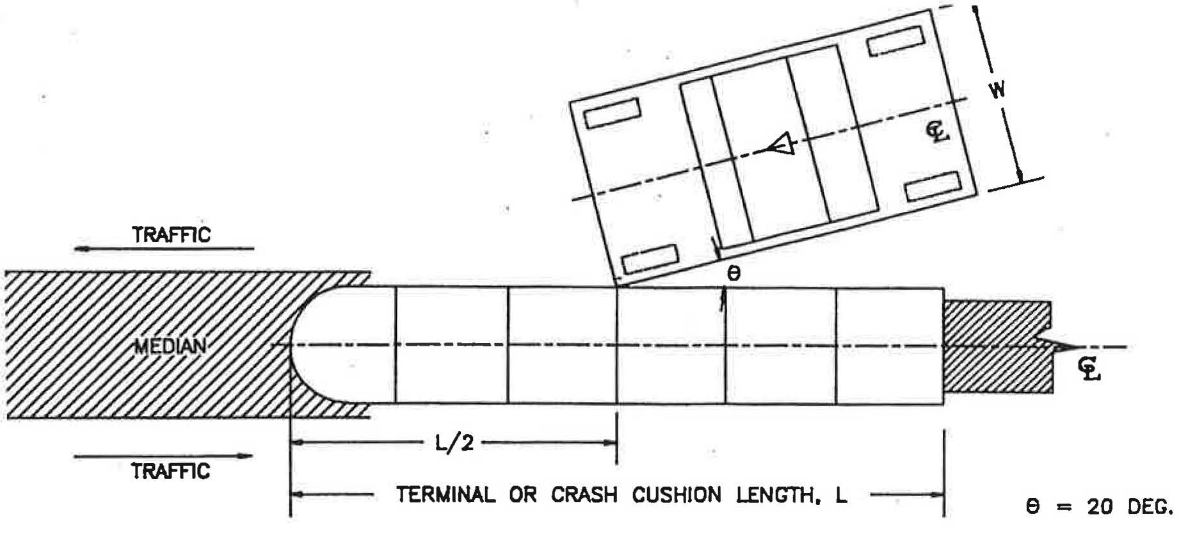


TEST 34 AND 35 FOR GATING DEVICE

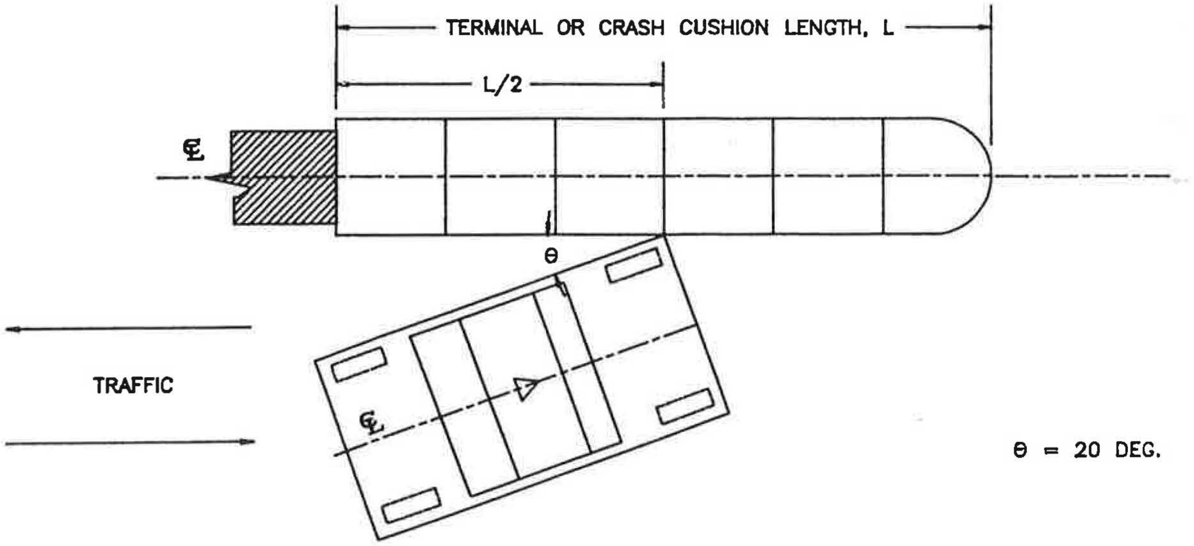


TESTS 34,35, AND 36 FOR NONGATING DEVICE

FIGURE 4 Geometry for terminal or crash cushion Tests 34-36.



TEST 37 FOR MEDIAN DEVICE



TEST 37 FOR ROADSIDE DEVICE

FIGURE 5 **Geometry for median and roadside device crash Test 37.**

TABLE 7 TEST MATRIX FOR SUPPORT STRUCTURES, TRAFFIC CONTROL

Severity Level	Feature	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[d] (See Table V-1)
			Vehicle	Nominal Speed (km/hr)	Nominal Angle, θ (deg)		
2 (Basic - Lower Speed)	Support Structures	2-60	V1	32	0-20	(b)	B,D,F,H,I,(J),K,N
		S2-60[a]	SV1	32	0-20	(b)	B,D,F,H,I,(J),K,N
		2-61	V1	72	0-20	(b)	B,D,F,H,I,(J),K,N
		S2-61[a]	SV1	72	0-20	(b)	B,D,F,H,I,(J),K,N
	Traffic Control Devices	2-70	V1	32	0-20	(b)	B,D,E,F,H,I,(J),K,N
		S2-70[a]	SV1	32	0-20	(b)	B,D,E,F,H,I,(J),K,N
		2-71	V1	72	0-20	(b)	B,D,E,F,H,I,(J),K,N
		S2-71[a]	SV1	72	0-20	(b)	B,D,E,F,H,I,(J),K,N
	Breakaway Utility Poles	2-80	V1	48	0-20	(b)	B,D,F,H,I,(J),K,N
		S2-80[a]	SV1	48	0-20	(b)	B,D,F,H,I,(J),K,N
		2-81	V1	72	0-20	(b)	B,D,F,H,I,(J),K,N
		S2-81[a]	SV1	72	0-20	(b)	B,D,F,H,I,(J),K,N
3[f] (Basic - High Speed)	Support Structures	3-60	V1	32	0-20	(b)	B,D,F,H,I,(J),K,N
		S3-60[a]	SV1	32	0-20	(b)	B,D,F,H,I,(J),K,N
		3-61	V1	97	0-20	(b)	B,D,F,H,I,(J),K,N
		S3-61[a]	SV1	97	0-20	(b)	B,D,F,H,I,(J),K,N
	Traffic Control Devices	3-70[e]	V1	32	0-20	(b)	B,D,E,F,H,I,(J),K,N
		S3-70[a,e]	SV1	32	0-20	(b)	B,D,E,F,H,I,(J),K,N
		3-71	V1	97	0-20	(b)	B,D,E,F,H,I,(J),K,N
		S3-71[a]	SV1	97	0-20	(b)	B,D,E,F,H,I,(J),K,N
	Breakaway Utility Poles	3-80	V1	48	0-20	(b)	B,D,F,H,I,(J),K,N
		S3-80[a]	SV1	48	0-20	(b)	B,D,F,H,I,(J),K,N
		3-81	V1	97	0-20	(b)	B,D,F,H,I,(J),K,N
		S3-81[a]	SV1	97	0-20	(b)	B,D,F,H,I,(J),K,N

[a] Test is optional. See Section III-A.
[b] See discussion in Section III-B-3 relative to impact point.
[c] See Section III-C for tolerances on impact conditions.
[d] Criteria in parenthesis are optional.
[e] See discussion in Section III-B-3 relative to test 70.
[f] See discussion in Section III-B-3 relative to severity level 3.

Test Matrix for Truck-Mounted Attenuators

The TMA test may be of interest to some of you. As shown in Table 8, two basic tests are proposed. A major change, if adopted, would be the high-speed test for TMAs. Up to now TMAs have been designed basically for 45-mph impacts. There may be some instances where a high-speed 60-mph TMA is needed. With reference to Figure 6, the first two would involve both the large and small hit centered on the rear of the TMA. The last two would involve the pickup truck. The third test would be off-centered, straight on; the last test would be off-centered at an angle.

Evaluation Criteria

The last thing I have to talk briefly about is evaluation criteria. Again, I think John covered these items real well as far as NCHRP Report 230. As far as structural adequacy, we don't propose any major changes to that. Under the occupant risk, we propose to retain the flail space model concept. We're debating whether or not to incorporate some refinement in the procedures that are used to calculate occupant impact velocity. The current procedure does not properly account for angular rotations of the vehicle during impacts with longitudinal barriers. Maybe we should improve that. In the update, we are going to maintain the unrestrained occupant assumption as far as the tolerances go because about 50 percent of our citizens don't use seat belts.

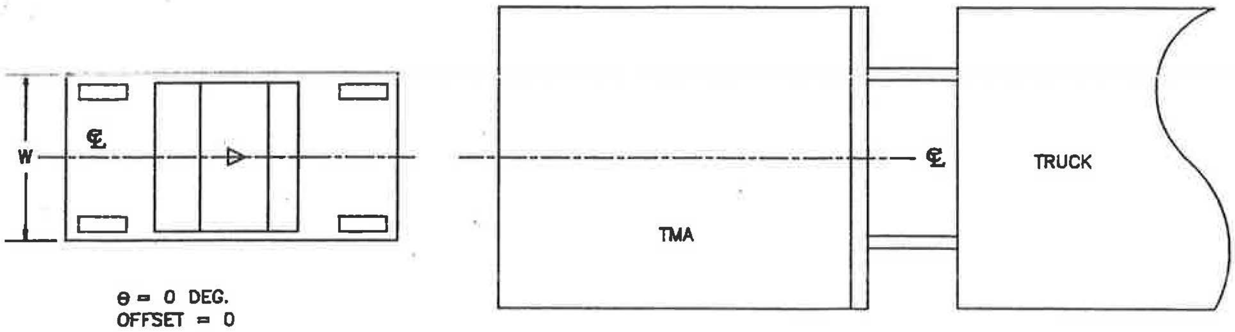
The following outline summarizes the proposed changes regarding the evaluation criteria:

- Structural adequacy, no major changes
- Occupant risk;
  - Retail flail space model;

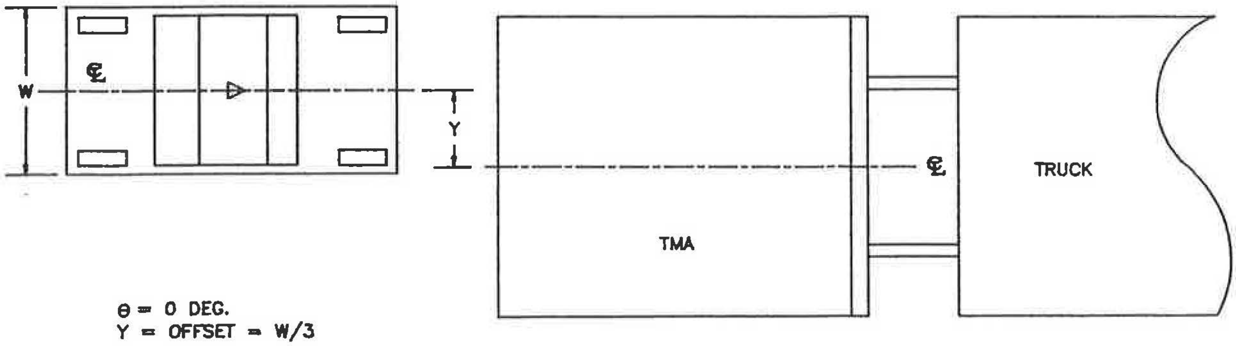
TABLE 8 TEXT MATRIX FOR TRUCK-MOUNTED ATTENUATORS

Severity Level	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[e,g] (See Table V-1)	EVALUATION CRITERIA[f,g] (See Table V-1)
		Vehicle	Nominal Speed (km/hr)	Nominal Angle, θ (deg)			
2 (Basic - Lower Speed)	2-50	V1	72	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	S2-50[a]	SV1	72	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	2-51	V2	72	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	2-52	V2	72	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	2-53	V2	72	10	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
3[d] (Basic - High Speed)	3-50	V1	97	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	S3-50[a]	SV1	97	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	3-51	V2	97	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	3-52	V2	97	0	(b)	C,D,F,H,I,(J),K	D,F,I,(J)
	3-53	V2	97	10	(b)	C,D,F,H,I,(J),K	D,F,I,(J)

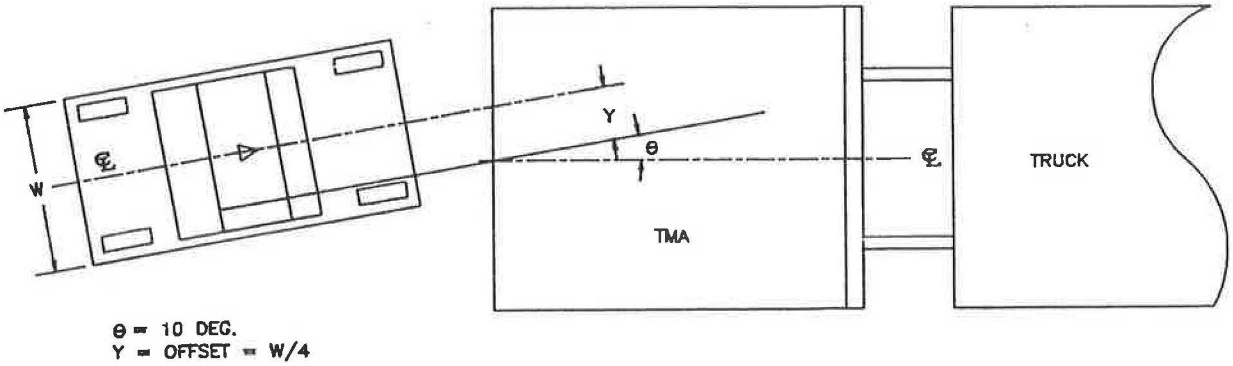
[a] Test is optional. See Section III-A.
[b] See Figure III-5 for impact point.
[c] See Section III-C for tolerances on impact conditions.
[d] See discussion in Section III-B-4 relative to severity level 3.
[e] For impacting vehicle and its occupants.
[f] For supporting truck and its driver. See discussion in Section V-C.
[g] Criteria in parenthesis are optional.



TEST NOS. 50 AND 51



TEST NO. 52



TEST NO. 53

NOTE: OFFSET TOLERANCE FOR ALL TESTS = ±0.05(W)

FIGURE 6 Geometry for truck-mounted attenuator crash Tests 5-53.

  - Change lateral occupant impact velocity limits to equal those for longitudinal direction barriers, crash cushions, TMAs, and breakaway utility poles; recommended 30 ft/sec (9.2 m/sec, and maximum 40 ft/sec (12.2 m/sec);
- Retain ridedown deceleration limits, recommended 15 Gs, and maximum 50 Gs;
- Retain occupant impact velocity limits for support structures and traffic control devices, maximum 16 ft/sec (4.9 m/sec); and
- Postimpact trajectory;
  - Omit 15-mph vehicular ΔV limit;
  - Add 40-ft/sec vehicular ΔV limit.

One of the refinements that was considered and rejected was that we not only consider updating to the calculations procedures, but that we also change the box that we have the unrestrained occupant in. In NCHRP Report 230, the box is 2 ft wide. The driver can flail to the left 1 ft or to the right 1 ft, and he can go forward 2 ft. But we all know that an unrestrained occupant is not restrained that way; there is no box in the vehicle. If you hit a barrier on the right side of the vehicle and you are the driver, you are going to flail about the front seat until you hit the right side of the vehicle. We thought about incorporating that, but the truth is, if you do that, then we have to rule out most barriers.

Experience has indicated that the numbers we are using are fairly reasonable. We do not see any evidence from the data that we have a major problem with occupant injury when we have smooth redirection, somewhat independent of impact conditions. I think we have some support for what we are doing. It may not be consistent with what might be expected from the real world. One of the changes being proposed is uniform limits for occupant impact velocities, both lateral and longitudinal. In discussions with the experts—General Motors and others—we were convinced that there were no major differences, at least within the context of the flail space calculations, for justifying lower lateral and longitudinal limits.

So, it is being proposed that the same limit be adopted for both cases—a recommended limit of 30 ft/sec, which is what NCHRP Report 230 has with the factor of safety, and a maximum of 40 ft/sec, the limit in NCHRP Report 230 with no factor of safety. We propose to retain the ridedown acceleration limits. We also propose to retain the occupant impact velocity limits for support structures.

Finally, a change is being proposed for the post-impact trajectory. In tests of most longitudinal barriers, we cannot meet the 15-mph velocity change requirement of NCHRP Report 230. So, let us add a 40-ft/sec velocity change limit that is consistent with the occupant risk criteria, and yet reasonable in terms of vehicle behavior after impact.

F. Effects of Differences Between European and American Automobiles on Testing Procedures

By: Thomas Turbell, National Swedish Road and Traffic Research Institute

I will start to say a few words about the European Committee for Standardization (CEN) work in Europe. The scope of this group so far is to propose a standard on longitudinal barriers and crash cushions. This scope is not finally confirmed. It will be discussed in London next week. But this is what we are working with so far. The schedule for this group is that we have had only one session in Paris; we will have the next session in Rome in a couple of weeks, and then two more sessions this year. The first draft will be ready by the end of 1991. The final standards will be ready in the middle of next year. That is the intention of the group, at least. In the past meeting, we were 10 countries with 25 delegates present, but this is a rather large group now.

Typical European Automobile

Then I will go on to the subject for today. That is: What is a typical European automobile? As far as I understand the CEN group, we are not looking for the smallest automobile like John Viner described. We are looking for the typical European automobile to use in the crash test. So, what is the typical European automobile? We can also remember that the proposed test vehicles in the NCHRP Report 230 update are the 860-kg (1,900 lb) automobile and the large passenger automobile or the pickup truck of 2,040 kg (4,500 lb).

Best-Selling Automobiles

If we look at the different countries in Europe, there is a difference in the best-selling models, as shown in Table 9. The range is 850 to 1,390 kg in the best-selling models. We can remember that the NCHRP Report 230 update is talking about 860 kg for the small automobile, that is. We can look a little closer at some of the countries.

Differences in European Automobiles

In my country, Sweden, 50 percent of the most-sold automobiles are shown in Table 10, and the weighted mean curb weight is 1,244 kg. Maybe a typical Swedish automobile would be 1,200 kg. Then, if we can compare this to Italy (Table 11), where they have the smallest automobiles in Europe, where 50 percent of the automobiles have a weighted mean curb weight of 918 kg, and then compare it to Sweden, 1,244 kg. This is 36 percent more in weight. So there we have a problem—What is the typical European automobile? What automobile should we use in Europe for the crash test?

TABLE 9 BEST SELLING MODELS 1989

Austria	VW Golf 1020 kg
Belgium	VW Golf 1020 kg
Denmark	Toyota Corolla 1040 kg
France	Renault R5 900 kg
Greece	Lada 1090 kg
Italy	Fiat Uno 850 kg
Netherlands	GM Opel Kadett 990 kg
Norway	Toyota Corolla 1040 kg
Portugal	Fiat Uno 850 kg
Spain	Renault R19 1080 kg
Eire	Ford Fiesta 930 kg
Finland	Toyota Corolla 1040 kg
Sweden	Volvo 700 1390 kg
Switzerland	VW Golf 1020 kg
United Kingdom	Ford Escort 1100 kg
West Germany	VW Golf 1020 kg
Western Europe	VW Golf 1020 kg
Range	850 - 1390 kg
NCHRP 230 Update 1900 lb	860 kg

We can also look at the total best-selling models in Europe (Table 12). If we compare this out of 50 percent of the passenger automobiles sold in Europe, there is a weighted mean curb weight for all these automobiles of 989 kg. The, we have some problems we didn't settle. Several of the CEN countries want to test with a specific automobile because of historical and other reasons, because all of their old tests have been made with a certain type of automobile. Of course, then we have problems with the different masses, different geometries, wheel sizes, center of gravity, moments of inertia, and all this. The question is, "Can we stick to this scheme in Europe, to have different automobiles in different countries, because then we would have different guardrails, etc." What is the aim of the CEN work if we don't stick to one type of automobile?

TABLE 10 BEST SELLING MODELS 1989 (SWEDEN)

Volvo 700	13.2%
SAAB 9000	4.7%
Volvo 200	3.9%
Volvo 400	3.9%
GM Opel Kadett	3.8%
VW Golf	3.7%
SAAB 900	3.7%
Ford Sierra	3.6%
Toyota Corolla	3.3%
Audi 100	3.1%
Mazda 626	2.8%
Ford Escort	2.6%
Total	52.3%
Weighted Mean Curb Wt	1244 kg

TABLE 11 BEST SELLING MODELS 1989 (ITALY)

Fiat Uno	16.2%
Fiat Tipo	11.1%
Fiat Panda	9.5%
Lancia Y10	5.3%
VW Golf	3.6%
Renault R5	3.2%
Peugeot 205	2.9%
Total:	51.8 kg
Weighted Mean Curb Wt	918 kg
Sweden:	
Total	52.3%
Weighted Mean Curb Wt (36% more than Italy)	1244 kg

TABLE 12 WESTERN EUROPE BEST SELLING MODELS 1989

VW Golf	5.4%
GM Opel Kadett	4.7%
Fiat Uno	4.4%
Peugeot 205	3.6%
Renault R5	3.6%
Ford Fiesta	3.5%
Ford Escort	3.3%
Renault R19	3.3%
Fiat Tipo	3.1%
Ford Sierra	2.9%
GM Opel Vectra	2.7%
Citroen AX	2.4%
GM Opel Corsa	2.4%
Peugeot 405	2.4%
Fiat Panda	2.4%
Total	50.0%
Weighted Mean Curb Wt	989 kg

Suggested Prescription for the Test Automobile

If we are going to use one test vehicle in Europe, maybe we have to for something like this: that we take the most-sold passenger automobile in the CEN countries 5 years before the year of the test. The 5 years is to get the reasonable price of the automobile, and a 5-year-old automobile would be a good thing to use in the tests. With a scheme like that, we would also have, if the automobiles are getting smaller, we would get the test vehicles also smaller in the future, and that can be a sort of running progress. If we look at the present situation, if we are going to make a test in 1993, then we would use a 1988 Volkswagon Golf, which the Americans know as the Volkswagon Rabbit. The same thing, a test in 1994 would also be the same automobile because that is the most-sold automobile in 1989. I don't know how this list would look in the future if it would go up and down, but I will bring this up in CEN. We could do for a thing like that—some sort of automatic change of automobile depending on the outcome of the sales of the automobiles in Europe.

G. French Testing Procedures and French Position on European Approach

By: Robert Quincy, INRETS, France

For many years, there has been a regulation of the French Ministry of Transportation concerning road safety equipment. In this regulation, performance classes are specified and some barriers are accepted.

Since 1988, manufacturers, authorities, and laboratories have been translating the regulation into standards to prepare for the 1993 European common market. This work, under the auspices of AFNOR, has enabled building up a set of about 30 standards on the subject. This work is nearing completion, and the main standards are already published.

The basic French standard, number NF P 98409, is included in Appendix D. It is a performance standard concerning lateral systems that includes two main levels corresponding to the restraint of light and heavy vehicles. There are three sublevels corresponding to classes of users.

Collision tests have been carried out for these standards, approval being given after the checking of the acceptance criteria, which are as follows:

1. No jumping the barrier.
2. Adherence to impact severity criteria in terms of ASI values for vehicle deceleration and VIDI values for vehicle body deformations.
3. Adherence to conditions of the barrier terminal.
4. Adherence to other conditions concerning the disposition and condition of the barrier following the impact.

In the framework of CEN, technical committee TC226 has been set up to deal with the standardization of road systems. This committee includes eight working groups, and the activation of WG1 on safety fences and barriers has been initiated in France. The first WG1 meeting took place in Paris in September 1990; the second one will take place in Rome on January 31 and February 1, 1991. The adjustment of European standards is a difficult operation because large present disparity exists between the various countries. An approach by successive steps must, therefore, be undertaken.

The first meeting enabled an agreement of the entire European delegation on the setting up of performance standards and an outline of terminology in this field. During the second meeting, performance classes will be determined according to the outline presented in Appendix E, probably to be further changed in accordance with the opinions of the various countries.

To determine performance classes for lateral barriers, severity criteria based on the transverse kinetic energy absorbed by the barrier will be considered, the objective being to establish four or five classes of performance. Following this will be steps for determining test conditions, according to the severity criteria, for the various vehicle types and acceptance criteria. Then, temporary lateral systems, e.g., equipment in working areas; and frontal systems, e.g., crash cushions, will be considered.

It is difficult to project deadlines; however, there appears to be desire of the various European countries to complete the standardization of equipment in this field.

H. Effects of Differences in Truck Size and Weights on Testing Procedures

By: Alessandro Ranzo and Francesco La Camera, University La Sapienza, Rome, Italy

Four years from the commencement of Anagni field test activities, and after completion of work to improve the launching system, an overview has been prepared of the tests conducted up to now with heavy vehicles. The guardrails tested have been essentially of three types: (a) central reserve (New Jersey-type profile in concrete, single- or double-file, with earth fill); (b) viaduct (New Jersey-type profile in concrete, reinforced and raised); and (c) roadside, in steel.

The vehicles used, limited to heavy vehicles, ranged from two to four axles and from 7 to 29 tonnes in weight.

The launch system used in tests consisted of towing by an auxiliary vehicle and release of the test vehicle near the guardrail (about 50 m). This system entailed limitations on the mass of the vehicle and the launch speed, as well as significant random errors regarding impact angle and impact point. It has been impossible to test vehicles with trailers with weight up to 44 tonnes, and the speed obtained has always been significantly less than that intended.

These limitations were accentuated following Test 21, when it became necessary to reduce the length of the tow track. Figure 7 shows how the space-velocity diagrams corresponding to vehicles of 24 and 44 tonnes were obtained with the power of the tow vehicle and the limit speeds for the various track lengths as parameters. Figure 8 shows the errors in impact angle obtained as functions of weight and speed. The intended impact angle was achieved in about two-thirds of the total number of tests, without any particular relationship between launch speed or vehicle weight, thus confirming the random nature of this error, which was linked to the launch method.

Test Parameters and Results

Characteristic parameters of the tests conducted included vehicle weight, vehicle speed, impact angle, and height of the center of gravity. The tests were conducted for vehicles of four, three, and two axles and various guardrail types; the maximum weight permitted under Italian regulations in the various cases was indicated on the vehicles. Load weights exceeded the maxima permitted under Italian law. In fact, surveys conducted on Italian roads have shown that about 5 percent of the vehicles in circulation violate these regulations, reaching 27 tonnes, as opposed to the prescribed 24 tonnes. At Anagni, loads ran up to 29 tonnes.

A certain inverse proportionality was found between vehicle mass and speed (see Figure 9), except for the case of metal guardrails, to which more severe testing conditions were not applied. This situation corresponds to a certain uniformity in impact energies. In effect, because of the high energies, the potential limit of the system was approached, increasing the probability of tow vehicle driver error.

The spread of the data confirmed that the error in the impact angle was random, in particular being unlinked to the vehicle weight (see Figure 10). The 1.60-m height of the center of gravity, prescribed in the new Italian standards, constituted practically the limit value for the trials conducted (see Figure 11). This height was linked in particular to the loading system adopted up to now, consisting of concrete blocks anchored some 20 to 30 cm up from the bed of the truck.

In the following paragraphs, the most important results of the tests conducted and the suggestions for standardizing the tests that emerged therefrom are summarized. Figure 12 shows types of guardrails as related to types and amounts of traffic and types of roads.

New Jersey-Profile Guardrail

Tests performed on the central-reserve-type, single-file, New Jersey-profile guardrail indicated the need for traction-resistant elements consisting of reinforcing in the prefabricated elements and connections between these to permit funicular-type action. In the absence of reinforcement and given the high impact energy, the guardrail system failed because of rupture of the elements or their disconnection from one another. Moreover, the limited height of 1 m combined with the significant displacements produced by very heavy vehicles resulted in vehicle rollover in cases of high center of gravity.

Tests on the central-reserve-type, double-file, earth-filled, New Jersey-profile guardrail confirmed these deductions. Moreover, they demonstrated that the presence of an energy-absorbing element (in this case, the earth fill) guaranteed safety even in cases of extremely heavy impact.

Tests on viaduct guardrails demonstrated the importance of having a connecting element at a height greater than 1 m (a steel toprail or a concrete beam for

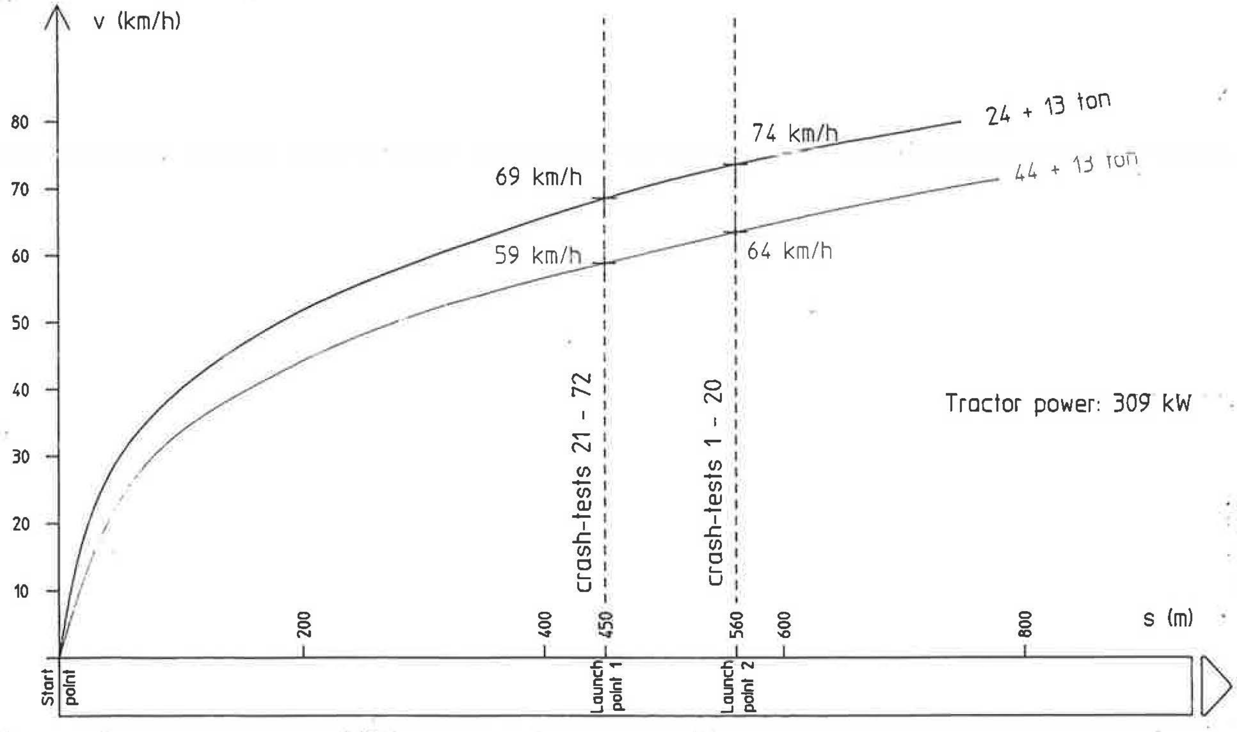


FIGURE 7 Space velocity diagrams for various load classes.

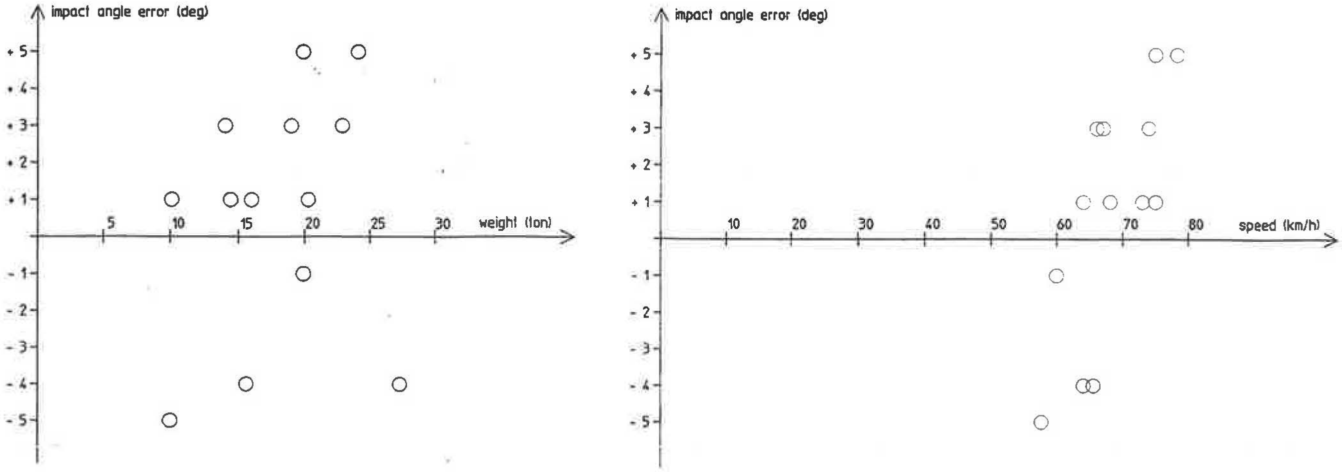


FIGURE 8 Vehicle weight-impact angle error diagrams.

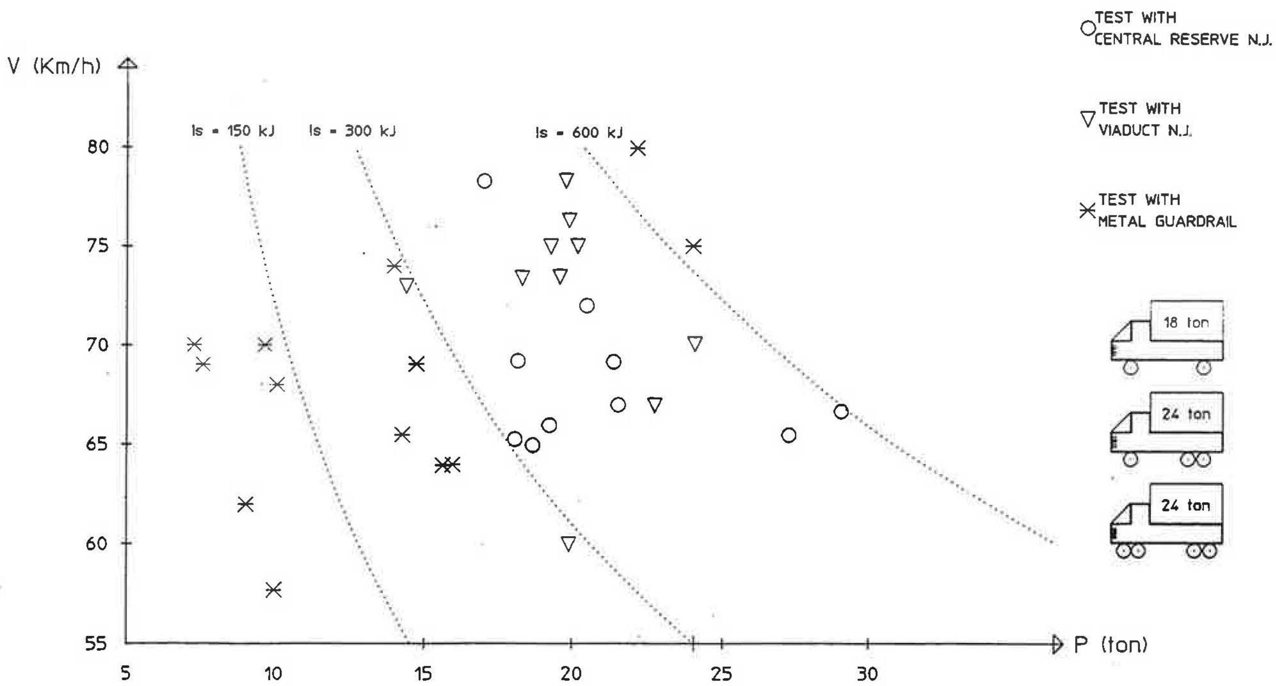


FIGURE 9 Weight versus launch speed diagram.

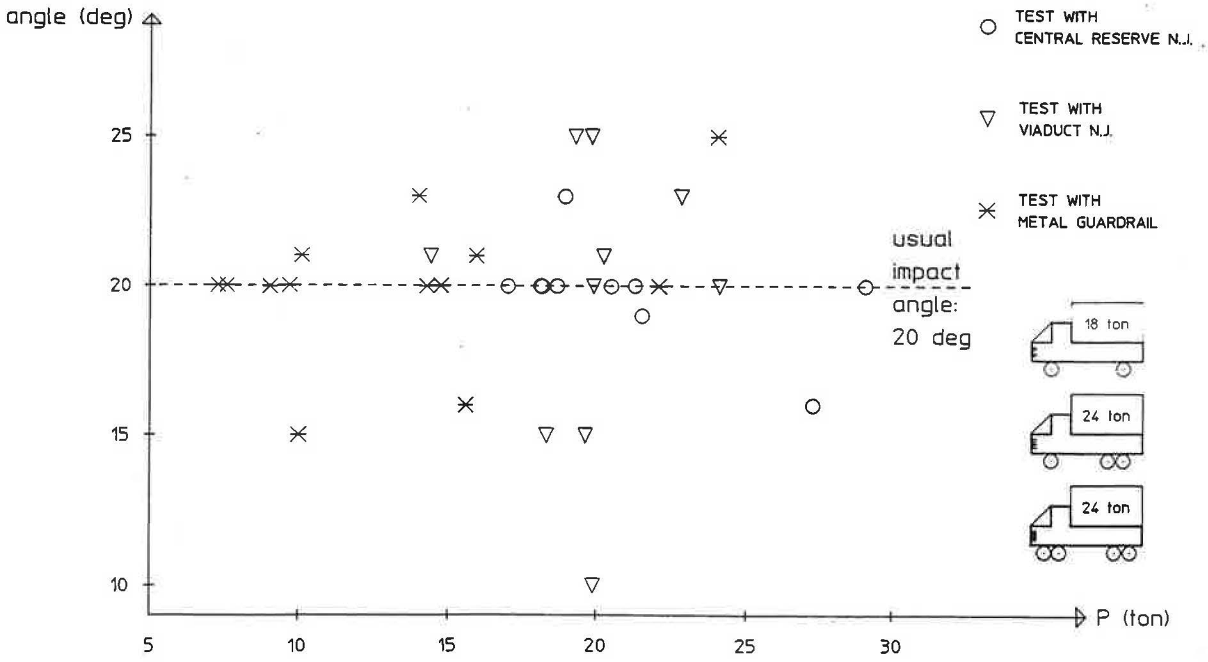


FIGURE 10 Weight versus impact angle diagram.

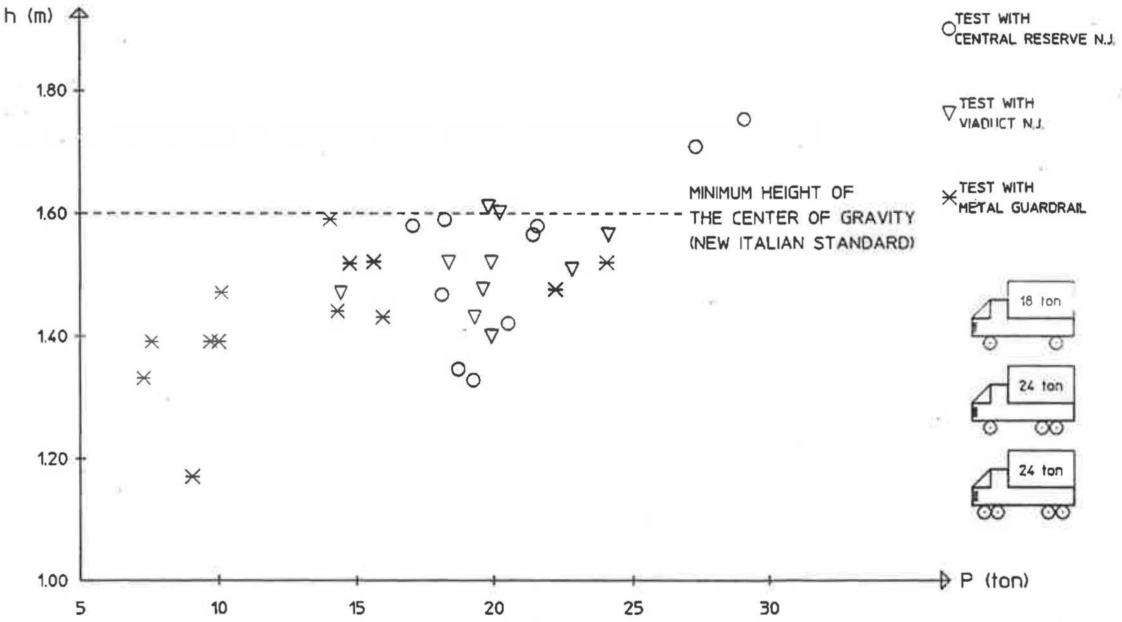
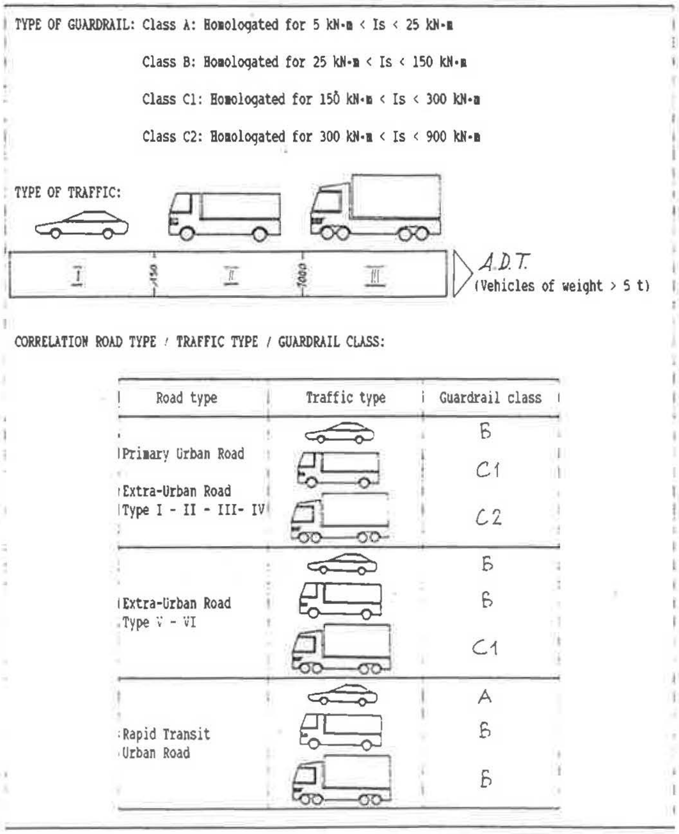


FIGURE 11 Weight versus height of center of gravity diagram.



TYPE OF GUARDRAIL: Class A: Homologated for 5 kN·m < Is < 25 kN·m

Class B: Homologated for 25 kN·m < Is < 150 kN·m

Class C1: Homologated for 150 kN·m < Is < 300 kN·m

Class C2: Homologated for 300 kN·m < Is < 900 kN·m

TYPE OF TRAFFIC:

A.D.T.
(Vehicles of weight > 5 t)

CORRELATION ROAD TYPE / TRAFFIC TYPE / GUARDRAIL CLASS:

Road type	Traffic type	Guardrail class
Primary Urban Road Extra-Urban Road Type I - II - III- IV		B C1 C2
Extra-Urban Road Type V - VI		B B C1
Rapid Transit Urban Road		A B B

FIGURE 12 Guardrail classification as a function of absorbable energy and in correlation with road and traffic types.

the Colosseum rail), so as to avoid rollover of vehicles with high center of gravity. In fact, in the only test with negative results, a fiberglass toprail lacked sufficient strength, broke under impact, and failed to ensure vehicle containment and effective connection between the guardrail elements.

Steel Guardrail

Finally, the tests on the metal guardrails confirmed the importance of guardrail height and mechanisms to limit height loss under impact so as to prevent rollover of vehicles with high center of gravity, and also the need to increase the strength of the longitudinal strip to compensate for increased impact energy. Two factors emerged as important in verifying guardrail performance: the energy of the vehicle at the moment of impact (especially its component orthogonal to the guardrail) and the height of the center of gravity.

Heavy Vehicles Tested

Italian regulations prescribe the following load limits:

1. Trucks of two axles: 18 tonnes.
2. Trucks of three or four axles: 24 tonnes.
3. Vehicles with trailers: 44 tonnes.

Up to now, the only vehicles tested have been those in the first and second categories. Because tractor and trailer act independently, as confirmed also from actual accident data, tests on vehicles of the third category would be of little additional value. However, the existence of a certain percentage of vehicles in circulation that exceed the official limits on loads and speeds suggests the advisability of using vehicles exceeding 24 tonnes in tests on maximum-strength guardrails.

Accident Cases

New Jersey-type guardrails have been used in Italy for about 3 years, and hence there is already sufficient documentation on accidents to permit verification of their effectiveness. Some particularly significant accidents that were studied included a viaduct guardrail after impact by a 19-tonne trailer truck at 90 km/hr at an impact angle of 30 degrees, with lateral energy about 1500 kJ. The vehicle was contained on the carriageway; in addition, the presence of the steel toprail not only served to redirect the vehicle, but also prevented the parts of the guardrail from falling off onto the underlying buildings. In a similar situation, the vehicle was contained, but the element struck, which was not connected by a steel toprail to its neighboring elements, was pushed off the structure.

In another case, a special guardrail installed on the Adriatica Motorway was almost undeformed. It consisted of two New Jersey-type profiles connected in an almost continuous manner, surmounted by a double-corrugated steel strip (W-beam) toprail. The vehicle, a five-axle tractor-semitrailer of about 25 tonnes, struck the guardrail at an impact angle of about 10 degrees and was redirected onto the carriageway.

Another case consisted of a double-file guardrail without interposed earthen fill or connecting elements that demonstrated a behavior similar to that of a single-file guardrail, insofar as it did not resist the impact, even though it did redirect the vehicle. In this case, the elements were of the older type (little reinforcing) and not connected. Consequently, the element at the point of impact was broken, and the two successive elements were disconnected.

In general, about 25 percent of all accidents consist of collisions against longitudinal guardrails, and except for rare cases, the impact angle is no more than about 12 degrees.

Test Specification

On the basis of the results of the tests conducted to date and accident findings, the Circulation Traffic Inspectorate of the Ministry of Transport has issued technical specifications for guardrail tests; these specifications are currently in process of being published. These specifications, besides defining guardrail performance characteristics, also stipulate procedures for performing the tests, with particular attention to vehicle weights and speeds (and hence the relevant energies), impact angle, height of center of gravity, and instrumentation necessary for proper documentation.

Severity Index

The dimensions, weights, speeds, and impact angles have been prescribed for the various categories of heavy vehicles. The center of gravity of the heavy vehicles is set at a minimum of 1.60 m from ground level. Weight, speed, and impact angle, which are variable so as to permit a certain elasticity in use, must nevertheless be such as to generate the lateral energy (also termed the "severity index" Is) prescribed for the various guardrail categories. The expression is

$$E(\text{lat}) = \text{Is} = W(V \sin a)^2/2g$$

where

$E(\text{lat})$ = kinetic energy in direction perpendicular to guardrail,
Is = severity index ($=E(\text{lat})$),
W = weight of vehicle,
g = acceleration of gravity,
V = vehicle speed, and
a = incident impact angle.

Anagni Launch System

The variables that must be checked with appropriate instrumentation are speed, impact angle, and the three spatial components of the vehicle deceleration. Taking into account these prescriptions, the Anagni launch system was completely modernized (the testing and final inspection stage have just been completed), to have maximum control over speed and impact angle, the two most important random variables. The new launch system shown in Figure 13 is of the diesel-hydraulic type; propulsion is provided by two coupled turbodiesel engines that drive a winch on which the towline is coiled; the vehicle is drawn by means of a trolley from which it is released a few meters from the guardrail.

The impact angle and point of impact are determined in an almost absolute manner, insofar as the vehicle trajectory is imposed almost right up to the guardrail. The trolley runs along a track. The angles are set at 10 and 20 degrees. The launch speed is controlled by regulating the capacity of the hydraulic system. Special software permits simulation of the test before execution, to optimize the length of track to be used and to obtain a space-speed diagram to follow during the crash test. During the test, the performance of the system is controlled electronically to supply the computer in real time both the spot speed and the distance traveled. In this way, the operator can reduce or increase the towing force to reach the release point at the speed desired. The speed error encountered during the system inspection trials was about 2 percent.

The vehicle trajectory before, during, and after impact is checked by an overhead high-speed motion picture camera at a film speed of 400 frames per second. The deceleration to which the vehicle is subjected with its longitudinal, transverse, and vertical components is measured directly by means of accelerometers installed on the vehicle and controlled by an on-board processor, and indirectly by the films. Using these devices, the crash tests can be performed with minimum deviation from the speed, impact angle, and energy determined beforehand or required by current Italian regulations or by any future international specifications.

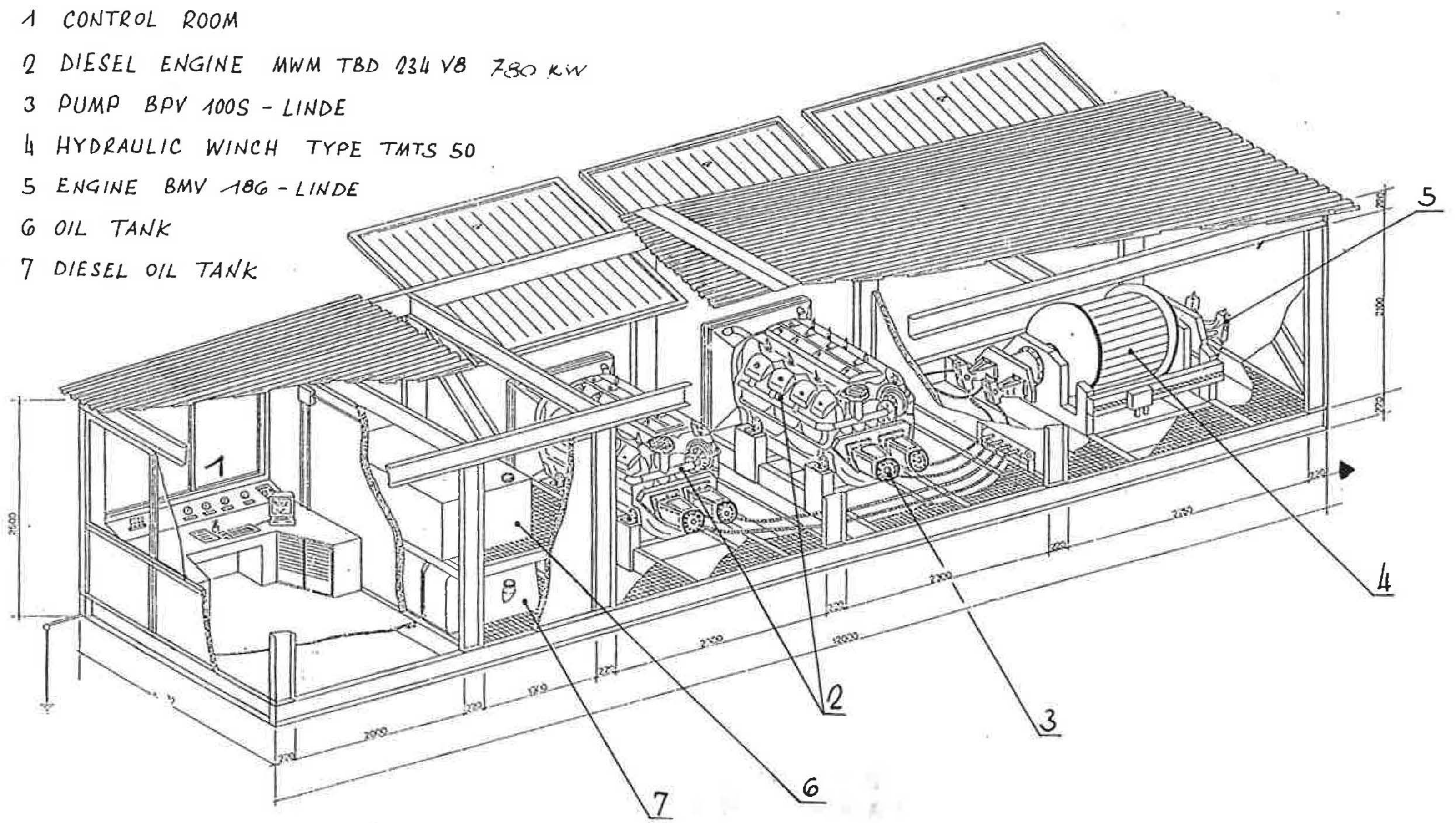


FIGURE 13 Axonometric view of launch system.

I. German Testing Procedures

By: Wolfgang Wink, Volkmann and Rossbach, Germany

The German standard for permanent safety barriers was published in 1972, on the basis of extensive tests conducted between 1962 and 1968. These tests already took into consideration the deceleration value as an important factor for road safety. The German standard is a standard for a definitive system. Test results have shown that the steel guardrail system is the most suitable system. Everything on this system is completely defined, and any change in the smallest detail is out of specification and unacceptable.

But do not be afraid either of German inflexibility or of our lack of dynamic development. As you may infer from the statement above, the German standard has been revised and amended several times since 1972. Here are some outstanding and decisive changes:

1. In 1980, it was decided by the federal ministry that it should be mandatory to install guardrails in central reserves of highways regardless of their width. This decision was made as a result of critical accidents that took place in central reserve sections that were wider than 10 m and had no guardrail. Since this amendment, the accident rate and severity of the accidents in central reserve areas have been dramatically reduced.
2. Another amendment was the introduction of a post with rounded edges called the "sigma" post. This change of the standard has also resulted in a tremendous success, considering the reduction of the severity of the accidents involving two-wheeled vehicles.

In August 1989, the German standard was extensively revised. The traditional steel guardrail system, however, was not at all changed as a permanent passive safety device. The revision, which has been published under the initials "RPS," mainly affects the guidelines for installation, taking into account the recent variations of vehicle weight and other components of public interest.

Other important amendments are the inclusion of crash cushions, which have been known for many years in the United States, and concrete barriers with very special applications on German roads. In the CEN committee, which consists of 18 European countries, we have taken over a huge responsibility. Our aim is to harmonize and standardize the traffic safety systems. In Germany we have found out that standardization of safety systems or devices does not make sense at all. In consequence, we are working on standardization of performance parameters, test procedures, test equipment, and test vehicles. We emphasize that the deceleration criteria is decisive for the effectiveness of a safety system. We also take into consideration other criteria, such as the displacement of the system upon impact, etc., which are of minor value, but useful for the overall evaluation. My personal opinion regarding deceleration values is that we can live with the ASI method for steel barrier safety systems because they are mainly installed for redirection purposes.

But for crash cushions, which are usually designed for frontal impacts, aiming to bring the vehicle to a controlled stop, we have to find another method for the evaluation. In this regard, I propose to intensify the cooperation between the United States and Europe because my understanding is that U.S. research and experience in this field is already both very advanced and efficient. See, for example, NCHRP Report 230 or other publications. Among the concerned European authorities and related industry, there are intensive discussions on rigid and nonrigid (flexible) systems as permanent passive safety devices. Regarding this problem, my personal opinion is as follows: it is impossible to please everybody. This is what common sense tells us.

The basis for my conception of promoting highway traffic safety is the prevention or the reduction of the number and severity of accidents, respectively, by the appropriate installation of passive safety devices, with the goal of providing adequate protection to those who are statistically the largest part of the highway accident rate and the aftereffects connected with them. Above all, this involves, of course, the prevention of fatal accidents and the decrease of accident severity from severe to medium or minor accidents, as well as a reduction of personal injury and material damages.

Getting back to my familiar quotation cited at the beginning, one cannot expect from the development and installation of passive safety devices for the highway, that all accidents and damage can be prevented or reduced, but rather numerically and qualitatively the largest part of a country's accident rate. Only this has a really good chance for economic success. It is not a matter of preventing one severe accident per year at a particular place and with a vehicle of a particular weight.

It is a matter of getting the greatest possible number of all potential accidents safely under control through the use of those safety devices that above all offer the person the greatest possible chance of surviving with, if possible, a simultaneous decrease in material damage.

If one agrees to this concept of safety and the understanding of safety connected with it, in my opinion, there cannot be any confusion about which basic system of passive safety devices has so far optimally met these requirements all over the world. It is the flexible and elastic steel guardrail system.

The inflexible (rigid) concrete barrier system (BGW) can never meet the requirements of modern safety systems, which are based on reasonable, that is, tolerable deceleration rates.

Again, if I set out to reduce the number and severity of accidents, for economic reasons I will have to follow the rules of the majority; and that means in this case that I have to consider the frequency curve of the highway accident rate. Therefore, to make sense economically, I must start with those accident groups that occur most often. The following are some round figures from Germany taken from official accident statistics for 1988:

Existing Vehicles

Automobiles	95 percent
Trucks	5 percent

Kilometers Traveled

Automobiles	90 percent
Trucks	10 percent

Accidental Deaths from

Automobiles	95 percent
Trucks	5 percent

On the basis of these bare numbers alone, it is obvious that approval of a trend towards inflexible systems is out of the question, simply because they are better in preventing a truck from breaking through a safety system. Actually, we rarely hear publicly of the tolerance of deceleration rates and their decisive effect on vehicle passengers, which are underestimated or hardly considered.

From the preceding, it is obvious to me that the development of the rigid BGW system as the commonly applied passive safety device for highways is clearly erroneous, which in reality overlooks modern knowledge of accident analysis. The BGW systems are justifiable in those cases that are cited in the German Standard RPS of 1989. At this point, for the good of highway traffic safety, the matter should rest.

Safety Barriers in Highway Work Zones

The subject of safety barriers in work zones has been characterized by requirements for separation of driving lanes, reduction in width of lanes, control of traffic flow, and transition from normal permanent to temporary situations. These situations have been dominated by products like road markings, including pre- fabricated foils; road studs or cat's eyes; plastic barriers; and portable concrete barrier sections.

But, because the frequency of results of recent accident analysis clearly shows that the numbers and severity of accidents in work zones are increasing dramatically, we have--as a steel guardrail manufacturer—decided to concentrate our efforts in research and development of new steel products and safety systems for work zones.

As steel people and hardliners for the flexible barrier systems, we are looking to find solutions on the basis of the safety parameters valid for flexible systems.

It is our aim to find the most adequate barrier combinations for

- Flexible and safe reaction after impact;
- Tolerable displacement of the system on impact;
- Smooth redirection of the vehicle after impact;
- Reduced danger of vaulting the system and crashing into oncoming traffic;
- Easy storage, loading, transportation, installation, repair, and maintenance of the system;
- Either no anchorage on the road or only anchorage at the beginning and end of the system;
- Easy disassembly in case of emergency;
- Easy reapplication after termination of the work zone;
- Easy transfer of the total system by special device in the work zone (e.g., changing from two to three lanes, or vice versa); and
- Reasonable costs.

Results of our first efforts in research and development are the systems Vario-Guard and Mini-Guard. These have been carefully tested by the University of Zurich, Switzerland (Vario-Guard) and the BAST, Federal Research Institute in Germany (Mini-Guard). Experience with our installation in Germany since last year is confirming our enthusiasm for these two systems, which may lead to a new successful era of steel guardrail systems as outstanding safety devices for the protection of people and vehicles in work zones.

J. Test Requirements for Safety Barriers and Light Poles on Australian Roads

By: R. J. Troutbeck, Queensland University of Technology, Brisbane, Australia

The design of safety barrier systems should consider characteristics and mass of the vehicle fleet as well as drivers' behaviors and aspirations. The Australian road network and demographic characteristics are described. Accident characteristics that might affect the full-scale testing requirements for safety barriers and lighting luminaries are discussed; the concerns and requests for new hardware made by the Australian road authorities are outlined.

Australian Road Network

The Australian roadways system and demographic conditions are unique. Australia has a population of about 16 million people and an area of 7.6 million km^2. The overall population density is about 2.1 persons/km^2, which is much less than the densities in other developed countries. Australians are becoming progressively more urbanized; some 62 percent of the population reside in capital cities. The population density of the greater part of the rural areas is less than 0.04 persons/km^2.

Australians are very mobile. Vehicle ownership in Australia is about 42 passenger cars per 100 persons. This value is similar to the value of 50 passenger cars per 100 persons in the United States. The average distance traveled in both countries is about 16,500 km per year.

Australia's road network is about 760,000 km in length, giving a road network density of about 0.1 km/km^2, compared with 0.7 km/km^2 in the United States and 1.5 km/km^2 in the United Kingdom. Table 13 also indicates that the length of road per person in Australia is about double that in the United States and about eight times that in the United Kingdom. In 1975, about 115,000 km of the rural road network was used to provide access to major cities and towns. About 0.3 percent of this rural network had separate carriageways for each direction (i.e., divided roads).

In 1983, there were about 1,086 km of divided rural road and about 1,765 km of divided urban road, with a further 177 km of freeway or motorway. Much of the urban divided road system has an arterial road function with considerable access to and from abutting properties and road. Most of these urban arterial roads cannot be conveniently protected with a median barrier. The divided rural road system and the urban freeway system are high-speed facilities and constitute 0.12 percent of the road network. Hence, the Australian high-speed road system consists predominantly of two-lane rural roads with only short lengths of divided road or freeway.

TABLE 13 DEMOGRAPHIC DETAILS

Country	United Kingdom	United States	Australia
Area (10^3 km^2)	224.0	9,373	7,682
Population (10^6 persons)	56.7	243.2	16.0
Population density (persons/km^2)	233	26	2.1
Road length (10^3 km)	351	6,366	790
Road length per person (m)	6.2	26.2	49.3
Motorway (10^3 km)	3.0	69.2	0.79

Since 1983, there has been a reduction in Australian federal government funding, and even if this funding remains static at 1987-1988 levels, there will still be a reduction in the amount of effort in new road works. Therefore, Australia's road network is not expected to be extended significantly in the foreseeable future. However, continued duplication of rural roads is expected, and a median barrier protection may be required on these roads. It is estimated that between 45 and 150 km per year will be duplicated, depending on road funding policies.

The traffic carried on these divided roads is expected to increase dramatically. In 1981, the 4 percent of the duplicated national highway carried 26 percent of the traffic. This trend is expected to continue, with the divided road system carrying about 9,600 million vehicle-kilometers in 1991. The road system will continue to have more traffic as the number of vehicles on register and the total distance traveled continue to increase.

A consequence of this increased traffic is the growing need to make the road system safer. It also becomes more cost-effective to install safety barriers. The lack of construction of new roads puts even more pressure on the existing system. There will be a continuing and increasing need for improved safety standards both on rural divided and undivided roads. This need will result in more safety barrier protection on the outer verge and on the median for divided roads. The increase in traffic will also require more traffic lanes. Again, this will put pressure on the road safety system and require the use of safety systems that operate in these locations. Some road authorities have been concerned about the reduction in verge widths, which has virtually eliminated the breakdown lanes adjacent to the median on some roads. If an accident occurs, access becomes severely restricted and travel is hazardous.

Australian Vehicle Fleets

The Australian passenger car vehicle fleet has been changing over recent years. The fuel crisis in the 1970s led to increased sales of smaller vehicles. Since then, the mass of the vehicle fleet has been increasing. Australians now prefer to buy larger cars than they did in the 1970s.

The Australian vehicle manufacturers are now producing world cars. These vehicles are essentially the same as others available in Japan, Europe, or America. This world car concept has caused vehicle fleets to be similar in many parts of the world. Figure 14 shows the proportion of new cars with tare masses less than the values indicated. Although data are only available for seven years, they do indicate that there has been a marginal trend to larger vehicles during this time.

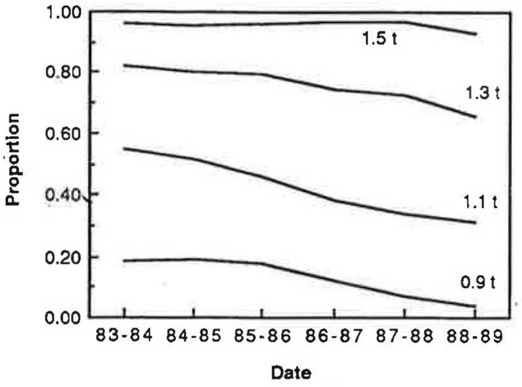


FIGURE 14 Distribution of the tare masses of new passenger cars and station wagons.

Data are not available for the year 1989-1990, but it is expected that these trends would continue. Table 14 presents the approximate median and 85th percentile passenger car vehicle masses. Over the recent 6-year period, the median vehicle mass has increased by 140 kg and the 85th-percentile value by 100 kg. This increase is comparable with the weight of an average occupant. The 95th-percentile value is close to 1.5 tonnes throughout the period. An analysis of the mass of vehicles on register was not able to establish "a significant downsizing effect." This result is contrary to the U.S. scene where there has been significant downsizing.

TABLE 14 VEHICLE MASSES

Year	50th Percentile Tare Mass (t)	85th Percentile Tare Mass (t)
1983-84	1.07	1.34
1984-85	1.09	1.36
1985-86	1.12	1.36
1986-87	1.16	1.39
1987-88	1.18	1.40
1988-89	1.21	1.41

The passenger car vehicle fleet in Australia is similar to that of the subcompact sedan. The smaller (lighter) vehicles may be more frequently involved in overturning accidents. Viner indicates that this increased frequency implies a greater use of safety barriers. Improved guard fence designs may also be required to better redirect these smaller vehicles. The current U.S. barriers performed better with the midsized vehicles.

There were approximately 44,000 heavy vehicles registered in Australia during 1988-1989, and when compared with the 523,000 light vehicles, this number represented less than 8 percent of all vehicles. A subset of heavy vehicles is rigid trucks, which constitute about 3.7 percent of the new vehicle sales. More than 50 percent of the rigid trucks include the 4x4 passenger vehicles. If these vehicles are excluded, then the proportion of rigid trucks in each mass category is shown in Figure 15. The 85th-percentile rigid truck for freight transport weighs about 16 tonnes.

The proportion of articulated vehicles is shown in Figure 16. Almost half of the articulated vehicles were in the over-40-tonne category. Unfortunately, a better breakdown of the figures was not available. In the northwestern part of Australia, large combination vehicles up to 50 m long and with a gross combination mass of 115 tonnes operate. These large combination vehicles have up to three articulated trailers, but although their mass is high they can be redirected reasonably easily. As soon as the prime mover is redirected by a safety barrier, the other units are pulled along or away from the barrier.

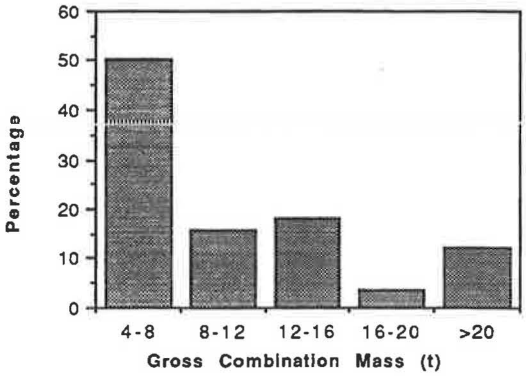


FIGURE 15 Proportion of rigid trucks over 4 tons registered during 1988-1989.

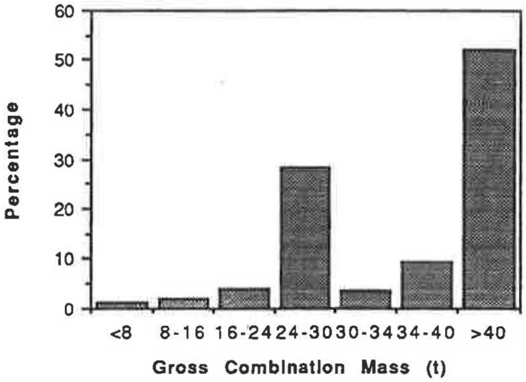


FIGURE 16 Proportion of articulated trucks registered during 1988-1989.

Speeds

Vehicle speeds on Australian rural roads are generally high. The mean speed of cars on rural roads in Victoria was 98 km/hr when the speed limit was 100 km/hr. The 85th-percentile speed was 109 km/hr. On urban roads, the mean speed is less than the statutory speed at the higher legal speeds, but significantly greater than the legal speeds for the lower-speed areas (see Table 15).

The speeds of large combination vehicles are governed to 85 km/hr. In some Australian states, interstate articulated vehicles are governed to 100 km/hr. The mean speeds of singly articulated vehicles were determined to be 89 and 80 km/hr for large combination vehicles on a single-lane bridge. (Traffic in one direction had to give way to traffic approaching from the other direction.) These mean speeds were less than those expected on a two-lane road or bridge. However, the governed speeds would be typical for most heavy vehicles.

Barrier impact speeds can be less than the travel speeds on roads if the verge offers some retardation. Similarly, the impact speeds may be greater than the travel speeds if the verge has an embankment falling down away from the road. It is recommended that the impact speeds should be equal to the traveled speeds.

A design impact speed for urban freeways and for rural roads should be greater than the 85th-percentile speed. Values of 110 or 113 km/hr (70 mph) are suggested.

Accident-Related Data

A recent in-depth study of single-vehicle accidents was conducted in Victoria by Armour, Carter, Cignegrana, and Griffith. A team of investigators collected data from fatal or injury-producing accidents on roads for which the speed limits were greater than 100 km/hr. It was further required that the injuries were severe enough to require hospitalization.

Data were collected concerning the following factors:

- The accident site (road geometry, roadside design, roadside objects, road condition, and delineation);
- The road network that contained the accident site (traffic counts, preceding curve geometry, gradients, and cross sections);
- The vehicle involved in the accident (vehicle defects were noted);
- The drivers involved in the accident (origin-destination information);
- Trip types by other drivers using the road at a similar time and day to those of the accident; and
- The speeds of drivers using the road at a similar time and day to those of the accident.

Using these data, the probable contributing factors were investigated. These factors were those considered to cause the accident and those that increased the severity after the accident process had begun. A further list of possible factors was also identified. The percentage of accidents contributed by a range of factors was listed. Note that there may be more than one probable contributing factor for each accident. Figure 17 shows the percentage of accidents in which the factor was a probable cause and when the factor was a possible cause. Almost two-thirds of the accidents occurred during the day, with only 32 percent at night and 5 percent at dawn or dusk.

TABLE 15 FREE SPEED DATA

		Mean Speed (km/hr)			85 Percentile Speed (km/hr)		
Subgroup	Number of Sample Sites	Cars	Rigid Trucks	Articulated Trucks	Cars	Rigid Trucks	Articulated Trucks
Rural Victoria speed limits: Cars 100 km/hr HCVs 65 km/hr	26	98	78	80	109	88	89
Urban Victoria speed limits: Cars 100 km/hr HCVs 65 km/hr	2	92	73	73	100	82	84
Urban Victoria speed limits: Cars 74 km/hr HCVs 65 km/hr	10	72	59	57	80	68	67
Urban Victoria speed limits: 6 Cars 60 km/hr HCVs 50 km/hr	18	66	59	58	74	66	66
Urban New South Wales speed limits: Cars 100 km/hr HCVs 80 km/hr	4	102	77	80	116	85	92

HCVs = heavy commercial vehicles.

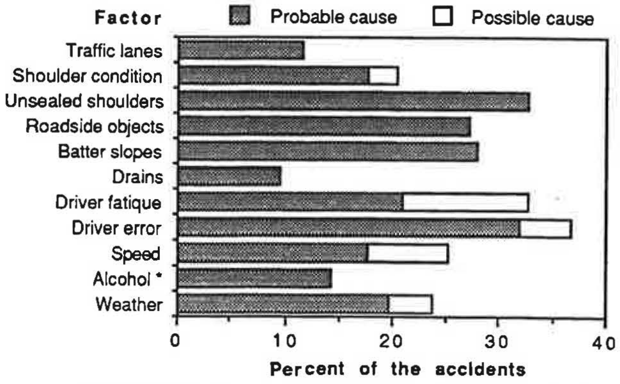


FIGURE 17 Probable and possible contributing factors to high speed vehicle accidents in Victoria, Australia.

It has also been reported that "in 27 percent of cases, roadside objects were considered to have been probable contributing factors to the severity of the accident. Out of 147 accidents, 110 involved a vehicle striking either a fixed roadside object, an embankment, or a cut batter slope. The most common objects struck were trees. In 54 percent of cases, the first object struck was less than 5.0 m from the traffic lane, and 89 percent of objects were less than 10 m from the traffic lane."

These comments reinforce the importance of forgiving roadsides. The high incidence of vehicles colliding with roadside objects is an expected outcome when drivers leave the road, but it indicates that drivers are not regaining control during the incident. The fact that 11 percent of objects were collided with even though they are more than 10 m from the traveled way indicated that clear zones greater than 9 or 10 m are required. There is no evidence of the frequency of other factors that may also contribute to a wider clear zone.

It has also been reported that "the major accident factor related to road design or road conditions was the presence of unsealed shoulders. The most common pattern being that drivers lost control of their vehicles after allowing the vehicle to move onto the left hand shoulder. The poor condition of many shoulders also played a part in many cases. Traffic lane problems played a part in a number of accidents, with the most common problem being a degraded road surface. Low skid resistance was recorded at 35 percent of accident sites."

The overriding factor is the loss of control on either the shoulder or in the traffic lanes. In either case, it can be assumed that many drivers will not be tracking when they hit the object or the barrier. Some accidents have involved the sides of vehicles impacting with guardfence terminals. This aspect of some traffic accidents has been of concern to a number of Australian road authorities.

It is recommended that nontracking, full-scale impacts be used for all types of hardware. These are seen to be more essential for those impacts involving the lighter vehicles.

Road Safety Products and Testing

Most drivers in Australia wear seat belts. It is mandatory that they be used and the observance of the law is high. It is therefore reasonable for the dummies to be restrained by seat belts during full-scale tests.

Australian road authorities have tended to use American safety products in the past. There are some moves now to use techniques from other continents.

The testing of safety devices has typically followed the American standards as in NCHRP Report 230. For example, two series of full-scale tests on lighting standards have been described. In both cases, a 1200-kg vehicle was used, and the impact speeds ranged from 17 to 58 km/hr for frontal impacts and about 35 km/hr for side impacts. Although it was recognized that these were low-energy collisions, the appraisal of the results was examined using the NCHRP Report 230 requirements. Unfortunately, the accelerations were averaged over 50 msec instead of the now-preferred 10-msec period. Nevertheless, the intention has been to conform to the U.S. safety barrier test procedures.

Australia has its own standards for the static testing of light standards. These tests require that both slip-base and impact-absorbent lighting poles must support a lantern with a mass of 20 kg and a projected area of 0.25 m^2. The design wind velocity is 39 m/sec, and the wind drag coefficients are 0.5 for the lanterns and 1.1 for the brackets. Further, the "deflection at the top of the pole when subject to a test load equal to 50 percent of the design load (dead load and wind load) . . . shall not exceed 5.5 percent of the nominal pole height." Refer to the standard specifications developed by Roads Corporation, Victoria.

Some designs that have performed satisfactorily when impact tested have failed these static test standards. It is important to develop suitable loadings for these standards and to apply appropriate dead loads to the lighting pole before dynamic testing. It is obviously not necessary to apply the wind loads when the standard or the pole is subjected to full-scale testing.

Future Requirements

In a discussion of the update of NCHRP, Ross and Michie commented:

"Another changing need is to develop roadside features with a range of performance capabilities and associated test procedures to evaluate the features." This range of performance levels allows the user to evaluate the use of the barrier in a particular location after deciding whether the features of the barrier will meet the requirements of the user and the authority. The multiple performance levels can be used in a benefit-cost analysis. In Australia, a cost-benefit analysis is not detailed for each installation, but rather included in the warrants for a barrier. (The warrants do not indicate when a barrier would offer improved post-impact conditions for a single driver, but rather when it would be cost-effective to install a barrier given the number of road users.) Nevertheless, it would be useful for Australian road authorities to have an indication of suitable substitute configurations.

More effort is required to develop barriers for the lower service level roadways. This effort certainly will be of benefit to Australian road authorities. Australia is a big country with many areas having a very low road density. Low-cost barriers would be of considerable value.

It has been suggested that "state-of-the-possible" criteria "could allow use of structures that vastly improve the safety of the traveling public while not meeting all the requirements of the NCHRP Report 230 or *Transportation Research Circular 191*." This would seem to be very useful and could be further developed using a set of qualitative statements that describes the full-scale test outcome and performance. There is at times a desire to use only quantitative measures. However, these should be augmented using qualitative measures. Tests that just fail could be so documented. Hardware that had a very poor performance should also be identified.

Australian authorities would favor the use of surrogate test vehicles. These have the potential of reducing testing costs at least for initial tests. The FHWA Federal Outdoor Impact Laboratory (FOIL) in McLean, Virginia, looks most promising. A standard and readily constructed generic car, pendulum, or bogie would be the most acceptable. This choice should allow testing from a large number of locations to be combined. Along with a standardized surrogate testing facility, some thought should be given to minimizing the specialized equipment and test facilities required for these tests. Australian authorities do not see that it is necessary to retest hardware used on Australian roads if well-documented tests have been undertaken in the United States, the United Kingdom, or Europe. However, it would be desirable if some standard preliminary testing could be undertaken on a new Australian innovation, if necessary.

There is a growing perceived need for a flexible barrier that would offer greater occupant protection through decreased decelerations. A cable barrier is considered appropriate as it offers the flexibility and is less visually obtrusive. There is concern about the possible excessive loading of cables on the A pillar of a car. There is also a greater possibility of vehicles overturning. Of the collisions with the median barrier of cable type, 3.9 percent were some 60 percent greater in the same year. The median cable barrier is no longer used on new construction. Nevertheless, it would be suitable to use a more flexible barrier with greater deflections on some freeways with moderate-to-light traffic volumes and wide medians.

The Australian passenger car fleet closely resembles the European fleet although our heavy commercial vehicle fleet can be very large. In the northwestern region of Australia, large combination vehicles operate and can impose considerable load on the barriers. Fortunately, these vehicles operate on roads where safety barriers would not normally be required.

On motorway sections of the road system, many Australian authorities are constructing extra lanes in the brake-down lanes. This process can often mean that accidents on the motorway can cause considerable and long-lasting congestion. Authorities are now constructing gates in the median barriers to allow vehicles to bypass an accident site. These gates remain untested. At other sites, relocatable barriers are used in the median. These offer the advantage that emergency openings can be quickly constructed. The Tric-Bloc barrier is an example that has been used in these circumstances.

Conclusion

Australia is a large country with long road lengths per head of population and for each registered vehicle. The protection of all errant vehicles under these conditions is costly. The long distances also affect travel speeds. The 85th-percentile speed on important highways on the eastern seaboard is around 110 km/hr. On other roads in the northwestern areas, speeds can be much higher. There has not been a significant downsizing of the passenger car vehicle fleet; the 85th-percentile mass is currently about 1.4 tonnes. A subcompact vehicle type is considered to be suitable for Australian conditions. The gross combination masses of commercial vehicles are varied. Some vehicles have a gross combination mass of 120 tonnes, whereas the median mass is less than 4 tonnes.

The structural requirements for Australian safety appurtenances have generally been based on the standards set out in NCHRP Report 230. This is historical because the Australian road authorities have based safety barrier requirements on the American practice. There have been few full-scale tests on safety barriers in Australia and those that have been done have generally been of a preliminary nature. Nevertheless, the NCHRP Report 230 testing requirements have been used in, or have been the basis of, the Australian tests.

It is recommended that an update of NCHRP Report 230 include

- Use of multiple performance levels;
- Provision for tests on safety barriers for low-volume roads;
- Use of standardized qualitative and quantitative test standards; and
- Use of surrogate test vehicles, pendulum testing, and bogies, including generic cars or test vehicles.

K. Theoretical Head Impact Velocity Concept

By: I. B. Laker, Road Accident and Road Safety Consultants
A. R. Payne, Motor Industry Research Association England

A method of quantifying the severity of impact is described for occupants in vehicles that are in collisions with roadside barriers. Analysis of the movement of the vehicle can lead to the prediction of occupant trajectory, and the magnitude of impact velocity with the interior of the vehicle.

The concept of assessing occupant injury as a result of vehicle acceleration or velocity change is used as a guideline for acceptable dynamic performance when a vehicle is in collision with a highway roadside safety feature. Accelerations measured at the center of mass lead to the computation of the forward and lateral components of displacement and velocity for an unrestrained front seat occupant.

In a redirection collision, in which, for example, the vehicle strikes a median barrier or parapet at an acute angle and is deflected away, even though vertical movement, pitch, and roll may be small, yaw angles and velocities can be large and occur within the same time interval as the principal linear accelerations. The trajectory of the unrestrained occupant is not a straight line and can follow a complex curve defined by the linear and rotational (yaw) motions of the vehicle. The analysis method proposed calculates the movement of an unrestrained occupant within the passenger compartment. During impact with the barrier, the vehicle rotates in yaw and translates longitudinally and laterally. The occupant maintains his initial path and eventually comes in contact with the interior of the vehicle. The relative impact velocity can be determined and is considered as a measure of vehicle impact severity in terms of occupant risk. The resultant contact velocity has been named the "theoretical head impact velocity" (THIV).

Over the years, the Transport and Road Research Laboratory (TRRL) has accumulated data from a large number of redirection collisions involving cars and trucks as part of the TRRL safety fence and bridge parapet research program. Almost all the cars contained instrumentation to measure longitudinal acceleration, lateral acceleration, and yaw velocity, and also had installed calibrated and instrumented Hybrid II dummies. This data base has been analyzed to correlate vehicle dynamics, barrier characteristics (mainly deflection), and other injury criteria measured in dummies, namely "head injury criteria" (HIC), and the "chest severity index" (CSI).

Typical occupant trajectories are given for car and truck collisions with safety fences and rigid parapets. Relationships between the dummy injury indices HIC, CSI, and THIV values are explained.

The THIV Concept

The THIV value is the velocity at which a freely moving body impacts a surface within the passenger compartment of a vehicle involved in a collision with a roadside safety feature, such as a safety fence or a lighting column. To calculate the relative impact velocity between the occupant and vehicle, assumptions have to be made about the motion both of the occupant and the vehicle.

Occupant Motion

The occupant is assumed to be an unrestrained object that continues on its precollision trajectory and velocity until it impacts the interior of the vehicle. Sliding friction between the occupant and seat or trim is neglected.

Vehicle Motion

The motion of the vehicle is derived, under impact conditions, from the results of accelerometers, arranged to measure the longitudinal and lateral direction of the vehicle's center of gravity. Only the horizontal trajectory of the vehicle is considered, that is, its lateral, longitudinal, and angle of yaw motions. The angles of pitch and roll are not considered.

The remaining information required to calculate the THIV value is the relative location of the occupant relative to the vehicle's center of gravity and the relative distance of the occupant from the front and sides of the passenger compartment. In this analysis the occupant is assumed to move from the position of the center of gravity.

The equations used to describe the relative motion of the vehicle and the occupant are as follows:

1. Accelerations of the vehicle relative to the ground

Forward:

$$\ddot{X}_c = \ddot{x} \cos \theta + \ddot{y} \cos \theta \qquad (1)$$

Lateral:

$$\ddot{Y}_c = \ddot{y} \cos \theta - \ddot{x} \sin \theta \qquad (2)$$

where x and y are the forward and lateral accelerations of the vehicle as measured by accelerometers (x positive forwards, y positive to vehicle left-hand side, and Θ is the angle of yaw (positive clockwise looking from above).

2. Velocity of the vehicle relative to the ground.

$$\dot{X}_c\,(t + \delta t) = \frac{\ddot{X}_c\,(t) + \ddot{X}_c\,(t + \delta t)}{2} \cdot \delta t + \dot{X}_c\,(t)$$
$$\dot{Y}_c\,(t + \delta t) = \frac{\ddot{Y}_c\,(t) + \ddot{Y}_c\,(t + \delta t)}{2} \cdot \delta t + \dot{Y}_c\,(t) \qquad (3)$$

where δt is the time interval for calculation.

Velocity of the body relative to the ground.

$$\dot{X}_B = V_0$$
$$\dot{Y}_B = 0 \qquad (4)$$

where V_0 is the vehicle impact velocity with the barrier.

3. Displacement of the vehicle relative to the impact point.

$$X_c\,(t + \delta t) = \frac{\dot{X}_c\,(t) + \dot{X}_c\,(t + \delta t)}{2} \cdot \delta t + X_c\,(t)$$
$$Y_c\,(t + \delta t) = \frac{\dot{Y}_c\,(t) + \dot{Y}_c\,(t + \delta t)}{2} \cdot \delta t + Y_c\,(t) \qquad (5)$$

Displacement of the body relative to the impact point.

$$X_B = V_0 t + X_o$$
$$Y_B = Y_0 \qquad (6)$$

4. Displacement of the body relative to the car coordinates.

$$x = X \cos \theta - Y \sin \theta$$
$$y = X \sin \theta + Y \cos \theta \qquad (7)$$

where

$$X = X_B - X_C$$
$$Y = Y_B + Y_C \qquad (8)$$

5. Velocity of the body relative to the car.

$$\dot{x} - (\dot{X}_B - \dot{X}_C) \cos \theta + \dot{Y}_C \sin \theta \qquad (9)$$

6. Theoretical head impact velocity (THIV).

$$THIV = (\dot{x}^2 - \dot{y}^2)^{1/2} \qquad (10)$$

The basic nomenclature is described in Figure 18.

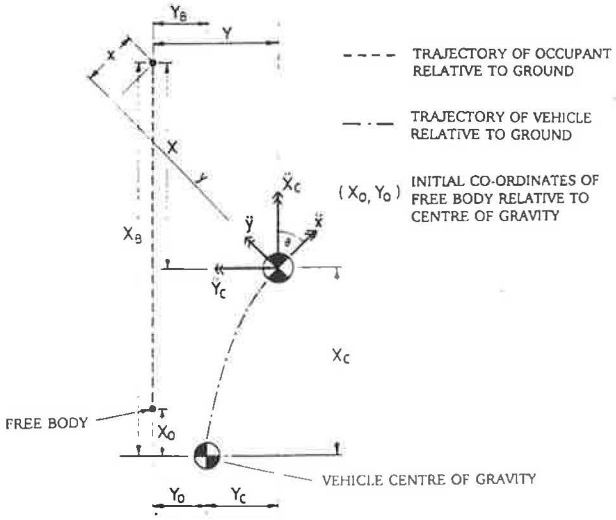


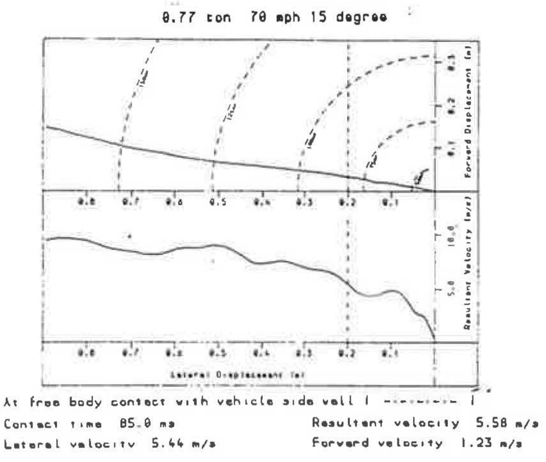
FIGURE 18 THIV diagram showing vehicle and body trajectories relative to ground.

The output from the longitudinal and lateral accelerometers plus the yaw rate transducer first undergo signal conditioning before being filtered and digitized. An analysis of the present signal and signal conditioning is given in Appendix F.

The average acceleration and yaw rate of the vehicle for each time step are calculated. The computation uses time steps of nominally 0.001 sec. The average acceleration and yaw rate of the vehicle for each time step are calculated. The equations of motion are then integrated and the appropriate transformation is made to find the trajectory of the occupant relative to the vehicle as described above.

Having calculated both the relative displacement and velocity trajectories of the occupant, the relative impact velocity of the occupant when the occupant has traveled to the side or front of the passenger compartment is easily found. The resultant velocity at impact is the THIV value.

The results can be presented both in tabulated and graphical form as shown in Figure 19. The graphical format is divided into two parts. The upper part contains the relative displacement of the freely moving head with respect to the center of gravity of the vehicle. This is a plan view with longitudinal (or forward) displacement on the *Y*-axis and lateral displacement on the *X*-axis. The head moves from its rest position at the origin of the forward and lateral displacement axis, and is shown to contact a surface 200 mm to the left of the origin. This may be considered to be the interior surface of a small car. Contact is shown to take place 85 msec after the vehicle impacts the barrier. The head hs moved forward about 40 mm.



```
At free body contact with vehicle side wall |  ---------  |
Contact time  85.0 ms                  Resultant velocity  5.58 m/s
Lateral velocity  5.44 m/s             Forward velocity  1.23 m/s
```

FIGURE 19 THIV program graphical output.

The lower part of the graph contains a plot of the occupant's velocity relative to the vehicle. The intersection of the velocity trajectory with the side of the vehicle gives the occupant contact velocity at 5.58 msec. Other impact values are displayed in the lower part of the graph. The resultant impact velocity, being the THIV value, is taken as a measure of impact severity.

Comparison with other Injury Severity Indices for Collisions with Roadside Barriers

Two other concepts for assessing injury severity of occupants in vehicles involved in collisions with roadside appurtenances are currently in use. The flail space model has been developed and used in the United States, and the acceleration severity index, originally conceived in the United States, is now used in Holland, Germany, and France. These models are compared with THIV in Table 16.

As does the THIV concept, the flail space concept uses the impact velocity of an unrestrained passenger impacting the interior passenger compartment. The flail space method has been extensively reported in NCHRP Report 230. However, the impact velocities in the lateral and longitudinal directions are calculated separately without reference to yaw rotations or resultant velocity. Separate limits of impact velocity are given, 12 m/sec in the longitudinal direction and 9 m/sec in the lateral direction. The nomenclature and terminology used in the flail space concept are shown in Figure 20.

Ray and Carney analyzed the methods associated with the flail space model as given in NCHRP Report 230 and have developed a computer model for coupling the equations of motion and also evaluating the effect of

TABLE 16 COMPARISON OF THE THEORETICAL HEAD IMPACT VELOCITY, FLAIL SPACE, AND ACCELERATION SEVERITY INDEX MODELS

Model/Concept	Input	Severity Parameter	Severity Parameter Limits
Theoretical Head Impact Velocity	Longitudinal and lateral acceleration at vehicle centre of gravity Angle of yaw (from yaw rate)	Resultant impact velocity of occupant relative to the vehicle at impact with the side or front of passenger compartment	Maximum resultant impact velocity To be agreed
Flail Space	Longitudinal and lateral acceleration at vehicle centre of gravity	Impact velocity of occupant with the side of passenger compartment. Impact velocity of occupant with the front of passenger compartment Acceleration level of occupant in lateral direction after impact Acceleration level of occupant in longitudinal direction after impact	Maximum lateral velocity 9 m/s Maximum longitudinal velocity 12 m/s Maximum lateral deceleration 20g Maximum longitudinal deceleration 20g
Acceleration Severity Index	Longitudinal, lateral and vertical acceleration of vehicle	Comparison of acceleration level of the vehicle with maximum G levels allowed for restrained occupant	$ASI=\left(\frac{Gx^{2}}{Gxd}+\frac{Gy^{2}}{Gyd}+\frac{Gz^{2}}{Gzd}\right)^{'}$ Gxd = Longitudinal = 12g Gyd = Lateral = 9g Gzd = Vertical = 10g

deformation in the passenger compartment. After the occupant makes contact with the interior of the vehicle, he is assumed to remain in contact and experience the same acceleration patterns as the vehicle. This acceleration is called "ride down acceleration." The flail space model evaluates the "ride down" acceleration, which is determined separately in the longitudinal and lateral directions from the accelerometer signals. Maximum acceleration limits of 20 gravities are used both for longitudinal and lateral directions.

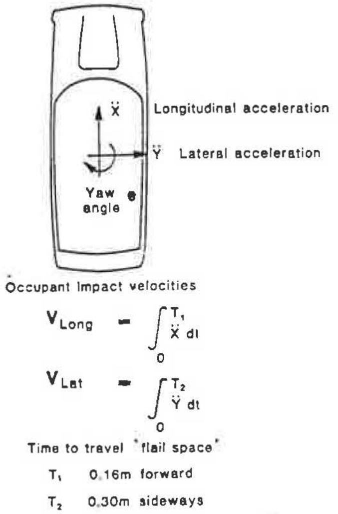


FIGURE 20 Terminology and equations used in the flail space model of NCHRP Report 230.

The THIV model uses the same input parameters as the flail space model with the addition of yaw rotation. This signal filterings used in each model are compared in Appendix F.

The acceleration severity index (ASI) concept was originally derived for applications in space and aero flight. Deceleration to rest was not necessarily considered. This differs both from the THIV and flail space concepts in that it considers both an unrestrained and restrained occupant, the injury being caused by rapid deceleration within the passenger compartment. The ASI value is the root mean square of the signals from accelerometers in longitudinal, lateral, and vertical directions averaged over 0.050-sec intervals taken relative to the given set of maximum acceptable accelerations, as follows:

$$ASI = \left(\frac{G_x^2}{G_xd} + \frac{G_y^2}{G_yd} + \frac{G_z^2}{G_zd}\right)^{1/2} \qquad (11)$$

where

$G_{x}d$ = maximum tolerable longitudinal acceleration,
$G_{y}d$ = maximum tolerable lateral acceleration, and
$G_{z}d$ = maximum tolerable vertical acceleration.

For occupants wearing a seat belt, Germany, Holland, and France use the following limiting values:

$G_{x}d$ = 12 gravities,
$G_{y}d$ = 9 gravities, and
$G_{z}d$ = 10 gravities.

THIV Compared with Other Injury Criteria

The THIV concept has been developed as a criterion for assessing occupant injury in vehicles involved in collisions with roadside barriers or appurtenances. Because most collisions with roadside barriers occur at small angles (0 to 25 degrees), these collisions invariably result in a redirection of the vehicle with lateral acceleration and some angular rotation. This lateral acceleration causes the occupant to initially impact the side, instead of the front, of the passenger compartment. Figure 21 shows the average lateral accelerations during contact produced in cars from full-scale testing of high-containment rigid to flexible barriers against the THIV evaluated for each impact. The lateral accelerations and THIV values are generally higher for smaller cars.

In evaluating vehicle crashworthiness, several injury criteria have been developed using the analysis of output from electronic transducers located inside anthropomorphic test devices (dummies). The HIC and CSI scales are more relevant. In several of the full-scale crash tests on roadside barriers, instrumented test dummies have been installed in the vehicles and the HIC and CSI values have been evaluated. Figure 22 shows these plotted against the THIV evaluated for the same impact tests. A clear correlation is indicated between the THIV values and these injury criteria. This correlation is important, first because it indicates that THIV can be used as a procedure for assessing occupant injury from roadside barrier impacts without the need for using expensive dummies and their associated data recording and analysis systems. Second, the correlation will also assist in determining limiting THIV values from the large amount of data and experience gained from tests on a wide range of safety barriers.

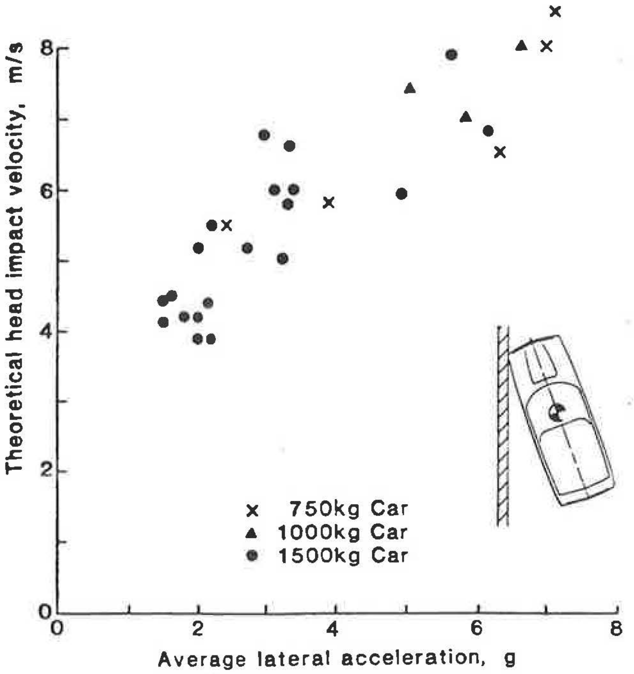


FIGURE 21 THIV versus lateral acceleration for cars impacting with barriers ranging from concrete to flexible steel.

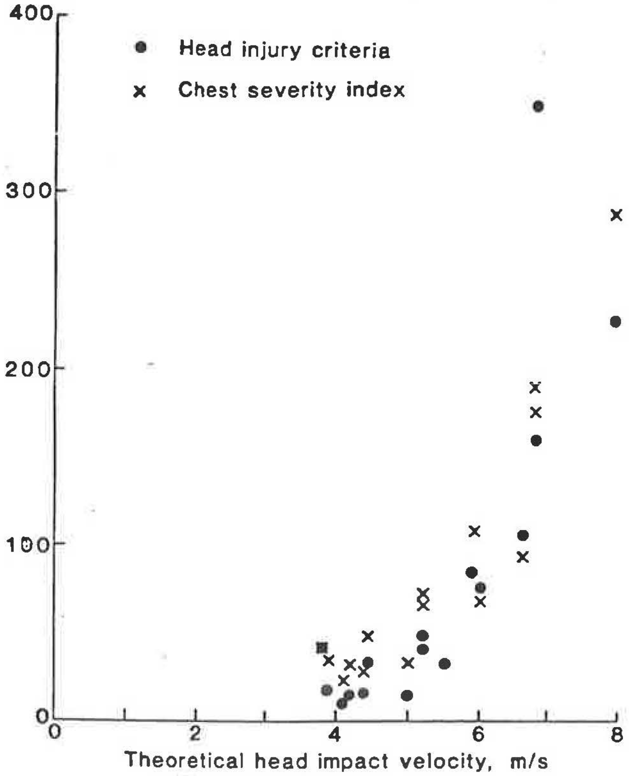


FIGURE 22 Head injury criteria and chest severity index versus THIV for cars impacting with barriers ranging from concrete to flexible steel.

Effects of Vehicle Size

Two major factors that determine THIV values are affected by vehicle size. First, mass and stiffness properties vary with size, affecting the trajectory and velocity of the vehicle after collision with the roadside barrier. Second, internal passenger compartment dimensions will generally increase with the size of the vehicle, altering the occupant position relative to the side and front of the passenger compartment.

In the full-scale roadside barrier testing conducted at Motor Industry Research Association (MIRA), a range of car models was used. For purposes of comparison, the extremes of size are indicated by a small and a large car as shown in Table 17. Both vehicles impacted a rigid barrier at 70 mph at an impact angle of 20 degrees. Figure 23 shows the results of the THIV analysis for both vehicles. The larger car experienced lower deceleration and slower rate of angular rotation. The THIV value is lower at 5.0 m/sec compared to 7.2 m/sec for the smaller car.

THIV analysis has also been conducted for heavier vehicles. Figure 24 shows the THIV results for full-scale crash tests of a 16-ton rigid truck and a 14-ton coach impacting different barriers. The larger and heavier vehicles tend to have lower THIV values (2.8 m/sec both for the truck and the coach). However, care must be taken in evaluating the distance from the occupant to the side of the passenger compartment and in determining whether the occupant will impact the front or side of the passenger compartment first. In these vehicles, the occupants were in the same positions in relation to the passenger compartment. The analysis is capable of calculating a THIV value for any position within the passenger compartment, making it particularly applicable to the different seating positions in coaches and large vehicles.

A large number of full-scale crash tests has been conducted against a variety of different barriers with vehicles of different masses at different speeds and angles. Figure 25 shows the THIV values for cars, 16-ton trucks, and 30-ton trucks impacting rigid barriers.

TABLE 17 RANGE OF VEHICLE PARAMETERS

Vehicle	Mass kg	Nominal Lateral Distance from Occupant to Inside of Passenger Compartment mm
Small car	750	200
Medium/ Large car	1,000-1,500	250
HGV	16,000-38,000	300

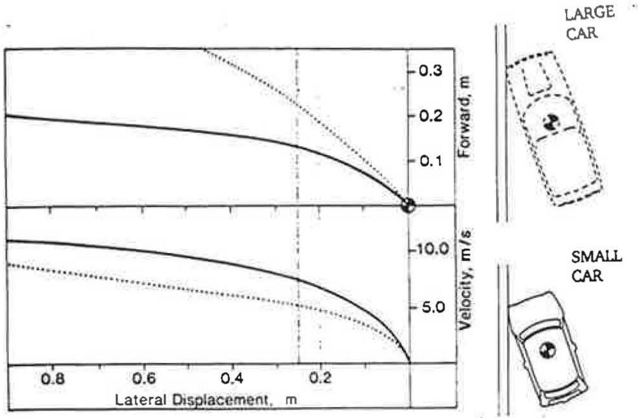


FIGURE 23 Effect of car size on THIV.

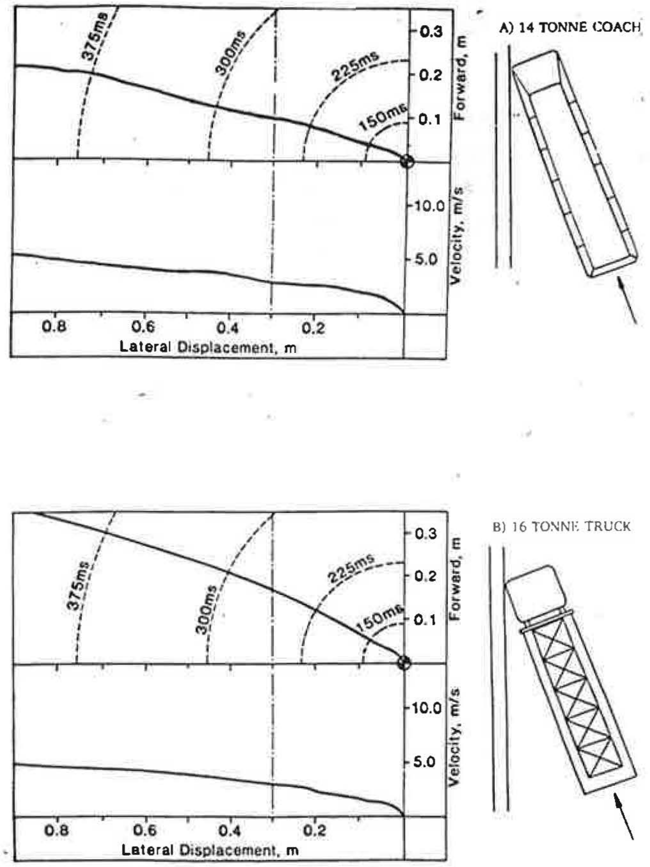


FIGURE 24 Effects of large vehicles on THIV.

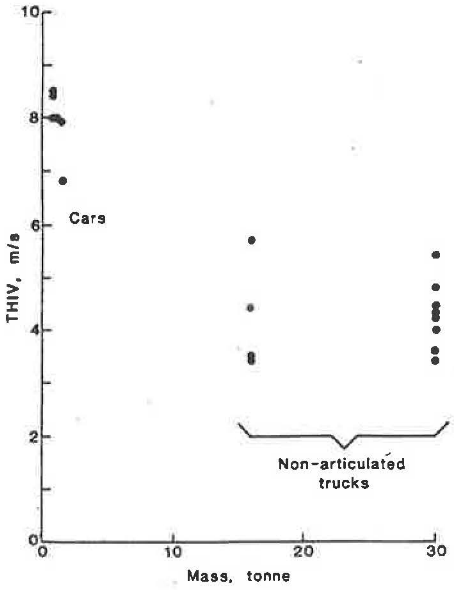


FIGURE 25 THIV versus vehicle mass for vehicles impacting concrete barriers.

Effects of Barrieer Stiffness

Roadside barriers of a variety of stiffnesses have been designed to contain vehicles. With a decrease in barrier stiffness, the vehicle has both a slower rate of deceleration and initially a lower rate of angular rotation. A comparison between rigid and deflecting barriers on THIV is shown in Figure 26. With the deflecting barrier, the THIV is reduced.

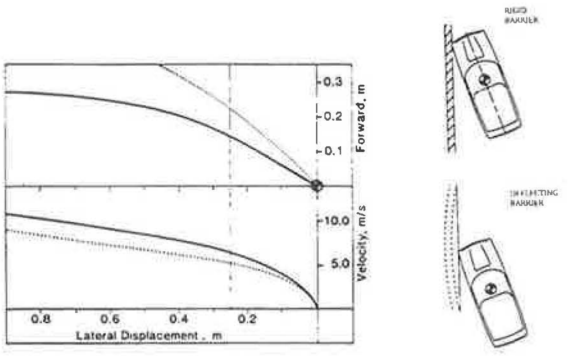


FIGURE 26 Effect of barrier stiffness on THIV.

The effect of increasing barrier deflection can also be seen in Figure 27, which shows head injury versus barrier deflection for a number of full-scale crash tests conducted using large cars against barriers of different stresses. The graph clearly shows a large reduction in the HIC for barrier deflections in the range of 0 to 1 m, with a smaller reduction from 1 to 2 m.

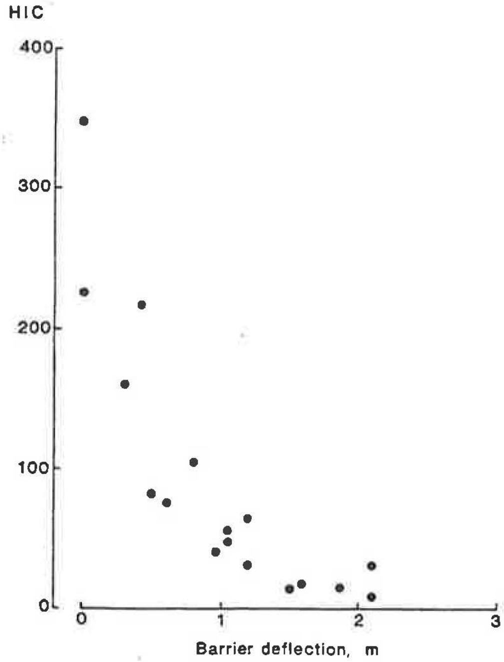


FIGURE 27 Barrier deflection versus HIC of 1500-kg car impacting with barriers ranging from concrete to flexible steel.

Conclusions

The THIV system has been developed to assess impact severity in vehicles involved in collisions with roadside barriers from full-scale impact tests using a minimal amount of instrumentation. Using filtered outputs from longitudinal and lateral accelerometers and a yaw rate sensor located at the vehicle's center of gravity, the trajectory and velocity of the vehicle can be calculated in relation to that of an unrestrained occupant. The resultant differential velocity of the occupant at impact with the interior of the passenger compartment is the THIV.

The trajectory and resultant velocity of the occupant is displayed in a graphical format that allows the occupant to be positioned anywhere within the passenger compartment.

In evaluating the application of THIV as an occupant injury criterion, the THIV values calculated from crash tests have been compared with the HIC and CSI values measured in instrumented dummies. The good resulting correlation not only indicates that THIV can be used for vehicle occupant impact severity, but the dummy measurement also could be used in determining limiting values of THIV when assessing vehicle and barrier performance. A maximum value of 9 m/sec seems appropriate for roadside barriers.

The effects of varying vehicle mass and size and barrier stiffness have also been investigated. A reduction in THIV value was most noticeable with the increase in mass and size from small to medium or large cars.

THIV has been demonstrated to be a relatively simple parameter to evaluate, yet an effective way of assessing occupant injury in collisions with roadside barriers.

PART 3 DISCUSSION TOPICS

The workshop attendees were divided up into the four discussion groups as shown in Table 18.

TABLE 18 DISCUSSION GROUPS

Group 1, Charles F. McDevitt, FHWA, Leader

Al-Lokaidan, Karim	Ministry of Communications	Saudi Arabia
Buth, Eugene	Texas A&M University	United States
Cobb, Lincoln	IBC	United States
Denman, Owen	Energy Absorption	United States
Durkas, John	Syro Steel	United States
Dutta, Piyush	U.S. Army—Cold Regions Lab	United States
Ebersole, George	Energy Absorption	United States
Hatton, James H.	Federal Highway Administration	United States
Janick, Thomas	Allied Tube and Conduit	United States
Lawson, Steve	Birmingham City Council	United States
McDevitt, Charles F.	Federal Highway Administration	United States
Payne, Anthony R.	Motor Industry Resources Assoc.	United Kingdom
Page, Robert A.	New Jersey Department of Transp.	United States
Pfeifer, Brian G.	University of Nebraska—Lincoln	United States
Sandhusen, Henry	Federal Highway Administration	United States
Turbell, Thomas	Vag-och Trafik Institutet	Sweden
Wink, Bernard	Gutte Gemeinachaft Stahlschutzplaken	Germany

Group 2, Ken Opiela, TRB, Leader

Al-Mogbel, Abdulah	Ministry of Communications	Saudi Arabia
Carney, John F.	Vanderbilt University	United States
Carson, Larry	Franklin Steel	United States
Giavotto, Vittorio	Politechnico Di Milano	Italy
Hensing, David J.	American Association of State Highway Transportation Officials	United States
King, Richard E.	Federal Highway Administration	United States
McHale, Gene M.	The Scientex Corporation	United States
Navin, Francis	University of British Columbia	Canada
Ranzo, Alassandro	University of Roma	Italy
Reese, David A.	Syro Steel Company	United States
Ross, Hayes E.	Texas A&M University	United States
Sanderson, Randolph	Transport Canada	Canada
Sillan, Seppo I.	Federal Highway Administration	United States
Stout, Dale	ENSCO, Incorporated	United States
Urlberger, Alexandra	Student	Germany
Urlberger, Karl	SPS-Schutzplanken GmbH	Germany

TABLE 18 *(continued)*

Group 3, Maurice E. Bronstad, DynaTech Engineering, Inc., Leader

Alocco, Vittorio	SINECO Spa	Italy
Anderson, Howard		United States
Bishop, Ralph	California Department of Transp.	United States
Hanna, Howard	Federal Highway Administration	United States
Hinch, John A.	National Highway Traffic Safety Administration	United States
Koch, Jost A.	Swiss Federal Highways Office	Switzerland
La Camera, Francesco	University of Rome	Italy
Lewis, David R.	Syro Steel Company	United States
Linah, Christer	Swedish National Road Administration	Sweden
MacDonald, Malcolm D.	Transportation and Road Research Laboratory	England
Meczkowski, Leonard C.	Federal Highway Administration	United States
Post, Edward R.	University of Nebraska—Lincoln	United States
Quincy, Robert	INRETS	France
Russell, John E.	Jett & Company, Tech, Specialties	United States
Smith, Ashley B.	Smith-Midland Corporation	United States
Strybos, John	Southwest Research Institute	United States
Viner, John C.	Federal Highway Administration	United States

Group 4, Malcolm Ray, Standard & Ray Associates, Leader

Aparicio, Angel C.	Centro de Estudions de Correteras	Spain
Bennett, R. Clarke	Federal Highway Administration	United States
Boozer, John	Shakespeare	United States
Busstra, Jan	Ministry of Transportation and Public Works	Netherlands
Dinitz, Arthur M.	Transpo Industries, Incorporated	United States
Drezenes, Michael	Federal Highway Administration	United States
Faller, Ronald K.	University of Nebraska—Lincoln	United States
Hargrave, Martin W.	Federal Highway Administration	United States
Hunter, William W.	University of North Carolina	United States
Laker, Ivor B.	Road Safety Consultants	England
Laplante, Denis	Quebec Transport Department	Canada
Lasek, Joseph	Federal Highway Administration	United States
Marcil, Paul	Societe Pole Lite Ltee	Canada
Reagan, Jerry A.	Federal Highway Administration	United States
Troutbeck, Rod	Queensland University of Technology	Australia
Wagman, F.	SWOV Institute for Road Safety Research	Netherlands

The principal purpose of the workshop was the identification of issues that might impede international harmonization of testing and evaluation procedures for roadside safety features. The following discussion topics were given to the group leaders to assist in achieving the purpose.

I. Identify critical differences in test and evaluation philosophies, such as

A. Average versus practical worst case;
B. Art-of-the-possible;
C. Protection of the occupant versus protection of innocent bystanders (tanker-trailer, barriers, which may be tested only for containment);
D. Methods of evaluation—crash testing versus, or in concert with, surrogate evaluation for acceptance; and

E. Occupant risk and other pass-fail criteria.

II. Identify specific national conditions that may affect test and evaluation philosophies and procedures.

A. Predominate traffic conditions.

1. Different vehicle sizes and weights—for example, the common use of pickups in the Unites States, or micro-mini's in Europe or Japan;
2. Roadway characteristics;
3. Speed limits; and
4. Frequency of seat belt use.

(Items 1-3 affect the choice of preimpact test conditions, such as type of vehicle, impact speeds, and angles.)

B. Types of devices to evaluate.

1. Longitudinal barriers,
2. Temporary barriers,
3. Work zone appurtenances,
4. Crash cushions, and
5. Sign and luminaire supports.

III. Identifying impediments to a common measurement framework or methods to translate the results for comparison.

A. Use of the metric system.

B. Essential documentation in one report for all potential users.

IV. Suggestions on the next steps needed to increase international harmonization.

PART 4 SUMMARY OF BREAKOUT GROUP DISCUSSIONS

BREAKOUT GROUP 1

By: Charles McDevitt, Federal Highway Administration

Critical Differences in Test and Evaluation Philosophies

There are two different philosophies, testing for the average case, and testing for the practical worst case. A case can be made for using both philosophies and having two specifications. In the United States, the practical worst-case approach is preferred over the typical or average case, to avoid missing problems at either the low or the high end. The average-case approach focuses on the largest number of accidents, to make the greatest improvement in safety. For example, in Germany and Italy, guardrails are designed primarily to provide protection for cars rather than trucks because most of the accidents will involve cars. There was agreement that we should work on those things that have the greatest payoff. However, the continuum goes farther out, so we may want to use truck barriers at some sites. This decision can be worked out in the selection of warranting procedures. We could jointly establish a series of performance levels, but each country would not have to use all of the levels.

From the standpoint of physics, a lot is possible, but it is unaffordable. In the United States, the art of the practical is stressed and benefit-cost analyses are used in the selection procedures.

The United Kingdom uses "strong lawn furniture", such as nonbreakaway poles, to protect pedestrians. The innocent bystander has a right to protection. However, many of the accidents that would involve pedestrians occur at night when pedestrians are not present.

We would like to do the best we can for the truck driver, too, but we may not be able to do it.

Some surrogate test vehicles have been developed, and the use of computer simulation is coming on strongly in some countries, e.g., Holland and Italy. However, crash testing is still considered to be the decisive method for evaluation.

Experience has shown that designs based solely on analysis are not as effective as suggested by the analysis. Computer modeling must be looked at within its bounds. Unpredictable changes in failure modes can occur. Computer models can be used to fill in the gaps.

Surrogate vehicles are desirable, but too complicated. We have been overdoing it to get the perfect vehicle. For example, the cost of the FMVSS deformable barrier is considerably more than the cost of two test cars. We need to use simpler and more rugged vehicles. The surrogate vehicle has merit if we can decide on what vehicle to model. However, it may become obsolete in the future, and it may be too expensive. The surrogate vehicle could be an excellent device at minimal cost for sign posts and poles, but will be too expensive for guardrails.

Containment and smooth redirection of the vehicle should be acceptable. However, we should have a qualitative evaluation of the pass or fail criteria in order to get a "level playing field." It is almost impossible to meet the lateral occupant velocity in NCHRP Report 230. Otherwise, in general, the limits of the evaluation criteria are so high now that it is not worth spending time to measure them. Exit trajectory is more critical.

Passenger airbags are not at all compatible with the flail space evaluation criteria. It takes a speed change of 10 mph (7.5 mph in the United States) in an impact with a rigid concrete barrier to activate the airbag. There have been cases where the airbag has deployed with disastrous results after the passenger has impacted the dashboard. The problem of compatibility of the flail space model with airbags should be addressed in the NCHRP Report 230 update study.

The United States is moving towards tests with 40-ton articulated vehicles. However, a 30-ton single-unit truck may be more critical because it will produce a greater impact force.

Specific National Conditions That May Affect Test and Evaluation Philosophies and Procedures

There is considerable disparity in the vehicle fleets (Australia is unique). However, there may be less disparity in the safety devices that are needed to handle these vehicles. At present, the smallest car in the United Kingdom weighs 750 kg. The cars in the United Kingdom are getting heavier. This trend has also been observed in the United States. If we could settle on an average weight of car, it may cover more countries than expected.

Pickup trucks are used as test vehicles in the United States. However, vans up to 1.5 tons are becoming common in Europe. Instead of looking at vehicle sizes, we should look at vehicle kinetic energy. The vehicle crush characteristics and geometrics would also have to be considered. It may be possible to show analytically that some tests are more critical than others from an acceptance standpoint.

In general, roadway characteristics are not an impediment to harmonization of testing and evaluation procedures. Hard shoulders are commonly used on roadways in Europe. Roadway characteristics are defined by the road design standards. The Autobahn and other new roads in Germany are designed to meet strict standards that take into account the German cars, traffic, and speed limits. Other roads are upgraded to these standards. To date, only 10 to 15 crash cushion units have been installed in Germany.

There was no discussion of in-service evaluation of safety devices.

Speed limits are the greatest source of lack of commonality. Speeds of 60 to 70 mph are common in Europe. Germany will ask for a speed greater than 120 km/hr (73 mph) as the impact test speed. This will affect the CEN talks. However, it is expected that a common speed will be established in Europe. Because speed limits may have some influence on performance levels and severity levels, if a standard speed is established in Europe, it may lead to a change in the test speed used in the United States.

Seat belt usage is mandatory in Germany and many other countries. At first, it would seem that mandatory seat belt usage would be a prerequisite to harmonization, but that is not the case. Seat belt usage is 90 percent in Europe, but 50 percent of the people involved in accidents are not wearing their seat belts. Tests could be conducted with unrestrained occupants. Then any actual usage of seat belts would only increase safety.

There were no problems with the list of devices that should be evaluated, i.e., longitudinal barriers, temporary barriers, work zone appurtenances, crash cushions, and sign and luminaire supports. Transitions from flexible barriers to rigid barriers should be added to the list. There is some merit in testing all of these devices. However, the degree of testing should differ in order to get the most return for the money spent on testing. Only those products that are still on the market after testing procedures have been established should be tested. Barriers should be separated into temporary and permanent types. The design objectives will have to be defined, i.e., decisions will have to be made on which devices are meant to contain vehicles, and which are meant to redirect them. For example, the issue of gating versus nongating crash cushions and terminals will have to be addressed in Europe. The performance levels or severity levels that these devices should meet will have to be considered. In the CEN talks, Germany will propose that the criteria for crash cushions be different than for other types of barriers. At this time, only longitudinal barriers and crash cushions will be covered by CEN, TC 226, Working Group 1. All of these devices should be addressed by that group.

Impediments to a Common Measurement Framework or Methods To Translate the Results for Comparison

Only the United States needs to change to the metric system. No legislation is necessary, only leadership. It should be a "hard" conversion rather than a "soft" conversion.

It is possible to have a complete listing of all evaluation criteria in each test report. The test report could also contain the raw data. SAE J211B is universally used for filtering data. Several different injury scales have been used to code injuries in accident reports. We should stick to one scale. A test document that everyone uses as a standard can only be developed after additional discussions are held on the subject. We will not satisfy everybody. However, we should be able to standardize the minimum amount needed to be included in test documents.

Steps Needed To Increase Harmonization

It was found that there is quite a lot of commonality, but the amount hasn't been adequately discussed. CEN should be made aware of the work in progress in the United States. A committee should be proposed to provide a link between CEN and TRB. Meetings could be scheduled and developed, but someone has to take the lead.

Some research needs were also identified. There is a lack of field data on what we need to protect people from, e.g., trees and gore areas. There is also a lack of accident data on central reserves (medians) without guardrails or median barriers. This accident data is needed to develop warrants for median barriers.

BREAKOUT GROUP 2

By: Ken Opiela, Transportation Research Board

My report will be somewhat briefer because a lot of the items McDevitt discussed were discussed in our group and very similar conclusions were reached. I will try to highlight differences and bring out a couple additional points on international harmonization. Breakout Group 2 included representatives of Canada, Germany, Italy, and the United States. These representatives had associations with public agencies, manufacturing firms, and universities.

There was considerable discussion on the issue of test and evaluation philosophies. Persuasive arguments for the average versus practical worst case were made, but the group did not come to a meeting of the minds on this particular subject. They recognized that this might become a point that would limit acceptance of common standards in countries around the world. The features for the worst case were also noted. It was suggested that as more knowledge is compiled about the differences in the crash performance between individual vehicles, it may become possible to better understand the implications of setting standards on an average versus worst-case vehicle. Better knowledge of safety performance of vehicles of varying size and weight could also help identify other critical points of limits.

In discussing the art-of-the-possible issue, it was noted that the European representatives favored the way this particular aspect was approached in the United States. These representatives didn't see a problem in adopting similar practices in Europe. The group clearly agreed that warrants that differentiate the protection of the occupants versus protection of innocent bystanders were the prerogative of each agency. They were in agreement with Ross's contention that such warranting conditions were not something that needed to be addressed in testing procedures.

The group discussed the issues of crash testing using simulation, surrogates, and other methods. There was general agreement among the representatives of the various countries that crash testing is still the best approach to determining the crashworthiness of a highway safety feature. Other methods may define a niche in the crash testing process over time as knowledge is accumulated. There was agreement that crash testing should remain the primary means to determine safety and, obviously, this indicates an opportunity for international harmonization.

On the issue of occupant risk and other pass-fail criteria, there was a very strong case made that one of the greatest opportunities to harmonize is in the area of the occupant risk model. It was proposed that the model described by the representative from the United Kingdom be adopted because it makes it possible to get a quantitative measure of risk to the occupant. Ross pointed out that, there is a strong interest in adopting such a model in the update to NCHRP Report 230 to provide a better means to correlate results.

The group did not take time to explicitly discuss the items under Element II because these issues had been raised as part of the preceding and following discussions. It was recognized that there will be significant differences in the vehicle fleets, roadway characteristics, and traffic speeds that will exist in the future. These differences will pose difficulties in coming up with a common evaluation or acceptance criteria, but certainly the opportunity exists for harmonization on testing procedures.

The breakout group briefly discussed impediments to common measurement framework or methods to translate the results for comparison. These issues were not viewed as an impediment to harmonization at this time because the decision has been made that the update to NCHRP Report 230 will be done in metric. There may remain points of difference, however, that will result from decisions on soft versus hard conversion of the various conversions from the U.S. measures to metric. These differences were not viewed as major impediments to harmonization. There was general agreement on the essential documentation of the process; it was concluded that there were no serious impediments to harmonization relative to measurement framework or documentation, because of general agreement on the use of metrics, SAE J211 for instrumentation, and other common aspects. It was noted that it would be useful if effort could be devoted towards some future standards for establishing the true center of gravity of a vehicle so that test results could be translated more definitely.

Last, under Item IV, suggestions to improve steps to improve harmonization, it was pointed out that there was an interest among representatives in this country to participate as observers or resource persons in the activities that are going on currently in Europe. Such participation is viewed as a primary means to foster interaction with experts in this field around the world to promote harmonization. The United States has indicated the willingness to consider the comments of the European community on the update to Report 30 in an effort to foster harmonization. Because similar efforts are being initiated in Europe, this would appear to be an excellent opportunity for them to reciprocate in the interest of harmonization. The group strongly encouraged more sanctioned involvement in European activities.

The issue of whether there was need to do more translating of documents was considered. In theory, it is viewed as potentially a useful thing to do, even though the representatives of the breakout group all speak and write English. It was suggested that there may be opportunities for manufacturers to do some networking with manufacturers in Europe and other parts of the world and develop some interactions that may be helpful to harmonization over the long term.

BREAKOUT GROUP 3

By: Maurice E. Bronstad, DynaTech Engineering, Inc.

My report will be somewhat briefer because many of the items McDevitt reported were also discussed in our group and very similar conclusions were reached. I will try to highlight differences and bring out a couple of additional points on international harmonization. Breakout Group 3 included representatives of Canada, Germany, Italy, and the United States. These representatives had associations with public agencies, manufacturing firms, and universities.

There was considerable discussion on the issue of test and evaluation philosophies. Persuasive arguments for the average versus practical worst case were made, but the group did not come to a meeting of the minds on this particular subject. They recognized that this might become a point that could limit acceptance of common standards in countries around the world. The difficulty in agreeing on an average vehicle in an ever-changing market was noted. The reality of not being able to provide safety features for the worst case was also noted. It was suggested that when more knowledge is compiled about the differences in the crash performance between individual vehicles, it may become possible to better understand the implications of setting standards on an average versus worst-case vehicle. Better knowledge of safety performance of vehicles of varying size and weight could also help identify other critical points or limits.

In discussing the art-of-the-possible issue, it was noted that the European representatives favored the way this particular aspect was approached in the United States. These representatives didn't see a problem in adopting similar practices in Europe. The group clearly agreed that warrants which differentiate the protection of the occupants versus protection of innocent bystanders were the prerogative of each agency. They were in agreement with Ross's contention that such warranting conditions were not something that needed to be addressed in testing procedures.

The group discussed the issues of crash testing using simulation, surrogates, and other methods. There was general agreement among the representatives of the various countries that crash testing is still the best approach to determining the crashworthiness of a highway safety feature. Other methods may find a niche in the crash testing process over time as knowledge is accumulated. There was agreement that crash testing should remain the primary means to determine safety and, obviously, this indicates an opportunity for international harmonization.

On the issues of occupant risk and other pass-fail criteria, a strong case was made that one of the greatest opportunities to harmonize is in the area of the occupant risk model. It was proposed that the model described by the representative from the United Kingdom be adopted because it makes it possible to get a quantitative measure of risk to the occupant. Ross pointed out that there is a strong interest in adopting such a model in the update to NCHRP Report 230 to provide a better means to correlate results.

The group did not take time to explicitly discuss the items under Element II because these issues had been raised as part of the preceding and following discussions. It was recognized that there will be significant differences in the vehicle fleets, roadway characteristics, and traffic speeds and that these will exist in the future. These differences will pose difficulties in coming up with a common evaluation or acceptance criteria, but certainly the opportunity exists for harmonization on testing procedures.

The breakout group briefly discussed impediments to common measurement framework or methods to translate the results for comparison. This was not viewed as an impediment to harmonization at this time because the decision has been made that the update to NCHRP Report 230 will be done in metric. There may remain points of difference, however, that will result from decisions on soft versus hard conversion of the various conversions from the U.S. measures to metric. These differences were not viewed as major impediments to harmonization. There was general agreement on the essential documentation of the process; and it was concluded that there were no serious impediments to harmonization relative to measurement framework or documentation, because of general agreement on the use of metrics, SAE J211 for instrumentation, and other common aspects. It was noted that it would be useful if effort could be devoted toward some future standards for establishing the true center of gravity of a vehicle so that test results could be translated more definitely.

Last, under Item IV, suggestions to improve steps to improve harmonization, it was pointed out that there was an interest among representatives in this country to participate as observers or resource persons in the activities that are going on currently in Europe. Such participation is viewed as a primary means to foster interaction with experts in this field around the world to promote harmonization. The United States has indicated the willingness to consider the comments of the European community on the update to Report 30 in an effort to foster harmonization. Because similar efforts are being initiated in Europe, this would appear to be an excellent opportunity for them to reciprocate in the interest of harmonization. The group strongly encouraged more sanctioned involvement in European activities.

The issue of whether there was need to do more translating of documents was considered. In theory, it is viewed as potentially a useful thing to do, even though the representatives of the breakout group all speak and write English. It was suggested that there may be opportunities for manufacturers to do some networking with manufacturers in Europe and other parts of the world and develop some interactions that may be helpful to harmonization over the long term.

BREAKOUT GROUP 4

By: Malcolm H. Ray, Standard and Ray, Inc.

There are two different views of harmonization: one view emphasizes the standardization of performance, the other communication. Standardizing testing and evaluation criteria for roadside hardware is probably not achievable among so many different national groups, each with its own unique problems, history, and philosophy. Harmonizing communication is both less ambitious and more achievable. Harmonization should specify a language for discourse rather than mandate what is said.

Identify Critical Differences in Test and Evaluation Philosophies

One basic philosophical issue that affects harmonizing test and evaluation criteria is whether roadside hardware should be designed for the average or reasonable worst-case collision conditions. From an engineering point of view, designs are usually intended to be effective for the reasonable worst case. Design codes for buildings and bridges would not be retained if, on average, most buildings did not collapse! Unfortunately, it is not as easy to apply this philosophy to roadside design. Hardware should be tested to a severity level that is high enough to be demanding while still being observable in the field. If a crash cushion is intended to dissipate energy, a high, though reasonable level of kinetic energy should be used in testing the performance of the device. In the United States, the reasonable worst case for occupant injury is thought to involve smaller vehicles. Typical test conditions in the United States, then, involve a large car to test at a high level of energy and a small car to test occupant responses. There is support in some European circles for using average-weight vehicles at average conditions. There is even some thought of using energy or rather "lateral" kinetic energy instead of specifying specific impact conditions. By definition, these approaches do not address the 50 percent of collisions above the average impact conditions. There are situations, though, when it does make sense to use an average approach. Failure scenarios that are vehicle dependent should be checked using vehicles that are common in the fleet. If cars with only the smallest tire sizes and largest tire sizes are tested, designs may be produced that cause the wheels of midsized cars to be trapped under the beam of a guardrail. Rather than rigidly advocating average or worst-case scenarios, tests should be designed to maximize reasonable opportunities for failures.

There are technological limits to how well different types of hardware can perform. Head-on, high-speed collisions result in very demanding impact loads for crash cushions. Evaluation criteria in NCHRP Report 230 recognize this by recommending higher occupant response parameters than, for example, luminaire supports. It is technologically possible to design luminaire supports that result in much lower occupant responses, so these are recommended. Because better occupant response is possible for luminaires, criteria have come to demand better performance for this type of device than, for example, crash cushions. In the United States, then, the art-of-the-possible has been implemented by using more demanding evaluation criteria for some types of hardware than is used for other types. The objective of placing hardware along the roadside is to reduce the harm and trauma to occupants of vehicles. This objective, however, is always constrained by cost. The interstate system in the United States is built with a high priority on safety. This level of safety, in principal, is achievable on all roads. The resources required to this degree of safety on the off-interstate system is too great; the art-of-the-possible is therefore constrained by economics. This situation has created a need for multiple performance levels that take into account the economic costs and benefits of safety improvements of roadways. In principal, there is a point of diminishing return where further improvements cost more than the resulting safety benefit. It seems unlikely, however, that much roadside hardware has reached this point of diminishing return.

Identify Specific National Conditions That May Affect Test and Evaluation Philosophies and Procedures

No one set of test conditions and evaluation criteria will be ideal for all nations. The vehicle populations of Europe and North America are, for instance, very different; Australian trucks are far larger and travel at higher speeds than trucks in either North America or Europe; cars on high-speed European highways travel much faster than those on interstates in the United States. Clearly, then, there are significant differences in the characteristics of traffic among nations; the practical worst cases desirable for testing can vary significantly from nation to nation.

One approach to finding common conditions might be to focus on ranges that are meaningful internationally. For example, the mean, maximum, and minimum weight of passenger cars varies significantly between countries. There is probably a range of weights, however, that represents a large proportion of all vehicles in most industrialized countries. According to information presented in the workshop, the average passenger car weight in Europe varies from as little as 1,850 lb in Portugal to as much as 3,070 lb in Sweden. It would clearly the difficult to select one European car that represents either an average or reasonable worst-case vehicle. On the other hand, however, the most popular selling car in Europe was shown to be VW Golf with a weight of about 2,150 lb. This car is essentially the same that is sold in North America as the VW Rabbit. This vehicle, which is already widely used in crash testing, is a meaningful selection in both Europe and the United States. In the United States, it is usually used to represent the lower-weight vehicles, whereas in Europe it represents the average vehicle. Vehicles that are representative of important segments of the vehicle population worldwide could probably be identified. This problem of selecting meaningful vehicles is likely to become less difficult as automobile manufacturers continue to market their vehicles worldwide.

Identify Impediments to a Common Measurement Framework or Methods to Translate the Results for Comparison

There are numerous steps that cold be taken that wold facilitate the exchange of information between researchers, policy makers, and practitioners in roadside safety. Reporting test results in the metric system would make the results of crash tests more accessible to researchers throughout the world. Other steps like establishing the types of information that should be gathered would likewise make research more accessible internationally. Identifying the type of information that should be obtained, however, is difficult because it is closely related to the choice of evaluation parameters. Using an evaluation criteria based on hypothetical occupants (like the flail space or THIV models) implies processing data one way, while using the ASI implies a somewhat different processing procedure. Ultimately though, all evaluation criteria are related to the velocity and acceleration of the vehicle. Providing the acceleration data gathered during a test in some standard format would be a useful step in harmonization because then other researchers could use the data to generate any evaluation parameter of interest. While agreeing on common data formats and measurement units does not address many of the most difficult aspects of harmonization, it does help encourage the exchange of information. Perhaps the sharing of information will of itself assist the process of finding a consensus on more fundamental issues relating to evaluation parameters and test criteria.

Clearly harmonization between any two groups is a formidable task. The revision of NCHRP Report 230 will greatly affect the development of roadside hardware in North America well into the next century. The development of the European-wide CEN standards, a harmonization effort in themselves, will likewise have a long-lasting affect on the development and use of roadside hardware in Europe. These two independent activities present a unique opportunity for international harmonization that would enhance roadside safety worldwide and make the most effective use of roadside research resources.

PART 5 WORKSHOP SUMMARIES AND FINDINGS

The afternoon was devoted to workshop groups on several issues related to international harmonization of test and evaluation procedures. On Monday evening the workshop group chairmen presented their summaries as part of the evening meeting of the Subcommittee A2A04(2) on International Research Activities. Each workshop group addressed as a minimum, four basic topics:

- Critical differences in test and evaluation philosophies,
- Impediments to a common measurement framework or methods to translate the results for comparison,
- Specific national conditions that may affect test and evaluation philosophies and procedures, and
- Steps needed to increase harmonization.

The objective of the Workshops was to provide an informal forum to discuss these issues and share individual experiences, knowledge, and observations as directed toward specific issues.

Workshop Findings

The following discussion presents the more significant findings and observations that were generated by the workshop groups. They are categorized according to Workshop Discussion Topics (Part 3). The reports in Part 4 present the summaries by the workshop group leaders and as can be seen there is considerable overlap in findings.

Critical Differences in Test and Evaluation Philosophies

There are two different philosophies, testing for the average case, and testing for the practical worst case. In the United States, the practical worst-case approach is preferred over the typical or average case, to avoid missing problems at either the low or high end. The average-case approach focuses on the largest number of accidents in an effort to make the greatest improvements in safety.

Some Europeans measure quantitatively the passenger compartment deformation in evaluating crash test results. In the United States, there is a passenger compartment intrusion criterion, but it is not quantified, so it is a judgment call.

The United States is moving toward testing with a 40-ton vehicle. However, a 30-ton single-unit truck may be more critical because it will produce a greater impact force.

Impediments to a Common Measurement Framework or Methods to Translate the Results for Comparison

The United States use of English measurement system in their procedures, while the other nation's procedures are in metric, is not expected to be an impediment because the updated United States procedures will be in metric.

Specific National Conditions That May Affect Test and Evaluation Philosophies and Procedures

Although there is considerable disparity in the vehicle fleets, traffic and road conditions, there may be less disparity in the safety devices that are needed to handle these vehicles. It was stated that although you might not be able to pick a particular condition, a range of conditions that are probably representative of conditions internationally.

Pickup trucks (small open trucks) are used as test vehicles in the United States, however, up to 1.5 tons are becoming common in Europe.

Differences in speed limits are the greatest source of lack of commonality. Speeds of 60 to 70 mph are common in Europe. Germany is expected to recommend a crash test impact speed of 120 km/hr (73 mph).

Steps Needed to Increase Harmonization

In a general sense there is substantial harmonization in existence. There is general agreement that crash testing is the primary and decisive method of evaluating barriers.

More involvement among observers in activities in developing test and evaluation procedures so interaction can take place and harmonization may be promoted.

The most likely harmonization of evaluation and crash test criteria should be in procedures and reporting. It seems that if there is one thing that should be done, it is to agree on the information that ought to be reported in crash test results. If all information from crash test results would be available in a usable and accurately translatable format, it would go a long way in promoting harmonization. However, a test document that everyone uses as a standard can only be developed after additional discussions are held on the subject.

APPENDIX A WORKSHOP ATTENDEES

Al-Lokaidan, Abdul Karim, Ministry of Communications, Saudi Arabia
Al-Mogbel, Aboullah, Ministry of Communications, Saudi Arabia
Alocco, Vittorio, SINECO Spa, Italy
Anderson, Howard L., U.S.A
Aparicio, Angel C., CEDEX, Spain

Bennett, R. Clarke, Federal Highway Administration, U.S.A.
Bishop, Ralph William, California Department of Transportation, U.S.A
Boozer, John F., Shakespeare, U.S.A.
Bronstad, Maurice E., Dynatech Engineering, Incorporated, U.S.A.
Busstra, Jan T., Ministry of Transportation and Public Works, Netherlands
Buth, Eugene, Texas A&M University, U.S.A.

Carlson, E. D., Federal Highway Administration, U.S.A.
Carney, John F. III, Vanderbilt University, U.S.A.
Carson, Larry, Franklin Steel Company, U.S.A.
Cobb, Lincoln, IBC, U.S.A.

Denman, Owen S., Energy Absorption Systems, Incorporated, U.S.A.
Dinitz, Arthur M., Transpo Industries, Incorporated, U.S.A.
Durkos, John C., Syro Steel Company, U.S.A.
Dutta, Piyush K., U.S. Army Corps Engineers, U.S.A.

Ebersole, George D., Energy Absorption S&S, U.S.A.

Faller, Ronald K., University of Nebraska—Lincoln, U.S.A.

Giavotto, Vittorio, Politechnico Di Milano, Italy

Hanna, Howard C., Federal Highway Administration, U.S.A.
Hargrave, Martin W., Federal Highway Administration, U.S.A.
Hatton, James H. Jr., Federal Highway Administration, U.S.A.
Hensing, David J., American Association of State Highway and Transportation Officials, U.S.A.
Hinch, John A., National Highway Traffic Safety Administration, U.S.A.
Hunter, William W., University of North Carolina, U.S.A.

Janick, Thomas R., Allied Tube and Conduit, U.S.A.
Judycki, Dennis C., Federal Highway Administration, U.S.A.

King, Richard E., Federal Highway Administration, U.S.A.
Koch, Jost A., Swiss Federal Highways Office, Switzerland

La Camera, Francesco, University of Roma, Italy
Laker, Ivor B., Road Safety Consultants, England
Laplante, Denis, Quebec Transport Department, Canada
Lasek, Joseph J., Federal Highway Administration, U.S.A.
Lawson, Steve D., Birmingham City Council, England
Lewis, David R., Syro Steel Company, U.S.A.
Linah, Christer, Swedish National Road Administration, Sweden

MacDonald, Malcolm D., Transportation and Road Research Laboratory, England
Marcil, Paul, Societe Pole Lite Ltee, Canada
McDevitt, Charles F., Federal Highway Administration, U.S.A.
McHale, Gene M., The Scientex Corporation, U.S.A.
Meczkowski, Leonard C., Federal Highway Administration, U.S.A.

Navin, Francis P., University of British Columbia, Canada

Opiela, Ken, Transportation Research Board, U.S.A.

Payne, Anthony R., Motor Industry Research Association, England
Pege, Robert A., New Jersey Department of Transportation, U.S.A.
Pfeifer, Brian G., University of Nebraska—Lincoln, U.S.A.
Post, Edward R., University of Nebraska—Lincoln, U.S.A.
Preznes, Michael G., Energy Absorption Systems, U.S.A.

Quincy, Robert, INRETS, France

Ranzo, Alessandro, University of Rome, Italy
Ray, Malcolm H., Standard and Ray Associates, U.S.A.
Reagan, Jerry A., Federal Highway Administration, U.S.A.
Reese, David A., Syro Steel Company, U.S.A.
Ross, Hayes E., Texas A&M University, U.S.A.
Russell, John E. Sr., Jett and Company, Technology Specialties, U.S.A.

Sanderson, Randolph W., Transport Canada, Canada
Sandhusen, Henry W., Federal Highway Administration, U.S.A.
Sillan, Seppo, I., Federal Highway Administration, U.S.A.
Smith, Ashley B., Smith-Midland Corporation, U.S.A.
Stout, Dale, ENSCO, Inc., U.S.A.
Strybos, John W., Southwest Research Institute, U.S.A.
Symmes, Donald G., Federal Highway Administration, U.S.A.

Taylor, Harry W., Federal Highway Administration, U.S.A.
Troutbeck, Rod J., Queensland University of Technology, Australia
Turbell, Thomas, Vag-och Trafik Institutet, Sweden

Urlberger, Alexandra, Student, Germany
Urlberger, Karl A., SPS-Schutzplanken GmbH, Germany

Viner, John C., Federal Highway Administration, U.S.A.

Wegman, F. C. M., SWOV Institute for Road Safety Research, Netherlands
Wink, Bernard W., Guete Gemeinschaft S. Planken, Germany

APPENDIX B 1985 AASHTO STANDARD SPECIFICATIONS FOR STRUCTURAL SUPPORTS FOR HIGHWAY SIGNS, LUMINAIRES AND TRAFFIC SIGNALS, SECTION 7—BREAKAWAY SUPPORTS

SECTION 7 — BREAKAWAY SUPPORTS

1.7.1 — USAGE

Breakaway supports are designed to yield when struck by a vehicle, thereby minimizing injury to the occupants of the vehicle and damage to the vehicle itself. All new roadside signs and luminaires on high speed highways located within the suggested clear zone width given in the AASHTO "Guide for Selecting, Locating, and Designing Traffic Barriers," shall be placed on breakaway supports, unless they are located behind a barrier or crash cushion which is necessary for other reasons. Supports outside this suggested clear zone should preferably be breakaway where there is a probability of being struck by errant vehicles.

1.7.2 — DESIGN

Breakaway supports should be designed to carry loads as provided in Section 2. Dynamic performance under automobile impact must also be considered. This is best accomplished by full-scale dynamic testing, sometimes coupled with model studies or computer simulations. Satisfactory dynamic performance is indicated when the maximum change in velocity for a standard 1800-pound (816.5 kg) vehicle, or its equivalent, striking a breakaway support at speeds from 20 mph to 60 mph (29.33 fps to 88 fps) (32 kmph to 97 kmph) does not exceed 15 fps (4.57 mps), but preferably does not exceed 10 fps (3.05 mps) or less.

All breakaway supports in multiple support sign structures shall be considered as acting together to cause a change in impact vehicle velocity unless each support is designed to independently release from the sign panel, the sign panel has sufficient torsional strength to ensure this release, and the clear distance between supports is eight feet (2.44 m) or greater.

To avoid vehicle undercarriage snagging, any substantial remains of a breakaway support, when it is broken away, should not project more than four inches (0.102 m) above a 60-inch (1.524 m) chord aligned radially to the centerline of the highway and connecting any point, within the length of the chord, on the ground surface on one side of the support to a point on the ground surface on the other side.

The Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals is available for purchase from the

American Association of State Highway and Transportation Officials
444 North Capitol Street, N.W.
Suite 249
Washington, D.C. 20001
(Phone: 202/624-5800)

APPENDIX C 1989 GUIDE SPECIFICATION FOR BRIDGE RAILINGS

G2.1 GENERAL

G2.1.1* Notations

A = Distance from front of vehicle to its center of gravity, ft. (Table G2.7.1.3A)
A_f = Area of Flange, in^2 (Article G3.7.4.3)
B = Width of vehicle, ft. (Table G2.7.1.3A)
b = Flange width, in. (Article G2.7.4.3)
D = clear unsupported distance between flange components, in. (Article G2.7.4.3)
d = depth of W or I section, in. (Article G2.7.4.3)
F_a = allowable axial stress, psi (Article G2.7.4.3)
F_b = allowable bending stress, psi (Article G2.7.4.2)
F_v = allowable shear stress, psi (Article G2.7.4.2)
F_y = minimum yield stress, psi (Article G2.7.4.2)
f_a = axial compression stress, psi (Article G2.7.4.3)
H_{cg} = Height of vehicle center of gravity, in. (Table G2.7.1.3A)
K_c = Traffic Adjustment Factor for Curvature (Article G2.7.1.3, Figure G2.7.1.3A, and Table G2.7.1.3B)
K_g = Traffic Adjustment Factor for Grade, (Article G2.7.1.3, Figure G2.7.1.3A, and Table G2.7.1.3B)
K_s = Traffic Adjustment Factor for deck height and under-structure conditions (Article G2.7.1.3, Figure G2.7.1.3B, and Table G2.7.1.3B)
L = post spacing (Figure G2.7.4)
R = Ratio of weight assumed to be acting on tractor unit to total vehicle weight (Table G2.7.1.3A)
t = web thickness, in. (Article G2.7.4.3)
V = Impact speed, mph (Table G2.7.1.3A)
V_p = Speed of vehicle when it becomes parallel to railing, mph (Table G2.7.1.3A)
W = Gross weight of vehicle, Kips (Table G2.7.1.3A)
w = pedestrian or bicycle loading (Articles G2.7.2.2, G2.7.3.2, and Figure G2.7.4)
θ = Impact angle, deg. (Table G2.7.1.3A)
μ = Effective coefficient of friction between railing and impacting vehicle (Table G2.7.1.3A)

G2.2.5 Curbs and Sidewalks

The face of the curb is defined as the vertical or sloping surface on the roadway side of the curb. Horizontal measurements of roadway curbs are from the bottom of the face or, in the case of stepped back curbs, from the bottom of the lower face. A sidewalk or a brush curb located on the highway traffic side of a bridge railing shall be considered an integral part of the railing and shall be subject to the crash test requirements of Article G2.7.1.1.3. The width of a brush curb shall not exceed 9 inches, desirably, should not exceed 6 inches. When curb and gutter sections are used on the roadway approach, at either or both ends of the bridge, the curb height on the bridge shall preferably equal, but may exceed, the curb height on the roadway approach. Changes in curb height shall be uniformly transitioned over a distance equal to or greater than 20 times the change in height. Where no curbs are used on the roadway approaches, the height of the bridge curb above the roadway shall be not less than 6 inches, and preferably not more than 8 inches.

Raised sidewalks on bridges usually should not be used where the approach roadway is not curbed. However, when staged construction, a change in roadway cross section from one end of the bridge to the other, or some other condition requires a raised sidewalk on a bridge with no connecting approach curb, a transition section of sidewalk with a length at least 20 times the height of the sidewalk curb on the bridge shall be provided to ramp the bridge sidewalk to the level of the approach surface.

For recommendations on sidewalk widths see AASHTO *A Policy on Geometric Design of Highways and Streets.*

Where sidewalks are used for pedestrian traffic on urban expressways they shall be separated from the bridge roadway by the use of a traffic railing or combination railing as discussed in Article G2.7.

In those cases where a New Jersey type parapet or other railing or a curb is constructed on a bridge, particularly in urban areas that have curbs and gutters leading to a bridge, the same width between curbs on the approach roadway will be maintained across the bridge structure. A parapet or other railing installed at or near the curb line shall have its ends properly flared, sloped, or shielded.

G2.7 RAILINGS

Railings shall be provided along the edges of structures for protection of traffic and pedestrians. A pedestrian walkway *may* be separated from an adjacent roadway by a traffic railing or combination railing, with a pedestrian railing along the edge of the

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* See preface for explanation of article numbering.

structure, except on urban expressways where a pedestrian walkway, if provided, *shall* be separated from the adjacent roadway by a traffic railing or combination railing.

G2.7.1 Traffic Railings and Combination Railings

G2.7.1.1 General

G2.7.1.1.1 Although the primary purpose of traffic railings is to contain vehicles using the structure, consideration should also be given to (a) protection of the occupants of a vehicle in collision with the railing, (b) protection of other vehicles near the collision, (c) protection of persons and property on roadways or other areas underneath the structure, (d) railing cost-effectiveness, and (e) appearance and freedom of view from passing vehicles.

G2.7.1.1.2 The approach end of a parapet or railing shall have an appropriate crashworthy configuration or be shielded by a crashworthy traffic barrier. Traffic barriers on bridge approaches must be properly transitioned to traffic railings on bridges. Bridge-end drainage control should be an integral part of the barrier transition design.

G2.7.1.1.3 To ensure safe performance, traffic railings, combination railings (traffic railings combined with pedestrian railings or bicycle railings), and barrier transitions shall be crash tested and evaluated in accordance with the crash test procedures given in the National Cooperative Highway Research Program Report 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances,* except as otherwise directed in Article G2.7.1.3 of these specifications. In addition, combination railings are to meet the loading requirements for bicycle railings given in Article G2.7.2.2 or for pedestrian railings given in Article G2.7.3.2, as appropriate.

A combination railing may be crash tested and certified for use with a raised sidewalk having unique dimensions. However, a combination railing crash tested with a flush roadway approach surface and with a sidewalk conforming to the dimensions given in Figure G2.7.1.1.3 may be considered as acceptable for use with sidewalks having widths 3.5 feet or greater and heights up to 8 inches, provided the crash test results meet the requirements given in Table G2.7.1.3A under "Crash Test Evaluation Criteria."

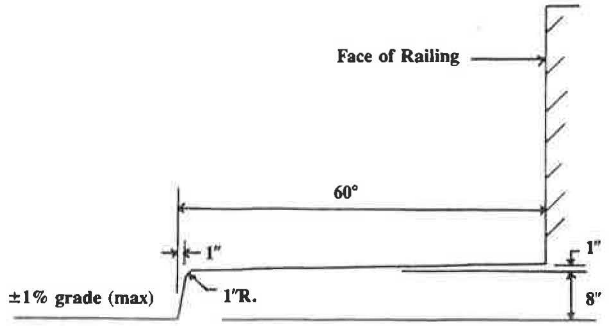


FIGURE G2.7.1.1.3 Standard Raised Sidewalk for Use in Combination Railing Testing.

G2.7.1.1.4 Variations in traffic volume, speed, vehicle mix, roadway alignment, under-structure activities and conditions, and other factors combine to produce a vast variation in traffic railing performance needs from one site to another. The performance requirements for traffic railings and the criteria for their selection are given in Article G2.7.1.3.

G2.7.1.2 Geometry

G2.7.1.2.1 Acceptability of traffic railing and combination railing geometry shall be verified through crash testing. However, the minimum height of a traffic railing, measured at its roadway face, from the top of the roadway or from the top of an anticipated future overlay shall not be less than 27 inches.

G2.7.1.2.2 When a traffic railing is located between the roadway and a sidewalk or bikeway, the minimum height of the railing above the surface of the sidewalk or bikeway shall be 24 inches and the railing should have a smooth surface to avoid snag points for pedestrians or cyclists. When a greater height of railing above a sidewalk or bikeway surface is desired to improve comfort or safety of pedestrians or cyclists with a potential of falling over the railings and onto the roadway, the railing may be a traffic railing or a modified combination railing giving a selected height other than required by Article G2.7.1.2.3.

G2.7.1.2.3 The minimum geometric requirements for combination railings, beyond those required to meet crash test requirements and the requirements of Article G2.7.1.2.1, shall be those required for bicycle railings or pedestrian railings, as appropriate. (See Articles G2.7.2 and G2.7.3.)

G2.7.1.3 Performance Levels and Selection Procedures

G2.7.1.3.1 Railing performance levels are described by crash test requirements. Table G2.7.1.3A

TABLE G2.7.1.3A Bridge Railing Performance Levels and Crash Test Criteria

PERFORMANCE LEVELS		TEST SPEEDS—mph[1,2]			
		TEST VEHICLE DESCRIPTIONS AND IMPACT ANGLES			
		Small Automobile	Pickup Truck	Medium Single-Unit Truck	Van-Type Tractor-Trailer[4]
		W = 1.8 Kips A = 5.4′ ± 0.1′ B = 5.5′ H_{cg} = 20″ ± 1″ θ = 20 deg.	W = 5.4 Kips A = 8.5′ ± 0.1′ B = 6.5′ H_{cg} = 27″ ± 1″ θ = 20 deg.	W = 18.0 Kips A = 12.8′ ± 0.2′ B = 7.5′ H_{cg} = 49″ ± 1″ θ = 15 deg.	W = 50.0 Kips A = 12.5′ ± 0.5′ B = 8.0′ H_{cg} = See Note 4 R = 0.61 ± 0.01 θ = 15 deg.
PL-1		50	45		
PL-2		60	60	50	
PL-3		60	60		50
CRASH TEST EVALUATION CRITERIA[3]	Required	a, b, c, d, g	a, b, c, d	a, b, c	a, b, c
	Desirable[5]	e, f, h	e, f, g, h	d, e, f, h	d, e, f, h

Notes:

1. Except as noted, all full-scale tests shall be conducted and reported in accordance with the requirements in NCHRP Report No. 230. In addition, the maximum loads that can be transmitted from the bridge railing to the bridge deck are to be determined from static force measurements or ultimate strength analysis and reported.
2. Permissible tolerances on the test speeds and angles are as follows:

Speed	−1.0 mph	+2.5 mph
Angle	−1.0 deg.	+2.5 deg.

   Tests that indicate acceptable railing performance but that exceed the allowable upper tolerances will be accepted.

3. Criteria for evaluating bridge railing crash test results are as follows:
   a. The test article shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.
   b. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.
   c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.
   d. The vehicle shall remain upright during and after collision.
   e. The test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle or, in the case of a combination vehicle, the rear of the tractor or trailer does not yaw more than 5 degrees away from the railing from time of impact until the vehicle separates from the railing.
   f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction, μ:

μ	Assessment
0–0.25	Good
0.26–0.35	Fair
>0.35	Marginal

where $\mu = (\cos\theta - V_p/V)/\sin\theta$

TABLE G2.7.1.3A (Continued) Bridge Railing Performance Levels and Crash Test Criteria

g. The impact velocity of a hypothetical front-seat passenger against the vehicle interior, calculated from vehicle accelerations and 2.0-ft. longitudinal and 1.0-ft. lateral diplacements, shall be less than:

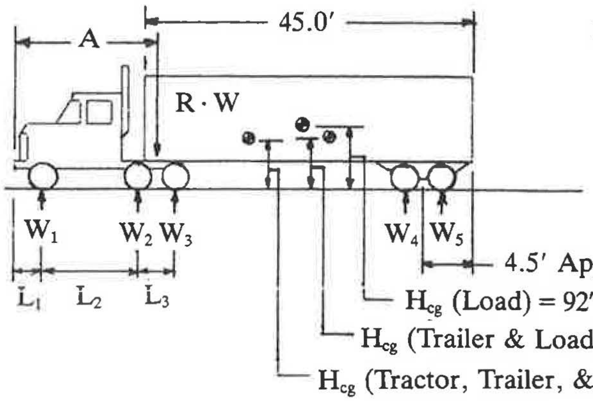
Occupant Impact Velocity–fps	
Longitudinal	Lateral
30	25

and the vehicle highest 10-ms average accelerations subsequent to the instant of hypothetical passenger impact should be less than:

Occupant Ridedown Acceleration—g's	
Longitudinal	Lateral
15	15

h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 100 ft. plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 20-ft. from the line of the traffic face of the railing. The brakes shall not be applied until the vehicle has traveled at least 100-ft. plus the length of the test vehicle from the point of initial impact.

4. Values A and R are estimated values describing the test vehicle and its loading. Values of A and R are described in the figure below and calculated as follows:



Min. Load = 20.5 Kips

$$L_1 = 30'' \pm 1''$$

$$L_2 + \frac{L_3}{2} = 169'' \pm 4''$$

$$A = L_1 + \frac{W_2L_2 + W_3(L_2 + L_3)}{W_1 + W_2 + W_3}$$

$$R = \frac{W_1 + W_2 + W_3}{W}$$

$$W = W_1 + W_2 + W_3 + W_4 + W_5$$
= total vehicle weight.

5. Test articles that do not meet the desirable evaluation criteria shall have their performance evaluated by a designated authority that will decide whether the test article is likely to meet its intended use requirements.

lists bridge railing performance levels and associated crash tests to be used in developing and qualifying railings.

G2.7.1.3.2 Unless a more exact method is used, Table G2.7.1.3B shall be used to estimate the appropriate performance level for a bridge railing. Values given in Table G2.7.1.3B are for bridges on tangent, level roadways, with deck surfaces approximately 35 feet above the under structure ground or water surface, and with low occupancy land use or shallow water under the structure. The traffic volume to be used to determine the appropriate performance level for a bridge railing is to be based on the estimated construction-year average daily traffic, provided this traffic includes that which will be contributed by any soon to be completed parts of the highway network or land development. For bridges carrying other than tangent, level roadways or with heights or understructure conditions that differ from those upon which Table G2.7.1.3B is based, the traffic volume used to determine an appropriate bridge railing performance level shall be the estimated construction-year traffic volume adjusted by correction factors given in Figures G2.7.1.3A and G2.7.1.3B.

Railing performance selection guidance in Table G2.7.1.3A assumes relatively free flowing traffic. To account for the effect traffic congestion has on traffic speeds, and thus the frequency of design level impacts on a railing, for sites with a design speed of 50 mph or greater and a construction-year ADT

TABLE G2.7.1.3B Bridge Railing Performance Level Selection Table

Site Characteristics			Adjusted ADT Ranges for Bridge Railing Performance Levels (10^3 vpd)		
			Highway Type		
			Divided (or Undivided with 5 or more Lanes)	Undivided with 4 Lanes or Less	One Way
DESIGN SPEED (mph)	PERCENT TRUCKS	BRIDGE RAIL OFFSET (ft)	PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3
30	0	0– 3	0 to 151.0 to ∞	0 to 144.3 to ∞	0 to 75.5 to ∞
30	0	3– 7	0 to 283.2 to ∞	0 to 265.2 to ∞	0 to 141.6 to ∞
30	0	7–12	0 to ∞	0 to ∞	0 to 316.1 to ∞
30	0	>12	0 to ∞	0 to ∞	0 to ∞
30	5	0– 3	0 to 56.6 to ∞	0 to 48.0 to ∞	0 to 28.3 to 357.1 to ∞
30	5	3– 7	0 to 90.4 to ∞	0 to 74.6 to ∞	0 to 45.2 to ∞
30	5	7–12	0 to 148.3 to ∞	0 to 128.9 to ∞	0 to 74.2 to ∞
30	5	>12	0 to 316.0 to ∞	0 to 277.9 to ∞	0 to 158.0 to ∞
30	10	0– 3	0 to 23.9 to 179.8 to ∞	0 to 19.3 to 147.9 to ∞	0 to 12.0 to 89.9 to ∞
30	10	3– 7	0 to 36.5 to 258.3 to ∞	0 to 28.8 to 228.7 to ∞	0 to 18.3 to 129.2 to ∞
30	10	7–12	0 to 55.9 to 404.4 to ∞	0 to 46.5 to 364.6 to ∞	0 to 28.0 to 202.2 to ∞
30	10	>12	0 to 100.7 to ∞	0 to 84.6 to ∞	0 to 50.4 to 417.1 to ∞
30	15	0– 3	0 to 15.1 to 102.9 to ∞	0 to 12.1 to 84.5 to ∞	0 to 7.6 to 51.5 to ∞
30	15	3– 7	0 to 22.8 to 146.6 to ∞	0 to 17.9 to 129.2 to ∞	0 to 11.4 to 73.3 to ∞
30	15	7–12	0 to 34.4 to 228.5 to ∞	0 to 28.3 to 205.3 to ∞	0 to 17.2 to 114.3 to ∞
30	15	>12	0 to 59.9 to 472.0 to ∞	0 to 49.9 to 466.5 to ∞	0 to 30.0 to 236.0 to ∞
30	20	0– 3	0 to 11.1 to 72.0 to ∞	0 to 8.8 to 59.1 to ∞	0 to 5.6 to 36.0 to ∞
30	20	3– 7	0 to 16.6 to 102.4 to ∞	0 to 13.0 to 90.0 to ∞	0 to 8.3 to 51.2 to ∞
30	20	7–12	0 to 24.9 to 159.2 to ∞	0 to 20.4 to 142.9 to ∞	0 to 12.5 to 79.6 to ∞
30	20	>12	0 to 42.6 to 329.1 to ∞	0 to 35.4 to 325.2 to ∞	0 to 21.3 to 164.6 to ∞
30	25	0– 3	0 to 8.7 to 55.4 to ∞	0 to 6.9 to 45.4 to ∞	0 to 4.4 to 27.7 to ∞
30	25	3– 7	0 to 13.1 to 78.6 to ∞	0 to 10.2 to 69.1 to ∞	0 to 6.6 to 39.3 to ∞
30	25	7–12	0 to 19.5 to 122.2 to ∞	0 to 15.9 to 109.6 to ∞	0 to 9.8 to 61.1 to ∞
30	25	>12	0 to 33.1 to 252.6 to ∞	0 to 27.4 to 249.6 to ∞	0 to 16.6 to 126.3 to ∞
30	30	0– 3	0 to 7.2 to 45.0 to ∞	0 to 5.7 to 36.9 to ∞	0 to 3.6 to 22.5 to ∞
30	30	3– 7	0 to 10.8 to 63.8 to ∞	0 to 8.4 to 56.1 to ∞	0 to 5.4 to 31.9 to ∞
30	30	7–12	0 to 16.0 to 99.1 to ∞	0 to 13.1 to 88.8 to ∞	0 to 8.0 to 49.6 to ∞
30	30	>12	0 to 27.0 to 205.0 to ∞	0 to 22.4 to 202.5 to ∞	0 to 13.5 to 102.5 to ∞
30	35	0– 3	0 to 6.1 to 37.9 to ∞	0 to 4.8 to 31.1 to ∞	0 to 3.1 to 19.0 to ∞
30	35	3– 7	0 to 9.2 to 53.7 to ∞	0 to 7.1 to 47.2 to ∞	0 to 4.6 to 26.9 to ∞
30	35	7–12	0 to 13.6 to 83.4 to ∞	0 to 11.1 to 74.7 to ∞	0 to 6.8 to 41.7 to ∞
30	35	>12	0 to 22.8 to 172.5 to ∞	0 to 18.9 to 170.4 to ∞	0 to 11.4 to 86.3 to ∞
30	40	0– 3	0 to 5.3 to 32.8 to ∞	0 to 4.2 to 26.8 to ∞	0 to 2.7 to 16.4 to ∞
30	40	3– 7	0 to 8.0 to 46.4 to ∞	0 to 6.2 to 40.7 to ∞	0 to 4.0 to 23.2 to ∞
30	40	7–12	0 to 11.8 to 72.0 to ∞	0 to 9.6 to 64.5 to ∞	0 to 5.9 to 36.0 to ∞
30	40	>12	0 to 19.8 to 148.9 to ∞	0 to 16.3 to 147.1 to ∞	0 to 9.9 to 74.5 to ∞

See Notes at the end of the Table.

TABLE G2.7.1.3B (Continued) Bridge Railing Performance Level Selection Table

Site Characteristics			Adjusted ADT Ranges for Bridge Railing Performance Levels (10^3 vpd)		
			Highway Type		
DESIGN SPEED (mph)	PERCENT TRUCKS	BRIDGE RAIL OFFSET (ft)	Divided (or Undivided with 5 or more Lanes) PERFORMANCE LEVEL PL-1 PL-2 PL-3	Undivided with 4 Lanes or Less PERFORMANCE LEVEL PL-1 PL-2 PL-3	One Way PERFORMANCE LEVEL PL-1 PL-2 PL-3
40	0	0– 3	0 to 19.0 to ∞	0 to 14.4 to ∞	0 to 9.5 to ∞
40	0	3– 7	0 to 24.8 to ∞	0 to 19.0 to ∞	0 to 12.4 to ∞
40	0	7–12	0 to 33.1 to ∞	0 to 27.2 to ∞	0 to 16.6 to ∞
40	0	<12	0 to 59.3 to ∞	0 to 51.1 to ∞	0 to 29.7 to ∞
40	5	0– 3	0 to 14.0 to 280.7 to ∞	0 to 10.4 to 202.4 to ∞	0 to 7.0 to 140.4 to ∞
40	5	3– 7	0 to 18.0 to 335.1 to ∞	0 to 13.4 to 253.8 to ∞	0 to 9.0 to 167.6 to ∞
40	5	7–12	0 to 24.4 to 452.0 to ∞	0 to 19.2 to 366.7 to ∞	0 to 12.2 to 226.0 to ∞
40	5	>12	0 to 39.5 to ∞	0 to 32.1 to ∞	0 to 19.8 to 362.7 to ∞
40	10	0– 3	0 to 9.8 to 79.7 to ∞	0 to 7.1 to 55.6 to ∞	0 to 4.9 to 39.9 to ∞
40	10	3– 7	0 to 12.7 to 89.8 to ∞	0 to 9.2 to 68.6 to ∞	0 to 6.4 to 44.9 to ∞
40	10	7–12	0 to 16.9 to 132.4 to ∞	0 to 12.8 to 102.3 to ∞	0 to 8.5 to 66.2 to ∞
40	10	>12	0 to 25.8 to 183.6 to ∞	0 to 20.1 to 157.2 to ∞	0 to 12.9 to 91.8 to ∞
40	15	0– 3	0 to 7.5 to 46.4 to ∞	0 to 5.4 to 32.2 to ∞	0 to 3.8 to 23.2 to ∞
40	15	3– 7	0 to 9.8 to 51.9 to ∞	0 to 7.0 to 39.6 to ∞	0 to 4.9 to 26.0 to ∞
40	15	7–12	0 to 12.9 to 77.6 to ∞	0 to 9.6 to 59.4 to ∞	0 to 6.5 to 38.8 to ∞
40	15	>12	0 to 19.1 to 105.1 to ∞	0 to 14.6 to 89.6 to ∞	0 to 9.6 to 52.6 to ∞
40	20	0– 3	0 to 6.1 to 32.8 to ∞	0 to 4.4 to 22.7 to ∞	0 to 3.1 to 16.4 to ∞
40	20	3– 7	0 to 8.0 to 36.5 to ∞	0 to 5.6 to 27.9 to ∞	0 to 4.0 to 18.3 to ∞
40	20	7–12	0 to 10.4 to 54.9 to ∞	0 to 7.7 to 41.9 to ∞	0 to 5.2 to 27.5 to ∞
40	20	>12	0 to 15.2 to 73.6 to ∞	0 to 11.5 to 62.7 to ∞	0 to 7.6 to 36.8 to ∞
40	25	0– 3	0 to 5.1 to 25.3 to ∞	0 to 3.6 to 17.5 to ∞	0 to 2.6 to 12.7 to ∞
40	25	3– 7	0 to 6.7 to 28.1 to ∞	0 to 4.7 to 21.5 to ∞	0 to 3.4 to 14.1 to ∞
40	25	7–12	0 to 8.8 to 42.4 to ∞	0 to 6.4 to 32.3 to ∞	0 to 4.4 to 21.2 to ∞
40	25	>12	0 to 12.6 to 56.7 to ∞	0 to 9.5 to 48.2 to ∞	0 to 6.3 to 28.4 to ∞
40	30	0– 3	0 to 4.4 to 20.6 to ∞	0 to 3.1 to 14.2 to ∞	0 to 2.2 to 10.3 to ∞
40	30	3– 7	0 to 5.8 to 22.9 to ∞	0 to 4.1 to 17.5 to ∞	0 to 2.9 to 11.5 to ∞
40	30	7–12	0 to 7.5 to 34.6 to ∞	0 to 5.5 to 26.3 to ∞	0 to 3.8 to 17.3 to ∞
40	30	>12	0 to 10.8 to 46.1 to ∞	0 to 8.0 to 39.1 to ∞	0 to 5.4 to 23.1 to ∞
40	35	0– 3	0 to 3.9 to 17.4 to ∞	0 to 2.8 to 12.0 to ∞	0 to 2.0 to 8.7 to ∞
40	35	3– 7	0 to 5.1 to 19.3 to ∞	0 to 3.6 to 14.7 to ∞	0 to 2.6 to 9.7 to ∞
40	35	7–12	0 to 6.6 to 29.2 to ∞	0 to 4.8 to 22.2 to ∞	0 to 3.3 to 14.6 to ∞
40	35	>12	0 to 9.4 to 38.8 to ∞	0 to 7.0 to 32.9 to ∞	0 to 4.7 to 19.4 to ∞
40	40	0– 3	0 to 3.5 to 15.0 to ∞	0 to 2.5 to 10.4 to ∞	0 to 1.8 to 7.5 to ∞
40	40	3– 7	0 to 4.6 to 16.7 to ∞	0 to 3.2 to 12.7 to ∞	0 to 2.3 to 8.4 to ∞
40	40	7–12	0 to 5.9 to 25.3 to ∞	0 to 4.2 to 19.2 to ∞	0 to 3.0 to 12.7 to ∞
40	40	>12	0 to 8.4 to 33.5 to ∞	0 to 6.2 to 28.4 to ∞	0 to 4.2 to 16.8 to ∞

See Notes at the end of the Table.

TABLE G2.7.1.3B (Continued) Bridge Railing Performance Level Selection Table

Site Characteristics			Adjusted ADT Ranges for Bridge Railing Performance Levels (10^3 vpd)		
			Highway Type		
DESIGN SPEED (mph)	PERCENT TRUCKS	BRIDGE RAIL OFFSET (ft)	Divided (or Undivided with 5 or more Lanes) PERFORMANCE LEVEL PL-1 PL-2 PL-3	Undivided with 4 Lanes or Less PERFORMANCE LEVEL PL-1 PL-2 PL-3	One Way PERFORMANCE LEVEL PL-1 PL-2 PL-3
50	0	0– 3	0 to 6.2 to ∞	0 to 4.2 to ∞	0 to 3.1 to ∞
50	0	3– 7	0 to 7.2 to ∞	0 to 5.0 to ∞	0 to 3.6 to ∞
50	0	7–12	0 to 9.9 to ∞	0 to 7.3 to ∞	0 to 5.0 to ∞
50	0	<12	0 to 13.0 to ∞	0 to 9.6 to ∞	0 to 6.5 to ∞
50	5	0– 3	0 to 5.5 to 162.2 to ∞	0 to 3.7 to 107.0 to ∞	0 to 2.8 to 81.1 to ∞
50	5	3– 7	0 to 6.3 to 188.6 to ∞	0 to 4.4 to 134.1 to ∞	0 to 3.2 to 94.3 to ∞
50	5	7–12	0 to 8.4 to 247.3 to ∞	0 to 6.1 to 171.9 to ∞	0 to 4.2 to 123.7 to ∞
50	5	>12	0 to 11.2 to 314.7 to ∞	0 to 8.2 to 245.4 to ∞	0 to 5.6 to 157.4 to ∞
50	10	0– 3	0 to 4.7 to 50.0 to ∞	0 to 3.2 to 32.0 to ∞	0 to 2.4 to 25.0 to ∞
50	10	3– 7	0 to 5.4 to 61.4 to ∞	0 to 3.7 to 41.8 to ∞	0 to 2.7 to 30.7 to ∞
50	10	7–12	0 to 7.2 to 70.6 to ∞	0 to 5.1 to 49.3 to ∞	0 to 3.6 to 35.3 to ∞
50	10	>12	0 to 9.6 to 88.5 to ∞	0 to 6.9 to 67.8 to ∞	0 to 4.8 to 44.3 to ∞
50	15	0– 3	0 to 4.1 to 29.6 to ∞	0 to 2.8 to 18.8 to ∞	0 to 2.1 to 14.8 to ∞
50	15	3– 7	0 to 4.8 to 36.7 to ∞	0 to 3.3 to 24.8 to ∞	0 to 2.4 to 18.4 to ∞
50	15	7–12	0 to 6.3 to 41.2 to ∞	0 to 4.4 to 28.8 to ∞	0 to 3.2 to 20.6 to ∞
50	15	>12	0 to 8.4 to 51.5 to ∞	0 to 5.9 to 39.4 to ∞	0 to 4.2 to 25.8 to ∞
50	20	0– 3	0 to 3.7 to 21.0 to ∞	0 to 2.5 to 13.3 to ∞	0 to 1.9 to 10.5 to ∞
50	20	3– 7	0 to 4.3 to 26.1 to ∞	0 to 2.9 to 17.6 to ∞	0 to 2.2 to 13.1 to ∞
50	20	7–12	0 to 5.6 to 29.1 to ∞	0 to 3.9 to 20.3 to ∞	0 to 2.8 to 14.6 to ∞
50	20	>12	0 to 7.5 to 36.3 to ∞	0 to 5.2 to 27.7 to ∞	0 to 3.8 to 18.2 to ∞
50	25	0– 3	0 to 3.3 to 16.3 to ∞	0 to 2.2 to 10.3 to ∞	0 to 1.7 to 8.2 to ∞
50	25	3– 7	0 to 3.9 to 20.3 to ∞	0 to 2.6 to 13.7 to ∞	0 to 2.0 to 10.2 to ∞
50	25	7–12	0 to 5.0 to 22.5 to ∞	0 to 3.5 to 15.7 to ∞	0 to 2.5 to 11.3 to ∞
50	25	>12	0 to 6.7 to 28.1 to ∞	0 to 4.7 to 21.4 to ∞	0 to 3.4 to 14.1 to ∞
50	30	0– 3	0 to 3.1 to 13.3 to ∞	0 to 2.0 to 8.4 to ∞	0 to 1.6 to 6.7 to ∞
50	30	3– 7	0 to 3.5 to 16.6 to ∞	0 to 2.4 to 11.1 to ∞	0 to 1.8 to 8.3 to ∞
50	30	7–12	0 to 4.5 to 18.3 to ∞	0 to 3.1 to 12.8 to ∞	0 to 2.3 to 9.2 to ∞
50	30	>12	0 to 6.1 to 22.9 to ∞	0 to 4.2 to 17.4 to ∞	0 to 3.1 to 11.5 to ∞
50	35	0– 3	0 to 2.8 to 11.2 to ∞	0 to 1.9 to 7.1 to ∞	0 to 1.4 to 5.6 to ∞
50	35	3– 7	0 to 3.2 to 14.0 to ∞	0 to 2.2 to 9.4 to ∞	0 to 1.6 to 7.0 to ∞
50	35	7–12	0 to 4.2 to 15.5 to ∞	0 to 2.9 to 10.8 to ∞	0 to 2.1 to 7.8 to ∞
50	35	>12	0 to 5.6 to 19.3 to ∞	0 to 3.8 to 14.7 to ∞	0 to 2.8 to 9.7 to ∞
50	40	0– 3	0 to 2.6 to 9.7 to ∞	0 to 1.7 to 6.1 to ∞	0 to 1.3 to 4.9 to ∞
50	40	3– 7	0 to 3.0 to 12.2 to ∞	0 to 2.0 to 8.2 to ∞	0 to 1.5 to 6.1 to ∞
50	40	7–12	0 to 3.8 to 13.4 to ∞	0 to 2.6 to 9.3 to ∞	0 to 1.9 to 6.7 to ∞
50	40	>12	0 to 5.2 to 16.7 to ∞	0 to 3.5 to 12.7 to ∞	0 to 2.6 to 8.4 to ∞

See Notes at the end of the Table.

TABLE G2.7.1.3B (Continued) Bridge Railing Performance Level Selection Table

Site Characteristics			Adjusted ADT Ranges for Bridge Railing Performance Levels (10^3 vpd)		
			Highway Type		
			Divided (or Undivided with 5 or more Lanes)	Undivided with 4 Lanes or Less	One Way
DESIGN SPEED (mph)	PERCENT TRUCKS	BRIDGE RAIL OFFSET (ft)	PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3
60	0	0– 3	0 to 3.2 to ∞	0 to 2.0 to ∞	0 to 1.6 to ∞
60	0	3– 7	0 to 3.6 to ∞	0 to 2.3 to ∞	0 to 1.8 to ∞
60	0	7–12	0 to 4.4 to ∞	0 to 2.9 to ∞	0 to 2.2 to ∞
60	0	<12	0 to 5.5 to ∞	0 to 3.5 to ∞	0 to 2.8 to ∞
60	5	0– 3	0 to 3.0 to 107.3 to ∞	0 to 1.9 to 70.3 to ∞	0 to 1.5 to 53.7 to ∞
60	5	3– 7	0 to 3.3 to 126.3 to ∞	0 to 2.1 to 82.8 to ∞	0 to 1.7 to 63.2 to ∞
60	5	7–12	0 to 4.1 to 158.4 to ∞	0 to 2.7 to 105.6 to ∞	0 to 2.1 to 79.2 to ∞
60	5	>12	0 to 5.0 to 203.8 to ∞	0 to 3.3 to 138.2 to ∞	0 to 2.5 to 101.9 to ∞
60	10	0– 3	0 to 2.8 to 39.6 to ∞	0 to 1.8 to 25.0 to ∞	0 to 1.4 to 19.8 to ∞
60	10	3– 7	0 to 3.1 to 47.5 to ∞	0 to 2.0 to 29.3 to ∞	0 to 1.6 to 23.8 to ∞
60	10	7–12	0 to 3.9 to 53.1 to ∞	0 to 2.5 to 33.7 to ∞	0 to 2.0 to 26.6 to ∞
60	10	>12	0 to 4.7 to 67.6 to ∞	0 to 3.1 to 44.1 to ∞	0 to 2.4 to 33.8 to ∞
60	15	0– 3	0 to 2.7 to 24.3 to ∞	0 to 1.7 to 15.2 to ∞	0 to 1.4 to 12.2 to ∞
60	15	3– 7	0 to 2.9 to 29.3 to ∞	0 to 1.9 to 17.8 to ∞	0 to 1.5 to 14.7 to ∞
60	15	7–12	0 to 3.7 to 31.9 to ∞	0 to 2.4 to 20.0 to ∞	0 to 1.9 to 16.0 to ∞
60	15	>12	0 to 4.5 to 40.5 to ∞	0 to 2.9 to 26.2 to ∞	0 to 2.3 to 20.3 to ∞
60	20	0– 3	0 to 2.5 to 17.5 to ∞	0 to 1.6 to 10.9 to ∞	0 to 1.3 to 8.8 to ∞
60	20	3– 7	0 to 2.8 to 21.1 to ∞	0 to 1.8 to 12.8 to ∞	0 to 1.4 to 10.6 to ∞
60	20	7–12	0 to 3.5 to 22.8 to ∞	0 to 2.2 to 14.3 to ∞	0 to 1.8 to 11.4 to ∞
60	20	>12	0 to 4.2 to 28.9 to ∞	0 to 2.8 to 18.7 to ∞	0 to 2.1 to 14.5 to ∞
60	25	0– 3	0 to 2.4 to 13.7 to ∞	0 to 1.5 to 8.5 to ∞	0 to 1.2 to 6.9 to ∞
60	25	3– 7	0 to 2.6 to 16.5 to ∞	0 to 1.7 to 10.0 to ∞	0 to 1.3 to 8.3 to ∞
60	25	7–12	0 to 3.3 to 17.7 to ∞	0 to 2.1 to 11.1 to ∞	0 to 1.7 to 8.9 to ∞
60	25	>12	0 to 4.0 to 22.5 to ∞	0 to 2.6 to 14.5 to ∞	0 to 2.0 to 11.3 to ∞
60	30	0– 3	0 to 2.3 to 11.2 to ∞	0 to 1.4 to 7.0 to ∞	0 to 1.2 to 5.6 to ∞
60	30	3– 7	0 to 2.5 to 13.6 to ∞	0 to 1.6 to 8.2 to ∞	0 to 1.3 to 6.8 to ∞
60	30	7–12	0 to 3.2 to 14.5 to ∞	0 to 2.0 to 9.0 to ∞	0 to 1.6 to 7.3 to ∞
60	30	>12	0 to 3.8 to 18.4 to ∞	0 to 2.5 to 11.9 to ∞	0 to 1.9 to 9.2 to ∞
60	35	0– 3	0 to 2.2 to 9.5 to ∞	0 to 1.4 to 5.9 to ∞	0 to 1.1 to 4.8 to ∞
60	35	3– 7	0 to 2.4 to 11.5 to ∞	0 to 1.5 to 6.9 to ∞	0 to 1.2 to 5.8 to ∞
60	35	7–12	0 to 3.0 to 12.3 to ∞	0 to 1.9 to 7.7 to ∞	0 to 1.5 to 6.2 to ∞
60	35	>12	0 to 3.6 to 15.6 to ∞	0 to 2.4 to 10.0 to ∞	0 to 1.8 to 7.8 to ∞
60	40	0– 3	0 to 2.1 to 8.3 to ∞	0 to 1.3 to 5.1 to ∞	0 to 1.1 to 4.2 to ∞
60	40	3– 7	0 to 2.3 to 10.0 to ∞	0 to 1.4 to 6.0 to ∞	0 to 1.2 to 5.0 to ∞
60	40	7–12	0 to 2.9 to 10.6 to ∞	0 to 1.9 to 6.6 to ∞	0 to 1.5 to 5.3 to ∞
60	40	>12	0 to 3.5 to 13.5 to ∞	0 to 2.3 to 8.7 to ∞	0 to 1.8 to 6.8 to ∞

See Notes at the end of the Table.

TABLE G2.7.1.3B (Continued) Bridge Railing Performance Level Selection Table

Site Characteristics			Adjusted ADT Ranges for Bridge Railing Performance Levels (10^3 vpd)		
			Highway Type		
DESIGN SPEED (mph)	PERCENT TRUCKS	BRIDGE RAIL OFFSET (ft)	Divided (or Undivided with 5 or more Lanes)	Undivided with 4 Lanes or Less	One Way
			PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3	PERFORMANCE LEVEL PL-1 PL-2 PL-3
70	0	0– 3	0 to 2.2 to 191.4 to ∞	0 to 1.3 to 165.0 to ∞	0 to 1.1 to 95.7 to ∞
70	0	3– 7	0 to 2.4 to 379.1 to ∞	0 to 1.5 to 301.5 to ∞	0 to 1.2 to 189.6 to ∞
70	0	7–12	0 to 2.8 to ∞	0 to 1.7 to 402.4 to ∞	0 to 1.4 to 256.4 to ∞
70	0	>12	0 to 3.2 to ∞	0 to 2.0 to ∞	0 to 1.6 to ∞
70	5	0– 3	0 to 2.1 to 63.1 to ∞	0 to 1.3 to 42.2 to ∞	0 to 1.1 to 31.6 to ∞
70	5	3– 7	0 to 2.3 to 80.0 to ∞	0 to 1.4 to 51.6 to ∞	0 to 1.2 to 40.0 to ∞
70	5	7–12	0 to 2.7 to 96.4 to ∞	0 to 1.6 to 64.0 to ∞	0 to 1.4 to 48.2 to ∞
70	5	>12	0 to 3.1 to 127.6 to ∞	0 to 1.9 to 84.0 to ∞	0 to 1.6 to 63.8 to ∞
70	10	0– 3	0 to 2.0 to 32.1 to ∞	0 to 1.2 to 20.0 to ∞	0 to 1.0 to 16.1 to ∞
70	10	3– 7	0 to 2.3 to 38.5 to ∞	0 to 1.4 to 22.9 to ∞	0 to 1.2 to 19.3 to ∞
70	10	7–12	0 to 2.6 to 42.2 to ∞	0 to 1.6 to 26.7 to ∞	0 to 1.3 to 21.1 to ∞
70	10	>12	0 to 3.0 to 53.0 to ∞	0 to 1.8 to 33.1 to ∞	0 to 1.5 to 26.5 to ∞
70	15	0– 3	0 to 2.0 to 21.5 to ∞	0 to 1.2 to 13.1 to ∞	0 to 1.0 to 10.8 to ∞
70	15	3– 7	0 to 2.2 to 25.3 to ∞	0 to 1.3 to 14.7 to ∞	0 to 1.1 to 12.7 to ∞
70	15	7–12	0 to 2.6 to 27.0 to ∞	0 to 1.6 to 16.9 to ∞	0 to 1.3 to 13.5 to ∞
70	15	>12	0 to 3.0 to 33.5 to ∞	0 to 1.8 to 20.6 to ∞	0 to 1.5 to 16.8 to ∞
70	20	0– 3	0 to 1.9 to 16.2 to ∞	0 to 1.2 to 9.7 to ∞	0 to 1.0 to 8.1 to ∞
70	20	3– 7	0 to 2.1 to 18.9 to ∞	0 to 1.3 to 10.8 to ∞	0 to 1.1 to 9.5 to ∞
70	20	7–12	0 to 2.5 to 19.9 to ∞	0 to 1.5 to 12.3 to ∞	0 to 1.3 to 10.0 to ∞
70	20	>12	0 to 2.9 to 24.4 to ∞	0 to 1.8 to 15.0 to ∞	0 to 1.5 to 12.2 to ∞
70	25	0– 3	0 to 1.9 to 13.0 to ∞	0 to 1.1 to 7.8 to ∞	0 to 1.0 to 6.5 to ∞
70	25	3– 7	0 to 2.0 to 15.1 to ∞	0 to 1.3 to 8.6 to ∞	0 to 1.0 to 7.6 to ∞
70	25	7–12	0 to 2.5 to 15.7 to ∞	0 to 1.5 to 9.7 to ∞	0 to 1.3 to 7.9 to ∞
70	25	>12	0 to 2.8 to 19.2 to ∞	0 to 1.7 to 11.8 to ∞	0 to 1.4 to 9.6 to ∞
70	30	0– 3	0 to 1.8 to 10.8 to ∞	0 to 1.1 to 6.4 to ∞	0 to 0.9 to 5.4 to ∞
70	30	3– 7	0 to 2.0 to 12.5 to ∞	0 to 1.2 to 7.1 to ∞	0 to 1.0 to 6.3 to ∞
70	30	7–12	0 to 2.4 to 13.0 to ∞	0 to 1.5 to 8.0 to ∞	0 to 1.2 to 6.5 to ∞
70	30	>12	0 to 2.8 to 15.9 to ∞	0 to 1.7 to 9.7 to ∞	0 to 1.4 to 8.0 to ∞
70	35	0– 3	0 to 1.8 to 9.3 to ∞	0 to 1.1 to 5.5 to ∞	0 to 0.9 to 4.7 to ∞
70	35	3– 7	0 to 1.9 to 10.7 to ∞	0 to 1.2 to 6.1 to ∞	0 to 1.0 to 5.4 to ∞
70	35	7–12	0 to 2.4 to 11.1 to ∞	0 to 1.5 to 6.8 to ∞	0 to 1.2 to 5.6 to ∞
70	35	>12	0 to 2.7 to 13.5 to ∞	0 to 1.7 to 8.2 to ∞	0 to 1.4 to 6.8 to ∞
70	40	0– 3	0 to 1.7 to 8.1 to ∞	0 to 1.0 to 4.8 to ∞	0 to 0.9 to 4.1 to ∞
70	40	3– 7	0 to 1.9 to 9.4 to ∞	0 to 1.2 to 5.3 to ∞	0 to 1.0 to 4.7 to ∞
70	40	7–12	0 to 2.3 to 9.6 to ∞	0 to 1.4 to 5.9 to ∞	0 to 1.2 to 4.8 to ∞
70	40	>12	0 to 2.7 to 11.8 to ∞	0 to 1.6 to 7.1 to ∞	0 to 1.4 to 5.9 to ∞

See Notes at the end of the Table.

TABLE G2.7.1.3B (Continued)

Notes for use of this Table:

Adjusted ADT = $K_c \cdot K_g \cdot K_s \cdot$ (estimated construction-year ADT)

To select bridge railing performance level:

- Calculate adjusted ADT by multiplying construction-year ADT (total for highway) by adjustment factors K_c, K_g, and K_s from Figures G2.7.1.3A and G2.7.1.3B. (The estimated construction-year ADT may be limited to 10,000 vehicles per day per lane for design speeds of 50 mph or greater, where the actual estimate exceeds that amount.)
- Locate line in table that describes site conditions (design speed, percent trucks, and bridge railing offset from traveled way).
- Move across to column describing type of highway upon which bridge is located.
- Locate adjusted ADT values in table that bracket the calculated adjusted ADT for bridge site.
- At top of column within which the calculated adjusted ADT is bracketed read the bridge railing performance level.

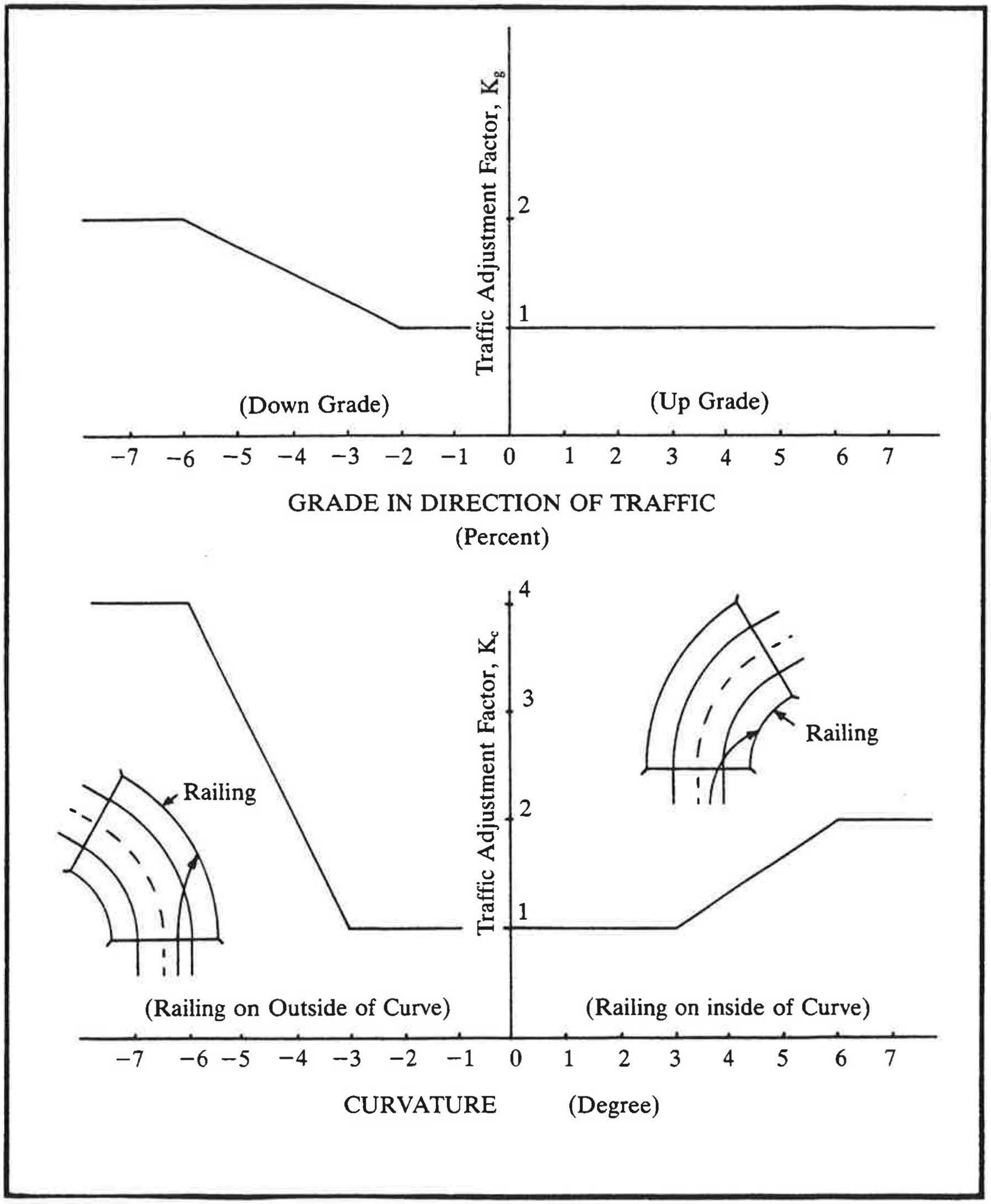


FIGURE G2.7.1.3A Grade Traffic Adjustment Factor (K_g) and Curvature Traffic Adjustment Factor (K_c) to be Applied to Estimated Construction-Year Average Daily Traffic

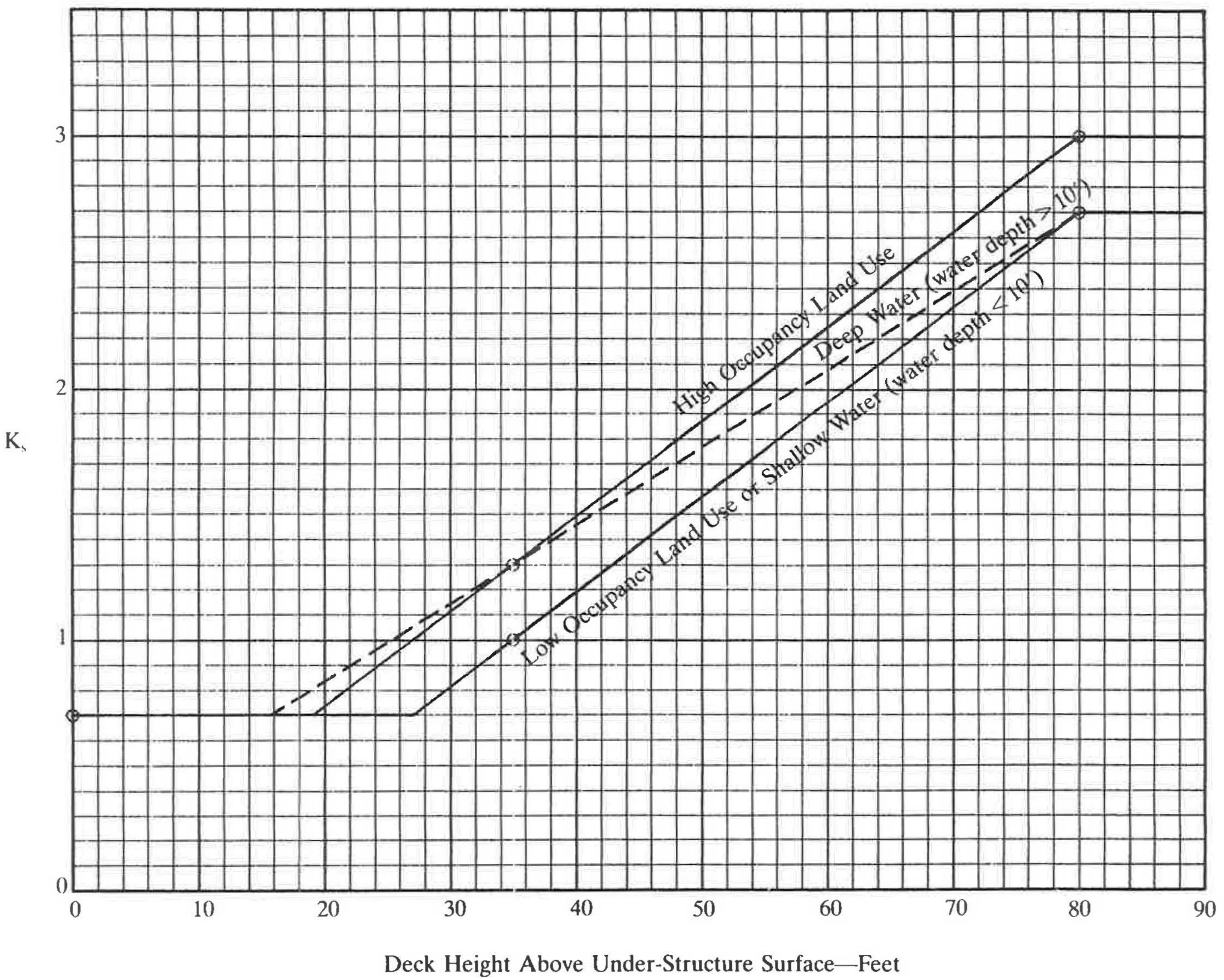


FIGURE G2.7.1.3.B Traffic Adjustment Factor (K_s) for Deck Height and Under-Structure Conditions greater than 10,000 vehicles per day per lane (vpdpl), the construction-year ADT value used in selecting a bridge railing performance level may be limited to 10,000 vpdpl.

G2.7.2 Bicycle Railing

G2.7.2.1 General

G2.7.2.1.1 Bicycle railings shall be used on bridges specifically designed to carry bicycle traffic, and on bridges where specific protection of bicyclists is deemed necessary.

G2.7.2.1.2 Railing components shall be designed with consideration to safety, appearance, and freedom of view.

G2.7.2.1.3 Materials for bicycle railing may be concrete, metal, timber, plastic, fiber reinforced plastic, or a combination thereof.

G2.7.2.2 Geometry and Loads

G2.7.2.2.1 The minimum height of a railing used to protect a bicyclist shall be 54 inches, measured from the top of the surface on which the bicycle rides to the top of the top rail.

G2.7.2.2.2 Within a band bordered by the riding surface and a line 54 inches above it, horizontal elements of the railing assembly shall have a maximum clear spacing of 15 inches. Vertical elements of the railing assembly shall have a maximum clear spacing of 8 inches. If a railing assembly employs both horizontal and vertical elements, the spacing requirements shall apply to one or the other, but not to both. Chain link fence is exempt from the rail spacing requirements listed above. In general, rails should project beyond the face of posts and/or pickets. Smooth rubrails should be attached to the railings at a height of 42 inches.

G2.7.2.2.3 The minimum design loadings for bicycle railing shall be w = 50 pounds per linear foot transversely and vertically, acting simultaneously on each rail.

G2.7.2.2.4 Design loads for rails located more than 54 inches above the riding surface shall be determined by the designer.

G2.7.2.2.5 Posts shall be designed for a transverse load of wL (where L is the post spacing) acting at the center of gravity of the upper rail, but at a height not greater than 54 inches.

G2.7.2.2.6 Refer to Figure G2.7.4 for more information concerning the application of loads.

G2.7.3 Pedestrian Railing

G2.7.3.1 General

G2.7.3.1.1 Railing components shall be designed with consideration to safety, appearance, and freedom of view.

G2.7.3.1.2 Materials for pedestrian railings may be concrete, metal, timber, plastic, fiber reinforced plastic, or a combination thereof.

G2.7.3.2 Geometry and Loads

G2.7.3.2.1 The minimum height of a pedestrian railing shall be 3 feet 6 inches measured from the top of the walkway to the top of the upper rail member.

G2.7.3.2.2 Within a band bordered by the walkway surface and a line 42 inches above it, horizontal elements of the railing assembly shall have a maximum clear spacing of 15 inches. Vertical elements of the railing assembly shall have a maximum clear spacing of 8 inches. If a railing assembly employs both horizontal and vertical elements, the spacing requirements shall apply to one or the other, but not to both. Chain link fence is exempt from the rail spacing requirements listed above. In general, rails should project beyond the face of posts and/or pickets.

G2.7.3.2.3 The minimum design loading for pedestrian railing shall be w = 50 pounds per linear foot, transversely and vertically, acting simultaneously on each longitudinal member. Rail members located more than 5 feet 0 inches above the walkway are excluded from these requirements.

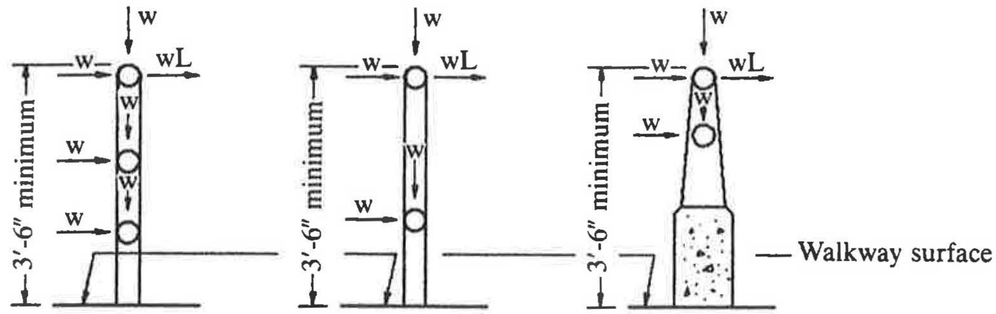
G2.7.3.2.4 Posts shall be designed for a transverse load of wL (where L is the post spacing) acting at the center of gravity of the upper rail or, for high rails, at 5 feet 0 inches maximum above the walkway.

G2.7.3.2.5 Refer to Figure G2.7.4 for more information concerning the application of loads.

G2.7.4 Structural Specifications and Guidelines for Bicycle and Pedestrian Railings

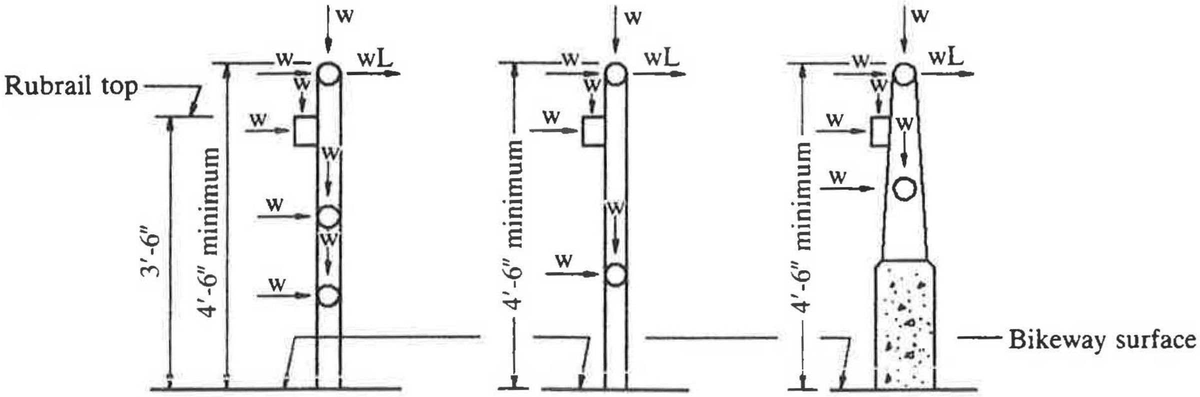
G2.7.4.1 Bicycle and Pedestrian Railings shall be designed by the elastic method to the allowable stresses for the appropriate material.

For aluminum alloys the design stresses given in the *Specifications for Aluminum Structures* Fifth Edition, December 1986, published by the Aluminum Association, Inc., for "Bridge and Similar Type Structures" for alloys 6061-T6 (Table A.6), 6351-T5 (Table A.6), and 6063-T6 (Table A.8) shall apply,



(To be used on the outer edge of a sidewalk when highway traffic is separated from pedestrian traffic by a traffic railing.)

PEDESTRIAN RAILING



(To be used on the outer edge of a bikeway when highway traffic is separated from bicycle traffic by a traffic railing.)

BICYCLE RAILING

NOTE:
If screening or solid face is presented, number of rails may be reduced; wind loads must be added if solid face is utilized.

NOTES:

1. Loadings on left are applied to rails.
2. Loads on right are applied to posts.
3. The shapes of rail members are illustrative only. Any material or combination of materials listed in Article G2.7 may be used in any configuration.

NOMENCLATURE:
w = Pedestrian or bicycle loading per unit length of rail
L = Post spacing

FIGURE G2.7.4 Pedestrian Railing, Bicycle Railing and for cast aluminum alloys the design stresses given for alloys A444.0-T4 (Table A.9), A356.0-T61 (Table A.9) and A356.0-T6 (Table A.9) shall apply.

For fabrication and welding of aluminum railing see Article 11.5 of the AASHTO *Standard Specifications for Highway Bridges.*

G2.7.4.2 The allowable unit stresses for steel shall be as given in Article 10.32 of the AASHTO *Standard Specifications for Highway Bridges,* except as modified below.

For steels not generally covered by the "Standard Specifications," but having a guaranteed yield strength, F_y, the allowable unit stress, shall be derived by applying the general formulas as given in the "Standard Specifications" under "Unit Stresses" except as indicated below.

The allowable unit stress for shear shall be $F_v = 0.33F_y$.

Round or oval steel tubes may be proportioned using an allowable bending stress, $F_b = 0.66F_y$, provided the R/t ratio (radius/thickness) is less than or equal to 40.

Square and rectangular steel tubes and steel W and I sections in bending with tension and compression on extreme fibers of laterally supported compact sections having an axis of symmetry in the plane of loading may be designed for an allowable stress $F_b = 0.60F_y$.

G2.7.4.3 The requirements for a compact section are as follows:

(a) The width to thickness ratio of projecting elements of the compression flange of W and I sections shall not exceed

$$\frac{b}{t} \leq \frac{1600}{\sqrt{F_y}} \qquad (2\text{-}1)$$

(b) The width to thickness ratio of the compression flange of square or rectangular tubes shall not exceed

$$\frac{b}{t} \leq \frac{6000}{\sqrt{F_y}} \qquad (2\text{-}2)$$

(c) The D/t ratio of webs shall not exceed

$$\frac{D}{t} \leq \frac{13000}{\sqrt{F_y}} \qquad (2\text{-}3)$$

(d) If subject to combined axial force and bending, the D/t ratio of webs shall not exceed

$$\frac{D}{t} < \frac{13{,}300\left[1 - 1.43\left(\frac{f_a}{F_a}\right)\right]}{\sqrt{F_y}} \qquad (2\text{-}4)$$

but need not be less than

$$\frac{D}{t} < \frac{7000}{\sqrt{F_y}} \qquad (2\text{-}5)$$

(e) The distance between lateral supports in inches of W or I sections shall not exceed

$$\leq \frac{2400b}{\sqrt{F_y}} \qquad (2\text{-}6)$$

or

$$\leq \frac{20{,}000{,}000\ A_f}{dF_y} \qquad (2\text{-}7)$$

G3.24 DISTRIBUTION OF LOADS AND DESIGN OF CONCRETE SLABS

G3.24.5 Cantilever Slabs

G3.24.5.2 Railing Loads on Bridge Decks

Railing loads applied to the bridge deck slab shall be based on the ultimate strength of the railing used (See Note 1 in Table G2.7.1.3A). Loads shall be applied and the deck designed in a manner to assure the ultimate strength of the slab will exceed that required to resist the maximum bending, shear, and punching loads that can be transmitted through the bridge railing, along with simultaneously applied wheel loads.

The handout distributed at the workshop included two appendices and the Commentaries section from the guide specifications. These items are omitted here. One of the omitted appendices is Appendix A, Bridge Railing Design Guidelines, which suggests loads, loading patterns, and analysis procedures that might be used to prepare a railing design that would have a high probability of meeting the test requirements for a given railing performance level. The other appendix omitted is Appendix B, Development of Performance Levels and Performance Level Selection Procedures for Bridge Railings, which provides background on the performance levels and selection procedures cited in the guide specifications. The commentaries provide background or clarification on specific articles in the guide specifications.

The Guide Specifications for Bridge Railings can be purchased from the:
American Association of State Highway and Transportation Officials
444 North Capitol Street, N.W.
Suite 249
Washington, D.C. 20001
(Phone: 202/624-5800)

APPENDIX D FRENCH STANDARD NF P 98-409, ROAD SAFETY BARRIERS—PERFORMANCE, CLASSIFICATION, AND QUALIFICATION CRITERIA

On safety grounds, the engineering of highways and motorways requires the installation, in certain sections or at particular points, of systems intended to retain vehicles straying from the roadway.

These systems, called road safety barriers, may be used near the roadway, where a vehicle is likely to run into various elements that may increase the vehicle or occupant consequences of its leaving the roadway.

These elements may be obstacles or obstructions able to cause blocking, uncontrolled change of course, or overturning of the vehicle, resulting in appreciable damage to the vehicle or the occupants.

They may also be the bordering zones of the roadway, if their penetration by a vehicle or its loading may produce severe damage to persons or to the environment.

Scope and Field of Application

Many products and provisions are liable to be used for this purpose. Nevertheless, the only equipment items to be considered and classified as road safety barriers are those systems that not only possess a retaining capacity superior to a given level but also secure the vehicle to remain on the road under safety conditions acceptable for the road users.

The present standard is aimed at defining the performance, classification, and qualification criteria of road safety barriers.

In some cases (e.g., equipment of a town boulevard, slow speeds, and environment), other equipment items (e.g., footway, curbs, raised curbs, and earthworks) may still be installed even if, in the terms of the present standard, they are not considered road safety barriers.

Definition

Road safety barriers are durably installed systems either along great lengths or close to particular points alongside highways and motorways.

These systems are intended to lessen all the consequences of leaving the roadway for the vehicle and for the occupants.

Terminology

Road safety barriers are classified as

- Side barriers—used in current sections on shoulders or on central reserves when the possible impact angles are less than 45 degrees.
- Frontal Barriers—used in divergents and for isolating the points of origin of the files of side road safety barriers when the possible impact angles are between 45 and 90 degrees.

Road safety barriers are classified as

- Simple—are effective on one side only.
- Double—may be struck and behave identically on both sides under impact.

Depending on their behavior during the impact tests carried out according to the conditions defined later, the road safety barriers may be

- Flexible—May become out of shape or place during impact and may eventually hold a permanent deformation,
- Rigid—Never become out of shape or place during impact.

Qualification Criteria for Road Safety Barriers

An effective side or frontal road safety barrier should ensure the retention of a striking vehicle without excessive deceleration, the kinetic energy being totally or partially absorbed during the impact by the deformations of the vehicle and of the barrier, as well as by the friction produced.

In view of their qualifications, road side safety barriers are submitted to full-size tests under the following conditions during which they should satisfy various essential requirements.

No Jumping Over the Barrier by the Vehicle

During and after the impact, the vehicle must neither jump over nor tend to jump over the horizontal resisting members of the road safety barrier.

In a practical manner, a barrier will be considered as being not jumped over if none of the wheels pass over the horizontal members, and if the vertical displacement of the vehicle during the impact is less than the barrier height.

Decelerations of the Vehicle During Impact

The decelerations measured on the vehicle during the test should be low enough to provoke no severe injuries of the passengers who are wearing safety belts. The decelerations are characterized by the ASI index. The maximum allowable values of this index depend on the class and performance of each road safety barrier.

Recorded Damage to Vehicle After Impact

The deformations of the vehicle caused by the impact on the barrier should be restrained. They are characterized by the VIDI index. The maximum allowable values of this index depend on the class and performance of each road safety barrier. Furthermore, the intrusion of some barrier members into the cockpit of the vehicle is considered unacceptable, and the deformations should not hinder the manual opening of the doors after the impact.

Behavior of the Barrier Under Impact

If the vehicle hits the barrier, the impact should not result in a fracture of the main members of the barrier or the structure: any potentially dangerous projection of structural members of the barrier is unacceptable. The elements that determine the installation conditions of a barrier are the dynamic and static deflections. These have to be moderate enough that the installation of barriers would be possible in many sites.

Behavior of the Vehicle Under Impact

The course of the vehicle is modified at the moment of impact against the road safety barrier. The bounce of the vehicle after the impact should occur only at low speed and within a small impact angle to reduce both the risk and the consequences of a secondary collision with other vehicles.

There are three angles that are characteristic of the behavior of the vehicle after the impact.

The exit angle is the angle formed by the velocity vector of the vehicle and the axis of the safety barrier at the moment the vehicle leaves the roadway. The allowable limit value for this angle is normally taken as half of the impact angle. In some particular cases defined later, the exit angle may be greater than this value but less than the impact angle.

The yaw angle is the angle formed after the impact by the longitudinal axis of the vehicle with the direction of its motion. This angle should not exceed 90 degrees.

The roll angle is the angle formed by a fixed vertical axis with the vertical axis of the vehicle. The allowable maximum value of this angle is taken as 45 degrees.

Determination of the Installation Conditions of a Road Safety Barrier

These tests allow ascertaining, under standard conditions, the deformations (dynamic and static) occurring during and after the impact of a system of flexible road safety barriers. These experimental deflections determine the installation conditions of each safety barrier and, more especially, define the distances to be observed in front of the obstacles to ensure the efficiency of the system.

Classification of Side Road Safety Barriers

The impact tests are carried out under well-defined conditions of mass, speed, and impact angle of the vehicle on the barrier. They may be completed by other tests adapted to the specific system and aimed at estimating the behavior of the barrier under different impact conditions. These tests allow determining two classes of side road safety barriers.

Side Road Safety Barriers—Type 1

Barriers of this type should detain the light vehicles under satisfactory safety conditions. After testing by sedans of 1250-kg mass, under different conditions of speed and impact angle, the safety conditions are classified in three levels, according to the performances recorded during the impact tests.

Barriers—Level 1A

These safety barriers are tested using light vehicles traveling at 80 km/hr at an entry angle of 30 degrees, and at 100 km/hr under an impact angle of 20 degrees. The required specifications are as follows:

- Safety Barriers of Long Section. The value of the ASI index should be less than or equal to 0.8 for flexible barriers, and 1.1 for rigid barriers. The VIDI index should be 0. The dynamic deflection should be taken as 1.80 m at a maximum. The limit value of the exit angle should be taken as half of the impact angle.

- Safety Barriers for Peculiar Points. The value of the ASI index should be less than 1.1 and that of the VIDI taken as 1 at a maximum. The limit value of the dynamic deflection should not exceed 1.20 m and the exit angle should be less than the impact angle.

Barriers—Level 1B

These safety barriers are tested by using light vehicles moving at 80 km/hr at an impact angle of 20 degrees. The required specifications are as follows:

- Safety Barriers of Long Section. The value of the ASI index should be less than or equal to 0.8 for flexible barriers, and 1.1 for rigid barriers. The VIDI index should be 0. The dynamic deflection should be taken as 1.20 m at a maximum. The limit value of the exit angle should be taken as half the way-in angle.
- Safety Barriers for Peculiar Points. The value of the ASI index should be less than 1.1 and that of the VIDI should be 0 or 1. The limit value of the dynamic deflection should not exceed 0.80 m, and the exit angle should be less than the impact angle.

Barriers—Level 1C

These safety barriers are tested by using light vehicles traveling at 60 km/hr at an impact angle of 20 degrees.

- Safety Barriers of Long Section. The value of the ASI index should be less than or equal to 0.8 for flexible barriers, and 1.1 for rigid barriers. That of the VIDI index should be 0. The dynamic deflection should be taken as 0.60 m at a maximum. The limit value of the exit angle should be taken as half the way-in angle.
- Safety Barriers for Peculiar Points. The value of the ASI index should be less than 1.1 and that of the VIDI should be 0 or 1. The dynamic deflection should be 0.40 m at a maximum. The exit should be less than the impact angle.

Side Road Safety Barriers—Type 2

These barriers should retain the heavy vehicles under satisfactory safety conditions. They are classified in three levels according to the performances recorded during the tests. The limit value of the ASI index is taken as 1.1.

Moreover, the side road safety barriers for heavy vehicles should meet the conditions required for qualification of a side road safety barrier for peculiar points at Level 1B.

Barriers—Level 2A

These safety barriers are tested by using heavy lorries of 38 tons traveling at 70 km/hr at an impact angle of 20 degrees. The dynamic deflection should be taken as 1.80 at a maximum.

Barriers—Level 2B

These safety barriers are tested by using heavy lorries of 12 tons traveling at 70 km/hr at an impact angle of 20 degrees. The dynamic deflection should be taken as 1.20 at a maximum.

Barriers—Level 2C

These safety barriers are tested by using heavy lorries of 3.5 tons traveling at 70 km/hr at an impact angle of 30 degrees. The dynamic deflection should be taken as 0.60 at a maximum.

Classification of Frontal Road Safety Barriers

The impact tests are carried out under well-defined conditions of mass, speed, and impact angle of the vehicle on the barrier. They may be completed by other tests adapted to the specific system, and aimed at estimating the behavior of the barrier under different impact conditions: center frontal impact, off-center frontal impact, and side impact.

Side road safety barriers for light vehicles are classified in three levels according to the performance recorded during the tests.

Barrier Levels	Impact Speed (km/hr)
A	100
B	80
C	60

For the centered and off-centered frontal impact tests, the values of the ASI index should be less than 1.1 and the VIDI index taken as 0. Under side impact, the frontal safety barriers for light vehicles should meet the required conditions for the qualification of side safety barriers of Type 1 for peculiar points, Levels 1A, 1B, or 1C.

APPENDIX E PERFORMANCE CLASSES PROPOSAL

In order to draw up performance classes and because of the differences currently existing in national regulations or standards, the following four study stages are proposed:

- Selection of criteria characterizing the test severity,
- Classes of lateral permanent systems,
- Classes of lateral temporary systems, and
- Classes of frontal systems.

Severity Criterion

At first, the study was based on a criterion representing the severity of an accident on a barrier. The criterion most frequently mentioned relates to transverse kinetic energy to be absorbed by the barrier. This index is expressed

$$\text{Is} = M(V \sin a)^2/2 \quad \text{(joules)}$$

where M is vehicle mass in kilograms and V is speed in m/sec.

Theoretical Approach

Figure E-1 shows the vehicle mass M as X-coordinate (logarithmic scale) and the product $(Vx \sin a)^2$ as Y-coordinate, which allows the assessment of the main European statutory tests, corresponding to the main system classes. The curves representing the isovalues of Is allow evaluating and comparing the severity of these different classes. This demonstrates the bimodal aspect of the problem, on the one hand the passenger cars being retained, and on the other hand the heavy vehicles being retained. In addition, an intermediate level including heavy vehicles at low impact angles as well as duty vehicles (Is 4000) can be defined.

When considering the main classes, these two classes are distributed between two envelope curves that are relatively easy to determine.

Classification Levels

A first attempt to determine the different classes consists of proposing classes that envelope the two main classes, i.e.,

- Passenger cars being retained,
  - A low class at about Is 1000,
  - A standard class at about Is 2000,
- Heavy vehicles being retained,
  - A standard class at about Is 8000, and
  - A high-capacity class at about Is 16 000.

In addition, an intermediate class about Is 4000 may also be contemplated. But the French experience tends to prove that the setting up of such a class is of minor significance.

Test Conditions

Because of the four or five classes defined, the first proposal is the following one:

- Passenger car level.
  - Class 1: 20 degrees, 80 km/hr, vehicle weight 1250 kg.
  - Class 2: 30 degrees, 80 km/hr, vehicle weight 1250 kg.
- Heavy vehicle level.
  - Class 1: 20 degrees, 70 km/hr, vehicle weight 13 000 kg.
  - Class 2: 20 degrees, 70 km/hr, vehicle weight 26 000 to 30 000 kg.

If required, an intermediate class can be defined.

Vehicles

To define the type and make of the test vehicles does not seem realistic. But it seems possible to determine the vehicle classes, including requirements on the vehicle architecture as well as a range of empty weights, the mass being defined by the standard. With regard to heavy vehicles, it is important to define their type and load configuration. In addition, the vehicles tested should be marketed vehicles.

System Use Type

Once there performance class is determined, the selection of the retaining system essentially depends on the space available on the roadside. The German

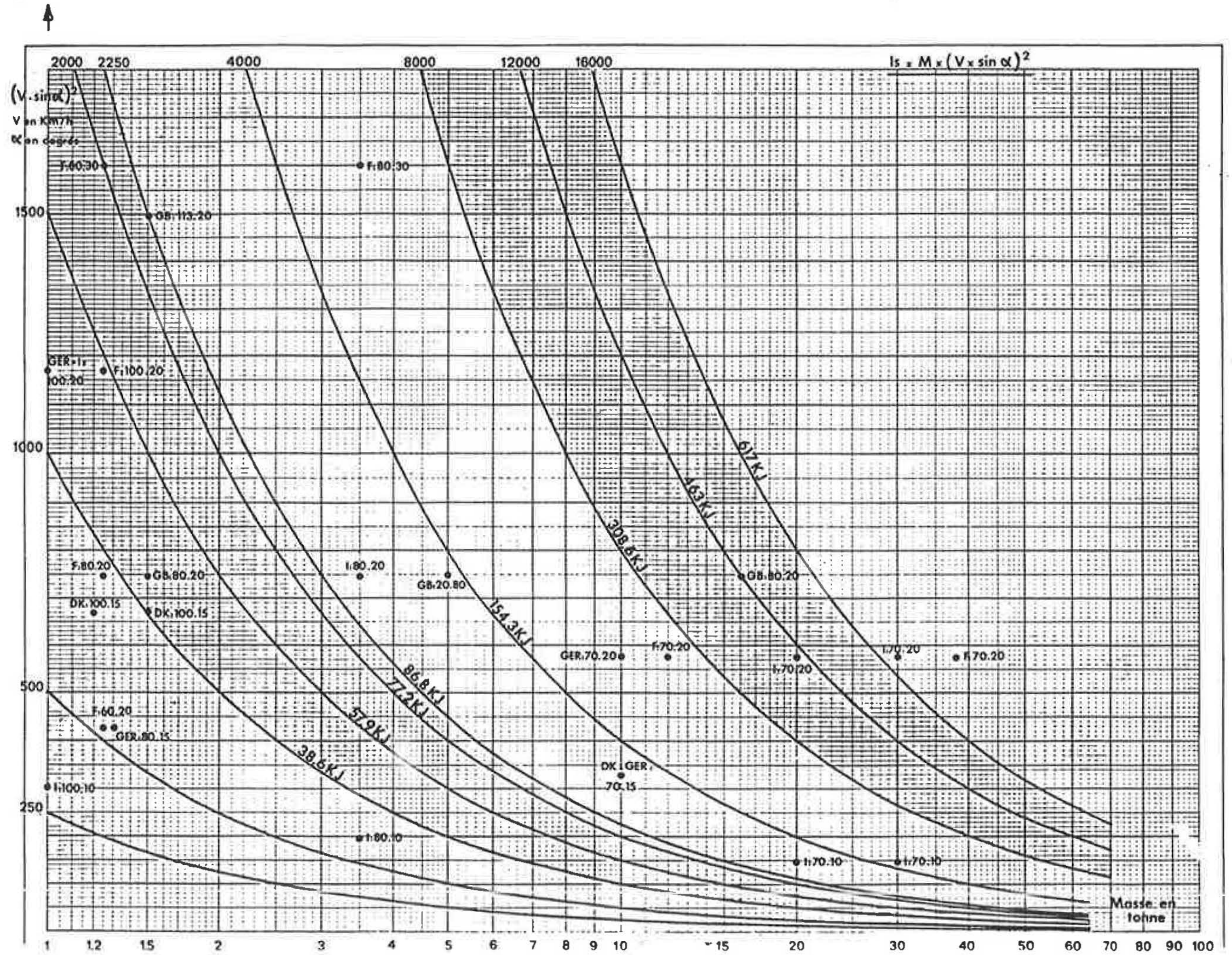


FIGURE E-1 Severity index (IS).

proposal, which consists of defining the retaining system according to the distance required for good operation, appears to be very interesting. Therefore, two, or even three, user classes, could be contemplated:

- A class corresponding to a maximum dynamic deflection equal to 0.60 m under design-basis test conditions,
- An intermediate class with a maximum distance of 1 to 1.20 m, and
- A standard class with a maximum distance less than 1.60 m.

Temporary Lateral Systems

The use of such systems, essentially aimed at ensuring safety in road work areas, is relatively recent and therefore fewer studies are available compared with studies for permanent systems. Nevertheless, it seems that there is a relatively wide range of systems. In several cases, limited-speed conditions are provided in addition, with lower impact angles caused by traffic channeling, which justifies the use of lower-performance systems.

Therefore, for temporary systems, a class range that includes the classes defined for permanent systems is proposed—including, if required, the Is 4000 class, to which should be added two additional classes with Is values of 500 and 250. The test conditions for a 1250-kg vehicle and an 80-km/hr speed lead to impact angles of 15 and 10 degrees, respectively.

APPENDIX F FILTERING TECHNIQUES

Both the THIV and the flail space model concepts use output from accelerometers and transducers located as close as possible to the center of gravity of the test vehicle. For comparison of the two models, the filtering or signal conditioning techniques used on transducer outputs need to be evaluated.

Theoretical Head Impact Velocity (THIV)

After initial signal conditioning, which includes a 10,000-Hz flat to 0.5-dB analogue filter, the transducer output is recorded as an analogue signal on magnetic tape. All the signal conditioning and filtering conform to J211B. On playback, the signals pass through a CFC 60 low-pass filter and are digitized at 16,000 samples per second. The digitized signal is then filtered with a 10-Hz 48- dB/ octave filter; the 10-Hz filter cut-off frequency determined that deceleration and vibrational effects of individual vehicle components are reduced so as not to influence the velocity and trajectory analysis of the vehicle. On input into the THIV analysis program, the values at each millisecond are used for evaluating the vehicle trajectory and THIV in graphical output. In tabular output, the acceleration values average 16 samples per millisecond.

Flail Space Model

The filtering technique used in the flail space model is defined in NCHRP Report 230 and conforms to J211B. The accelerometer signals are filtered by a CFC 180 filter before single and double integrations, to produce the distance traveled before impact with the interior of the passenger compartment and the velocity at that distance.

In calculating the ride-down accelerations, a moving 10 msec average instantaneous acceleration technique is used to remove spikes of less than 7 m/sec, which are deemed not to be critical.

Figure F-1 shows the frequency characteristics of the 10-Hz, 40-dB digital filter used in the THIV model with the standard CFC 180 filter and 0.01-sec time filter for ride down accelerations.

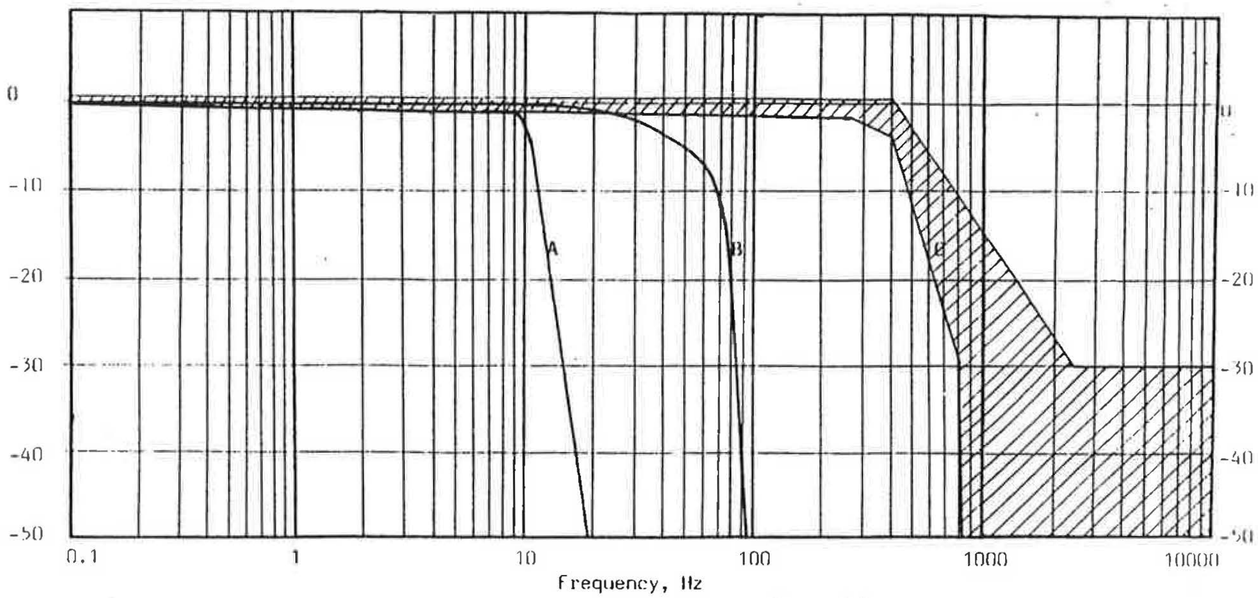


FIGURE F-1 Comparison of the frequency response characteristics of filters used in the theortetical head impact velocity and flail space model.