APPENDIX A

COMMENTARY

Further discussion and elaboration are provided on certain sections in the text. Those sections for which commentary is given correspond to section numbers in the text preceded by the letter "A." For example, "A3.2.1" refers to Section 3.2.1 in the text.

CHAPTER ONE

A .1.1

Vehicle crash tests are complex experiments that are not easily replicated because of difficulties in controlling critical test conditions such as speed, angle, and condition of test vehicle and the sometimes random and unstable behavior of dynamic crush and fracture mechanisms. Testing guidelines are intended to enhance precision of these experiments while maintaining their costs within acceptable bounds. User agencies should recognize the limitations of these tests and exercise care in interpreting the results.

It is impractical or impossible to duplicate the innumerable highway site and safety feature layout conditions that exist in a limited number of standardized tests. Accordingly, the aim of the guidelines is to normalize or idealize test conditions. Hence, straight longitudinal barriers are tested, although curved installations exist; a flat grade is recommended, even though installations are sometimes situated on sloped shoulders and behind curbs. These normalized factors have significant effect on a barrier's performance and may obscure serious safety deficiencies that exist under more typical but less ideal conditions. However, these normalized factors are thought to be secondary in importance when the object of a test program is to compare the results of two or more systems. Moreover, the normalized conditions are more easily duplicated by testing agencies than say, a unique feature. Consequently, they should promote correlation of results from different groups. Nevertheless, when the highway engineer requires the performance of a system for specified site conditions (such as a unique soil or curb layout) or the performance of a safety feature is suspected of being unacceptable under some likely conditions, it is important that these conditions be used instead of, or in addition to, the idealized conditions.

These guidelines are intended for use with highway safety features that will be permanently or temporarily installed along the highway. Temporary features are generally used in work or construction zones or other temporary locations and their duration of use is normally relatively small. An important additional characteristic of a work zone is the exposure of work zone personnel to errant traffic. Thus, a barrier in a work zone may be required to (1) redirect errant traffic away from a roadside hazard of other traffic and (2) to shield workers from errant vehicles. Depending on specific site conditions, potential collision severity may equal or even exceed conditions found at typical nonconstruction zone sites.

A1..2

The intent of this section is to make the designer/developer of a safety feature aware of the process that must typically be followed and aware of available tools so that the most cost-effective approach or combination of tools may be selected. This report does not endorse or approve any one design method, procedure, or analytical technique or suggest that one procedure is equivalent to another. Rather, the basic purpose of the report is to provide guidelines for the full-scale crash testing and in-service evaluation of a feature once a decision has been made to proceed with step 4 of Figure 1.1. Users of the document should follow as closely as practical the recommended guidelines. Acceptability of a complementary technique in lieu of, or in addition to, full-scale crash testing is a policy decision beyond the purview of this report.

As indicated in steps 2 and 3 of Figure 1.1, there are various design and analysis tools and experimental tools that can be used in the initial development of a safety feature. Reference should be made to Appendix D for information on these tools. Also, as indicated, the developer should be cognizant of the various factors, other than those related to impact performance, that must be considered in the development of a feature. Conventional structural analysis and design techniques are most useful in early development stages of a safety feature.   Computer simulations of the vehicle/feature dynamic interactions are useful in gaining insight for a wide range of impact conditions. The potential for obtaining valuable insight from simple static tests of components and assemblies should not be overlooked.

CHAPTER TWO

A2.2.1

Impact performance of many longitudinal barriers and breakaway or yielding support structures depends on strength and fixity of the soil foundation. Soil foundation is an integral part of such systems. For example, displacement and/or rotation of a breakaway device footing during collision can adversely affect the fracture mechanism. Insufficient soil support can lead to excessive guardrail post movements and guardrail lateral deflection during vehicle collision and result in a lower system capacity to contain and redirect errant vehicles. Insufficient soil strength can also be a critical and limiting factor for the anchoring function of a longitudinal barrier terminal. On the other hand, an unusually firm soil can increase the lateral stiffness of a longitudinal barrier and subject occupants of a colliding vehicle to undue hazard.

Soil conditions along the highway are variable. Strength is a function of soil type and ranges from soft sand materials to hard rock materials; moreover, the soil type may vary considerably within a locale as well as from region to region. Soil strength may also be a function of the season as it can be significantly affected by moisture content and whether it is frozen. The testing agency should be aware of the importance of soil strength and select the most appropriate soil type consistent with potential application of the feature.

Recommended soils are well-graded materials that should be readily available to most testing agencies. The standard soil of Section 2.2.1.1 is a selected AASHTO material that compacts to form a relatively strong foundation. The weak soil of Section 2.2.1.2 is a typical

AASHTO fine aggregate. These soils are essentially the same as the "strong" and "weak" soils of NCHRP Report 230.

The following general guidance is offered the user agency and the testing agency in soil selection:

Standard Soil

Unless the test article is limited to areas of weak soils, the standard soil should be used with any feature whose impact performance is sensitive to soil-foundation or soil-structure interaction. A large percentage of previous testing has been performed in similar soil and a historical tie is needed. Although it is probably stronger than the average condition found along the roadside, it is still representative of a considerable amount of existing installations.

Weak Soil

The weak soil should be used, in addition to the standard soil, for any feature whose impact performance is sensitive to soil-foundation or soil-structure interaction if identifiable areas of the state or local jurisdiction in which the feature will be installed contain soil with similar properties, and if there is a reasonable uncertainty regarding performance of the feature in the weak soil. Tests have shown that some base-bending or yielding small sign supports readily pull out of the weak soil upon impact. For features of this type, the strong soil is generally more critical and tests in the weak soil may not be necessary.

In addition to soil selection, the footing or foundation used in a test of a breakaway support structure should be designed for the minimum wind conditions permitted, thus yielding a minimum footing mass and size; a larger footing will yield a greater breakaway device fixity and, hence, is less critical.

It has been shown that the standard soil of Section 2.2.1.1 is especially sensitive to moisture content. The testing agency should sample and test the soil to insure moisture content is within recommended limits given in the specification at the time of the test.

A2.3.1

Failure or adverse performance of a highway safety feature during crash testing can often be attributed to seemingly insignificant design or construction details, something as innocuous as a substandard washer. For this reason it is most important to assure that the test article has been properly assembled and erected and that critical materials have the specified design properties. Details of most concern are those that are highly stressed (such as welded and bolted connections, anchor cables, cable connections, and concrete footings) or those that must fracture or tear away during impact (such as transformer bases or weakened barrier posts). Compressive tests of concrete cylinders, proof tests of cable assemblies, and physical and chemical properties of materials, in general, should be performed on a random sample of the test article elements or obtained from the supplier of the material. Even though well-defined material specifications

and appropriate fracture modes may not be fully developed, the properties of all material used in the test article should be documented in detail in the test report.

A2.3.2.1

Proper judgment must be exercised in establishing test installation length. In specifying minimum length of a longitudinal barrier installation, the intent is to minimize influence of terminals and thereby simulate a long barrier. Also to be considered is the possible need to extend the barrier installation to observe a second collision between vehicle and barrier.

A2.3.2.4

See commentary in Section A3.2.4.

A2.4.1

The vehicle's design and condition at the time of testing can have major influence on the dynamic performance of a feature. Among the more important parameters are vehicle bumper height, configuration, and stiffness; vehicle mass distribution and suspension system; and vehicle structure. For these reasons the test vehicles should correspond closely to the recommended vehicle properties.

A2.4.1.1

Changes have occurred in the vehicle fleet since publication of NCHRP Report 230. Automobiles with curb masses of 725 kg and less are now operating on U.S. highways. The typical family sedan now has a mass somewhere between 900 kg and 1800 kg with only the expensive luxury cars and a few station wagons weighing more than 1800 kg. The mix also contains a significant number of "light-duty trucks," such as pickups, vans, Suburbans, Blazers, Broncos, etc., and "recreational vehicles," such as van conversions (customized vans), motor homes, etc. A significant portion of the light-duty trucks has a mass over 1800 kg. Many, if not most, of the light-duty trucks, in fact, serve as a passenger vehicle as opposed to a commercial or utility vehicle. Cars and light-duty trucks are combined herein into a single "passenger vehicle" category.

Sales of trucks above the light-duty category totaled 368,703 in 1988. These are trucks with a gross vehicle mass in excess of 4500 kg. Of this total, 40% were in the 15,000 kg and over category.

Unfortunately it is difficult, at best, to project even short term trends in the vehicle mix due to the volatile and unpredictable nature of factors that influence vehicle design. Due to the intense competitive and proprietary nature of the automobile industry, future vehicular design data are simply not available. Further, the development cycle time from inception to production of a new model has been decreasing over the years and is projected to continue to decrease. Perhaps the best available source for projected trends in automotive design is a recent report prepared by the University of Michigan (54). The study was conducted in 1988 and it was the fifth in a series of Delphi surveys of high-level automotive industry leaders. According to the

report, "More than 300 CEO's, presidents, vice presidents, directors, and managers - organized into three panels - responded to 160 questions concerning technological, marketing, and materials developments within the automotive industry through the year 2000." One of the many projections of this study was that the "expected total vehicle weight will remain fairly constant through the year 2000 based on present fuel economy regulations and vehicle sizes." However, it was predicted that there will be a slight downward trend in weights due primarily to the increased use of structural composites. The total curb mass for the average North American produced passenger car was predicted to be between 1375 kg and 1430 kg for model year 1985 and between 1335 kg and 1380 kg for model year 2000. The average weight for the 1987 model year was estimated to be 1440 kg.

Upon review of available data and after careful review of various options, the recommended test vehicles listed in Tables 2.1 and 2.2 were selected. Consideration was given to including a vehicle more representative of the automobile population, i.e., a car with a mass of approximately 1550 kg. In some special cases it may be possible to design a feature to meet the performance recommendations for the 820C and 2000P test vehicles, leaving a potential problem for the typical car. A crash cushion is one such feature. It may also be possible for a longitudinal barrier to perform satisfactorily for the small and large vehicles but exhibit a snagging problem for the typical car. However, tests with a typical car were ultimately dismissed for three basic reasons: (1) they would not, in most cases, reveal problems that would not be identified with the 820C and 2000P vehicles, (2) technology has advanced to the point that potential problems with a typical car can usually be foreseen prior to the testing phase of the feature's development or can be inferred upon careful review of the recommended tests, and (3) they would significantly increase the cost of testing. If after exhausting all design and evaluation procedures a reasonable doubt remains, additional tests with the typical car may be warranted.

Test Vehicle 700C

This is a new test vehicle and it represents the very low end of the passenger car spectrum in terms of mass. Test experience with this vehicle is limited. Reference should be made to a study of the impact performance of widely-used highway safety features for a vehicle similar to 700C (7). In general this study found that acceptable impact performance can be expected for impacts with rigid and semirigid longitudinal barriers. As expected, marginal or unacceptable performance can be expected for most in-service features sensitive to the mass of the impacting vehicle, such as terminals, crash cushions, and some support structures. It was predicted that most support structures utilizing a slip-base breakaway device or other devices with similar behavior would have acceptable impact performance. Even so, it was pointed out that impact performance of slip-base devices for a 700C type vehicle is much more sensitive to factors such as bolt torques (and, hence, breakaway force), frontal crush stiffness of vehicle, and proper activation of the upper hinge in a sign support than a larger vehicle. It was also reported that more overturns can be expected with a vehicle of this size due to its inherently lower stability. Roadway or roadside surface discontinuities or irregularities such as curbs, ruts, and vegetation that would not upset a sliding larger vehicle would cause this vehicle to overturn.

Although agencies should consider the 700C vehicle in safety feature development, its use in lieu of the 820C vehicle should be viewed as desirable but not required. A suggested policy is to design for the 700C vehicle when it can be done cost effectively.

Test Vehicle 820C

The recommended test inertial mass of the 820C test vehicle (820 kg or approximately 1800 lb) is essentially the same as the 1800S vehicle of NCHRP Report 230. It was chosen as a basic test vehicle for the following reasons: (1) it is representative of a reasonable portion of passenger cars at the lower end of the spectrum in terms of mass, (2) although tenuous, predictions suggest minor changes in passenger car sizes over the next 10 years, and (3) its use will provide linkage with a considerable crash test database accumulated since publication of Report 230.

Although several makes of cars were used for the 1800S vehicle of Report 230, the vast majority of tests were conducted with Honda Civics of various model years. In recent years the mass of the Civic has increased to the point that it can no longer be used as an 1800S test vehicle. While a specific vehicle make was not recommended in Report 230, the unofficial adoption of the Honda Civic as the standard for the 1800S vehicle had its obvious advantages.

A specific make for the 820C vehicle is not required herein either. However, in view of the diversity of key vehicular properties of small cars (see, for example, the variations in frontal crush stiffness of small cars reported in reference 7) and in view of the population differences of available makes, consideration should be given to the selection of an "unofficial" make for the 820C vehicle. After reviewing candidate vehicles that would meet recommended properties for the 820C vehicle for at least through 1996, it was concluded that the Ford Festiva should be given strong consideration as an unofficial 820C test vehicle. Sales of the Festiva exceeded other cars in the sub-820 kg category for the 1987-1990 model years. It should therefore be readily available.

Test Vehicle 2000P

A pickup truck was selected to replace the full-size automobile widely used in the past (4500S vehicle in Report 230) for the following reasons:

(1) Sales of light-duty trucks, in general, and pickup trucks, in particular, have increased to the point that they now constitute a significant portion of all passenger vehicles operating on U.S. highways.

(2) Full-size automobiles with the mass of the 4500S test vehicle (2040 kg) are no longer sold in the U.S. with the exception of a few expensive luxury cars. The nominal mass of a full-size family sedan now being sold in the U.S. is about 1350 kg.

(3) Although there are structural and profile differences, the recommended 2000 kg pickup will produce impact loading reasonably similar to the 4500S vehicle of Report 230. Limited full-scale crash tests with an instrumented wall (17) indicate that a pickup will produce a maximum impact force slightly less than that of an automobile

of equal mass, whereas the effective height of the impact force will be slightly higher for the pickup, all other conditions being equal. Consequently, the 2000P test vehicle is expected to provide linkage with the numerous tests conducted with the 4500S vehicle.

A 3/4-ton pickup is recommended for the following reasons:

(1) Section 1073 of the Intermodal Surface Transportation Efficiency Act of 1991 mandated the development of standards for roadside barriers and other safety appurtenances "...which provide an enhanced level of crashworthy performance to accommodate vans, minivans, pickup trucks, and 4-wheel drive vehicles..." The 3/4-ton pickup is believed to be representative of a large segment of the light-duty truck population. The light-duty truck population includes large numbers of conversion vans on 3/4-ton chassis, Blazers, Broncos, and pickups with and without 4-wheel drive, pickups with campers, minivans, etc., whose mass and center of mass above ground approximate those of the 3/4-ton pickup. However, the exact degree to which features designed to meet test and evaluation requirements recommended herein will satisfy the intent of Section 1073 is not known at this time. Impact performance of any given feature is known to be sensitive to small changes in test parameters, especially those associated with the test vehicle. It must also be noted that some 4-wheel drive vehicles, as well as some conventional-drive vehicles, are either manufactured or customized by their owners to have oversized tires, extended suspension systems, small track widths, etc.. These design features can greatly diminish a vehicle's stability, i.e., its resistance to overturn. It is not economically feasible to design safety features to accommodate vehicles of this type.

(2) Very little, if any, ballast will be needed to meet the recommended test inertial mass.

(3) Use of a specific pickup type will enhance test standardization.

Test Vehicles 8000S, 36000V, and 36000T

These three heavy vehicles were selected for use in crash test evaluation of longitudinal barriers designed for the higher test or service levels. Several tests have been conducted with each of the three vehicles. Studies have indicated heights of approximately 81 cm, 107 cm, and 205 cm will be required for rigid barriers for the 8000S, 36000V, and 36000T vehicles, respectively, when ballasted as recommended.

Note in Table 2.2 that some of the dimension parameters have a suggested maximum value but no minimum value. This was done for two basic reasons: (1) it allows the testing agency more flexibility in purchasing the test vehicle and (2) impact loads will tend to increase as the value of these parameters decrease. Thus, although it is preferable to select vehicles with parameters near the maximum permissible values, lower values will provide an added factor of safety in the test.

Testing and user agencies should be aware of potential problems that may occur with a test using the 36000V test vehicle. In particular, the undercarriage attachment of the trailer

tandems to the trailer frame may not be of sufficient strength to provide necessary restraint during the specified test. This problem is believed to be peculiar to sliding undercarriage or sliding axle designs. In at least one test, the attachment (which was the sliding undercarriage type) failed due to an inability to transfer lateral impact loads and the trailer went over the barrier. In a similar test with a fixed undercarriage attachment, no such failure occurred and the trailer did not go over the barrier. A sliding attachment is recommended for the test trailer since it is widely used in the industry. While it is desirable to test with widely-used vehicles and equipment, the primary purpose of the test is to demonstrate structural adequacy of the barrier, not the trailer. A barrier capable of containing a trailer with a sliding axle may have to be considerably taller than one capable of containing a trailer with a fixed axle. Nevertheless, public safety requires effective containment of vehicles on the road. If testing reveals this defect in trailer design will cause significant increases in the cost of effective barrier designs, support should be sought from appropriate officials and agencies to develop improved trailer designs and possibly the retrofitting of existing designs.

Each of the above test vehicles should be in sound structural shape without major sheet metal damage. Use of a vehicle for more than one crash test without repairs should be avoided because vehicle damage may affect performance in a subsequent test. This is particularly important in evaluating safety features such as a breakaway support where vehicle crush significantly affects the fracture mechanism.

A2.4.1.2

An emerging trend in evaluating impact performance of selected features is the use of surrogate test devices such as a bogie vehicle or a pendulum. A bogie vehicle is now being used by FHWA at the Federal Outdoor Impact Laboratory (FOIL) facility for compliance testing of breakaway sign and luminaire supports. It has exhibited a good degree of repeatability in replicating the response of a small car. Another key attribute is its relatively low cost of operation.

A wheeled bogie vehicle and a swinging pendulum with a crushable nose are the two primary types of surrogates used to date. While the pendulum can be used to evaluate certain aspects of impact performance, it is limited in terms of impact speed and replication of the postimpact behavior of an actual vehicle. It is also limited basically to single-support type structures. For certain features the bogie can replicate the full, three-dimensional dynamic behavior of an actual vehicle for the full range of design impact speeds. Although the following discussion will concentrate on the wheeled bogie, issues relevant to the pendulum are also relevant to the bogie.

A bogie is defined as a surrogate vehicle mounted on four wheels whose mass and other relevant characteristics match a particular vehicle or are representative of a typical or generic vehicle. It can be directed into the test article by a guide rail or cable, by remote control, or other means. It can be accelerated to impact speeds up to about 100 km/h by a push or tow vehicle, by self-power, or by a stationary windlass. The cost of operation is low since it can be reused without major repairs.

In addition to mass, properties such as frontal crush stiffness, weight distribution and center-of-mass location, dimensional properties including wheelbase and track width, and tire properties can be adjusted to represent a selected vehicle. Frontal crush stiffness can be simulated by adjusting the size and type of crushable modules.

Currently, the bogie at the FOIL is the only operational one in the U.S. designed for roadside safety studies. It is presently configured and has been validated to replicate a 1979 Volkswagen Rabbit. However, automobiles weighing from 635 kg up to 1,020 kg can be modeled. At the time of this writing, the California Department of Transportation (Caltrans) was developing two bogies for its California Automotive Research Test Site (CARTS) located at the University of California at Davis. One will cover weight ranges of 680-1,360 kg and the other will cover the range of 1,350-2,725 kg. The CARTS bogies can be configured with or without a suspension system (i.e., springs, shock absorbers, and suspension stops). The FOIL bogie does not have a suspension system. The FOIL bogie vehicle has exhibited a good degree of repeatability in replicating the response of a small car impacting breakaway support structures.

It is recommended that the surrogate be configured to model a specific vehicle, as opposed to a generic vehicle, with the stipulation that the vehicle being modeled meet specifications for production model test vehicles, i.e., specifications that define tolerances on age, weight, etc. This is by far the least expensive of the two options since properties of only one vehicle have to be measured and the validation process involves crash testing with only one vehicle model.

It would be desirable for FHWA or NCHRP to establish a project in which all bogie properties would be updated and validated periodically to keep current bogies within specifications. This would not only be the most efficient approach since each testing agency would not have to do it independently, it would insure uniformity throughout the testing community.

A2.4.1.3

See commentary in Section A3.2.4.

A2.4.2.2

Ballast for test vehicles that is free to shift or that can break loose during impact may be totally ineffective or only partially effective in initial loading of the feature because it tends to move independently of the vehicle. Unless specifically designed to evaluate effects of cargo shifting, tests with the 8000S and 36000V vehicles are to be conducted with a firmly secured ballast. The tie-down system should preferably be capable of resisting a lateral load equal to approximately ten times the weight of the ballast.

It must be noted, however, that test experience has shown that it is quite difficult to design a ballast tie-down system for a van truck or trailer with sufficient strength to resist typical impact loads for two reasons: (1) the absence of lateral stiffness in the walls of the van and (2) the height the ballast must be placed above the floor of the van to achieve the recommended

center of mass of the ballast. For reasons of economy and convenience, sand bags on pallets are commonly used as a ballast in tests of van trucks or van trailers. While this achieves the required mass and center-of-mass height, it is difficult to secure this type of ballast and it creates a concentrated lateral load at some height above the floor of the van during impact. It would be preferable to use a ballast material with a density as low as possible so that the ballast would be uniformly distributed along the length, width, and height of the van, thus minimizing the need and structural requirements of the tie-down system. Bales of hay have been used as a relatively low density ballast.

A2.4.3

Because front wheel brakes of the test vehicle are sometimes damaged during impact, remotely actuated brakes are generally applied to the rear wheels only. This braking mode may cause the vehicle to yaw or spin during after-collision trajectory. For this reason braking should be delayed as long as safely feasible so that the unbraked after-collision trajectory can be observed. One suggestion is to use diagonal wheels, the front wheel away from impact and the impact-side rear wheel for braking in order to reduce vehicle spin. This practice would also be representative of brake designs on many automobiles. In any case, vehicle position at the time of brake application should be noted in the report.

A2.5

The automobile manufacturers and the National Highway Traffic Safety Administration (NHTSA) have devoted considerable effort in upgrading responsiveness and measurement techniques for dummies, primarily in the chest and head/neck regions. New and highly advanced dummies such as Hybrid III and Eurosid (developed in Europe) have been developed with 40 or more channels of data. However, it was concluded that the greatly increased cost of acquiring, maintaining, and applying dummies of this type and the added complexity of and demands on data acquisition and data reduction systems would more than offset the added benefits that may be realized in roadside safety design. Use of these dummies is therefore optional. Effectiveness of dummies that preceded Hybrid III and Eurosid in accurately quantifying the severity of a crash test has been found to be very limited. They are, therefore, not recommended except for use in studying the gross motion of an occupant and/or in studying the added mass effects of an occupant.

Also, expanded use is being made of sophisticated collision victim simulation computer simulation models. The CVS model developed under sponsorship of **NHTSA** is a three dimensional model with many features and complexities. To use it to evaluate a crash test one would input the response of the test vehicle into CVS, and the program would compute the dynamic response of an occupant positioned anywhere in the passenger compartment for either a restrained or an unrestrained condition. However, the amount and complexity of input data required for its use, the cost of running the program and, more importantly, the absence of any past record of performance and demonstrated efficacy of the program in the assessment of crash tests by the roadside safety community essentially precludes its application at this time.

CHAPTER THREE

A3.1

The "multiple service level" (MSL) concept for highway safety features was first introduced in NCHRP Report 239 (55). This study only addressed bridge railings. Report 230 adopted the MSL concept to a degree. Table 3 in NCHRP Report 230, "Crash Test Conditions for Minimum Matrix," provided testing for a MSL of 2. Table 4 of Report 230, "Typical Supplementary Crash Test Conditions," provided testing for an MSL of 1 and 3. The supplementary matrix applied primarily to longitudinal barriers. In recent years there has been an increased interest in the concept, not only for longitudinal barriers but for other features. AASHTO recently endorsed the MPL concept for the design of bridge railings (29). Three performance levels were selected for bridge railings.

For the present document it was decided that "test level" would be a more appropriate term than "service level." Selection of the recommended set of test levels and associated test conditions was based on the collective judgment of the researchers and the advisory panel after carefully reviewing past and current practices and anticipated future needs. It was also made in close collaboration with those responsible for developing AASHTO policies relevant to the safety performance of bridge rails and sign and luminaire support structures. The advantage of this approach is that it utilized current information and it reflects the combined expertise of a cross-section of disciplines and agencies directly involved in the full array of roadside safety issues. The disadvantage is that some of the decisions were, of necessity, based on limited quantitative data. As noted in the text, there are no warrants or criteria that identify roadway classifications, traffic conditions, traffic volumes, etc., for which a safety feature meeting a given test or performance level should be used. Given the choice, it would be preferable to first establish conditions or warrants for which features having given capabilities would be cost effective and thereby define appropriate test levels than to first establish a set of test levels with the uncertainty as to where features developed to meet these levels would have application. If and when warrants for multiple test level features are developed, it is possible that some of the levels will prove to be unnecessary or redundant and/or that other levels are needed.

A3.2

Errant vehicles of all sizes and classes leave the travelway and strike highway safety features with a wide range of speeds, angles, and attitudes. It should be a goal of transportation officials to design safety features that will satisfactorily perform for this range of impact conditions. Combinations of vehicle speed, mass, and approach angle that occur are unlimited. However, impact conditions must be reduced to a very limited number to keep an evaluation test series within economic and practical bounds. The approach used in formulating the recommended test conditions is to evaluate the devices for cases that are very severe, yet practical. Accordingly, there is no assurance that a safety feature will perform acceptably with other vehicle types presently in service or those vehicle types that may come into use during the normal service life of the device.

For test levels 3 through 6 and for the passenger test vehicles (700C, 820C, and 2000P), features are tested at a 100 km/h speed instead of the 89 km/h limit applicable to all highways

other than rural freeways (most of which have a 105 km/h limit). Since a large percentage of high-speed travel occurs on other than rural freeways, the 100 km/h test speed should provide some degree of additional conservatism to the design of a feature. In addition to examining safety features for a range of impacts, the low-speed tests are important for certain features since they explore the activation of fracture or breakaway devices at relatively low kinetic energy levels.

A3.2.1

For test levels 4 through 6 and for the truck test vehicles (8000S, 36000V, and 36000T), longitudinal barriers are tested at a speed of 80 km/h. This is in recognition that speed limits for trucks are generally lower than for passenger vehicles. Also, most truck tests have been conducted at 80 km/h and linkage to past practices is desirable.

While vehicles leave the travelway and impact barriers within a wide spectrum of angles, most reported collisions with longitudinal barriers occur at impact angles less than 25 deg with the majority less than 15 deg. Historically, the 25 deg impact angle has been accepted as a practical worst case and the 15 deg approach angle as a more typical collision condition. The 25 deg angle test with the 2000P vehicle has been retained in the present document and is intended as a strength test for test levels 1 through 3. Tests with vehicles 8000S, 36000V, and 36000T are at 15 deg and are intended as strength tests for test levels 4, 5, and 6, respectively.

Since publication of Report 230 there has been a recognition and acceptance that while the 15 deg impact angle is more typical, a 20 deg angle is more discerning for tests with the 820C vehicle. The 20 deg angle has therefore been adopted for evaluating the impact severity of longitudinal barriers.

Critical impact point (CIP) is a new concept in testing of longitudinal barriers and other features. Rather than requiring the initial impact point to be at a specified point, e.g., midway between posts in Report 230, it is recommended that an effort be made to determine the CIP or the point with the greatest potential for causing a failure of the test. Failure can be caused by excessive snagging or pocketing of the vehicle, fracture of the barrier, vehicular override or underride of the barrier, vehicular overturn, etc. Suggested procedures for determining the CIP are given in Sections 3.4 and A3.4.

A3.2.2

Terminals and crash cushions function in the same or similar manner, i.e., they either bring the vehicle to a controlled stop, redirect the vehicle, allow controlled penetration of the vehicle, or a combination thereof. However, since any given design will generally not function in all three of these modes, it was necessary to categorize the recommended test matrices.

The two major categories are "terminals and redirective crash cushions" and "nonredirective crash cushions." This was done in recognition that there are two distinct types of crash cushions widely used in the U.S., i.e., those that redirect a vehicle if impacted along their length and those that do not, and in recognition that both types have proven very effective in reducing roadside hazards when properly applied. As noted in the text, terminals and

redirective crash cushions are subjected to a more rigorous and demanding test series than nonredirective crash cushions. Consequently, impact performance capabilities of a redirective crash cushion will generally be greater than for a nonredirective cushion. Determining site conditions for which each type would have application is the responsibility of the user agency and was beyond the scope of this document.

Terminals and redirective crash cushions are further categorized into "gating" and "nongating" devices. As a general rule, a gating device is designed to allow controlled penetration of the vehicle for impacts upstream of the beginning of the length of need (LON). The breakaway cable terminal and its successor, the eccentric loader terminal, are examples of a gating device. As a general rule, a nongating device will redirect the vehicle if impacted along its side and brings the vehicle to a controlled stop if impacted on its end. The "GREAT" terminal (56) is considered to be a nongating device. Unfortunately, these subcategories do not uniquely describe the manner in which all terminals and redirective crash cushions function. For example, the "ET-2000" terminal (57) permits controlled penetration along portions of its length and it brings the vehicle to a controlled stop when impacted on its end if the impact angle is within a certain envelope.

The above discussion underscores an important point made in Section 3.1, i.e., the recommended test matrices cannot and should not be expected to be an all inclusive set of standardized procedures. When appropriate, the testing agency and/or the user agency should devise other critical test conditions consistent with the range of expected impact conditions.

In comparison to Report 230, additional tests are recommended for terminals and/or redirective crash cushions. Tests 32, 33, 37 and 39 are new tests. As indicated in Table 3.2 and in the text, some of these tests may not be required, depending on the design of the terminal and on its intended application. Note in the redirective "strength" tests (35, 37, and 38), the recommended impact angle is now 20 deg compared to 25 deg in Report 230. Selection of 20 deg was based on a recognition that design of a terminal or crash cushion is very sensitive to the redirective requirements of the 2000P vehicle and the associated impact angle, and crash cushions have historically been designed for a 20 deg side impact angle.

While it is preferable that the test vehicle remain upright after each test described herein, exceptions are made for all heavy vehicle tests and for tests of crash cushions and terminals within test level 1 (see Criterion G of Table 5.1). Overturn is permitted in the heavy vehicle tests since the primary goal in these tests is to demonstrate that the longitudinal barrier being evaluated can contain and redirect the vehicle. Crash test experience with heavy vehicles has shown that if overturn occurs, the vehicle usually undergoes only a 90 degree roll, remaining on its side while coming to rest. Exceptions are made for tests of crash cushions and terminals for test level 1 since most overturns at 50 km/h are not believed to be life-threatening. Exceptions are also made to permit and encourage the development and use of cost-effective crash cushion and terminals for low-speed applications. For example, a concrete, sloped-end terminal section can probably be designed to satisfy test level 1 criterion. Note that even though overturn is permitted for all heavy vehicle tests and level 1 tests of crash cushions and terminals, evaluation criterion D of Table 5.1 must be satisfied, i.e.. the overturn must not result in deformations of the occupant compartment that could cause serious injuries.

A3.2.3

Test matrices for work zone traffic control devices and breakaway utility poles are new. Limited testing has been conducted on both types of features and the recommended tests and evaluation criteria were based in part on these studies. As more experience is gained in the test and evaluation of these features, it may be desirable to amend the recommendations.

The energy or force required to fracture a breakaway device or support structure, in general, may be sensitive to its orientation with respect to direction of impact or the impact angle. For example, tests have indicated a breakaway transformer base breaks more readily when struck on a corner than on a flat side. Because errant vehicles may approach a support structure, work zone traffic control device, or a breakaway utility pole at various angles, it is recommended that the device be tested assuming the most severe direction of vehicle approach consistent with expected traffic conditions or at the critical impact angle (CIA) discussed in Section 3.2.3 For instance, the transformer base should be oriented so the vehicle strikes a flat side. Moreover, because the energy required to fracture a device can be increased due to buckling of the support at the point of contact with the vehicle, the handhold in the luminaire shaft should be positioned during a test so that probability of local collapse of the shaft is maximized.

Development of an energy-absorbing, yielding luminaire support pole was under way at the time of this writing. It is designed to decelerate the vehicle to a safe stop, similar to a crash cushion, rather than permit the vehicle to break through and continue with minimal reduction in speed. Rigid, nonbreakaway supports are often used in urban areas where encroachment of the vehicle beyond the pole could endanger pedestrians or other innocent bystanders. While this practice may offer protection for the innocent bystander, it may also increase risks to errant motorists. The yielding pole may have application in these areas, and/or areas where trees or other hazards exist just beyond the pole line that could endanger occupants of the encroaching vehicle. However, since such a design would not pass occupant risk criteria recommended for breakaway support structures, it would be necessary to use criteria recommended for a crash cushion. Recommendations on use of such features is beyond the purview of this document. Their use must be based on policy decisions by the user agency.

Breakaway utility poles are tested and evaluated somewhat differently from other support structures. A higher occupant impact velocity is permitted in a utility pole test. This is-in recognition of the relatively high change in vehicular velocity and, hence, occupant impact velocity that occurs during impact with commonly used wooden utility poles with the 820C test vehicle, irrespective of the breakaway mechanism. The change in vehicular velocity occurs in large part as a result of momentum transfer caused by the mass of the pole. Since a higher occupant impact velocity is permitted, the impact speed for the "low speed" test was set at 50 km/h, or 13.9 m/s. Note that for an impact speed of 35 km/h or 9.7 m/s (as used for other support structures), the vehicle could come to an abrupt stop and still pass the 12 m/s maximum occupant impact velocity criterion. Recommended tests and assessment criteria notwithstanding, it should be a goal of the designer to develop breakaway utility pole systems that minimize vehicular velocity change and, when possible, limiting occupant velocities should equal those for other support structures. Replacement of solid timber poles with lighter structures, if

feasible, could reduce or eliminate problems associated with the relatively large mass of timber poles. Utility poles could then be expected to meet the same safety standards as other support structures.

A special feature somewhat related to support structures and not specifically included in the test guidelines is a fire hydrant. When it is required to evaluate the impact performance of a fire hydrant, it is recommended that it be tested to an appropriate test level and evaluated in accordance with the recommendations for a support structure.

A3.2.4

There are three basic areas of concern in an impact with a TMA: (1) risks to occupants of the impacting vehicle, (2) risks to occupants of the support truck to which the attenuator is attached, and (3) risks to workers if the support truck is pushed or rolls forward into the area occupied by the workers. All other factors being equal, risks to the occupants of the impacting vehicle generally increase as the mass of the support truck increases and/or as the degree of braking of the support truck increases. On the other hand all other factors being equal, risks to the occupants of the support truck and to workers ahead of the truck generally increase as the mass of the support truck decreases and/or the degree of braking decreases. Roll-ahead distance, the distance the support truck will advance upon impact, increases as the mass of the support truck decreases and as the degree of braking of the support truck decreases. Preferably, all these areas of concern would be evaluated in a given test series. It was concluded that at a minimum the recommended test series should focus on the first area of concern identified above, and additional optional tests could be conducted to evaluate other areas if necessary. Furthermore, it was concluded that the recommended tests should be standardized to the extent practicable, recognizing the rather wide variance in TMA specifications, support truck sizes and weights, and operating conditions (53). Thus, for test with the 820C (or the 700C) vehicle the support truck is braced against a rigid wall to prevent movement, thereby eliminating support truck mass effects. It can be shown that the small car test when conducted in this manner in most cases will not produce results significantly different from those with a braked support truck, considering the mass of most support trucks now in use. It is believed that this test will have major safety implications since it will require that all TMA's meet a minimum performance standard, regardless of support truck mass, and since risks to occupants of a small car impacting a TMA are generally greater than occupants of a larger vehicle, all other factors being equal. For test with the 2000P vehicle, the standardized truck mass (see Section 2.4.1.3) is representative of the heavier trucks used by state transportation agencies. The recommended braking is believed to be representative of typical in-service conditions. Test with the 2000P vehicle are designed to assess occupant risks and the roll-ahead distance of the support truck. It is noted that roll-ahead distances can be accurately estimated from the "conservation of momentum" principle of mechanics, knowing the frictional resistance of the support truck to forward movement. Reference 53 contains a description of the use of this principle in calculating roll-ahead distances.

A3.4.2

Longitudinal barriers generally fail due to structural inadequacies that allow snagging or pocketing on stiff points in the barrier systems or rupture of one of the "weak points" in the

barrier system, such as a connection point. Thus, most barrier systems have one or more critical locations where failure is likely to take place, whether it be through wheel snag or rupture of a barrier element. The potential for each type of failure is affected to some extent by the selected impact point.

Report 230 recommended that the impact point be selected to provide a worst-case loading on the redirective device. However, in the absence of guidelines, most testing agencies used the default recommendation, i.e., impacting midway between posts for a length-of-need test, 4.6 m upstream from stiffer system for transitions, midway between nose and beginning of length of need for terminals, and at midlength for crash cushions. Recent studies have developed procedures for quantifying the critical impact point for certain devices.

Whenever possible, Barrier VII or another simulation program should be used to identify CIP's for longitudinal barrier tests. The following procedure may be followed to identify the CIP for snagging:

(a) Input the appropriate barrier and vehicular properties.

(b) Select an impact point with respect to the reference post. It is preferable, although not necessary, that this point be in reasonable proximity to the expected CIP so as to minimize the number of computer runs necessary to converge on the CIP.

(c) Determine vehicular and barrier response for the impact conditions of concern. The primary measure of snagging potential is the degree of wheel overlap with the reference post. Reference 15 discusses the manner in which the overlap is measured.

(d) Make incremental changes in the location of the impact point, repeating step c for each increment. Sufficient runs must be made to clearly bracket and then determine the CIP, i.e., the point that produces the greatest wheel overlap with the reference post. Experience has indicated the distance from the reference post to the CIP, denoted as "x," ranges from approximately 1 m for stiff systems to approximately 6 m for flexible systems.

A3.4.2.1

The small mass and low crush stiffness of passenger vehicles increases the likelihood and severity of wheel snag or pocketing on stiff elements of longitudinal barriers. Therefore, testing of longitudinal barriers with the 700C, 820C, and 2000P vehicles must be planned to examine the potential for wheel snag and pocketing as well as structural failure of the barrier elements. Wheel snagging and vehicular pocketing are the two barrier failure modes that exhibit the greatest sensitivity to impact point selection. When an impact point is too close to a post or other stiff point in a barrier system, the vehicle will not penetrate into the barrier prior to reaching the snag point. Conversely, when the selected impact point is too far from a snag point, the vehicle will redirect and begin to exit the barrier prior to snagging.

Connection loading is another important test parameter that is affected by impact location. Fortunately, impact locations that maximize wheel snagging or pocketing at one point in the barrier will also maximize connection loads near that same point in the barrier. Therefore, whenever rail splices or other critical connections fall at or near (within 1 meter) a snag point such as a barrier post, the impact location can be chosen to maximize both the potential for snagging and connection loadings. Since barrier loadings are generally higher upstream of the snag point, critical connections should be placed at or just upstream of the snag point, provided the connection locations are consistent with in-service locations. Rail tensile loads are maximized all along the length of the first span upstream from the snag point. Thus, the potential for rail splice tensile failure can generally be maximized by choosing the CIP for snagging if the connection is placed at the snag point or anywhere within the first span upstream from the snag point.

However, when a barrier connection is not located within approximately one meter of a snag point, bending moment and shear in the connection will not be maximized by an impact location chosen to maximize snagging. When barrier connections are not within one meter of a snag point and when wheel snag or pocketing as well as connection loading in bending and/or shear are significant concerns, the designer may consider conducting two tests with different impact locations. Barrier VII or a similar simulation program is recommended to investigate the need for two tests and to select CIP's.

It has been found that the CIP with regard to snagging is sensitive primarily to dynamic yield force of barrier posts, plastic moment of rail elements, and post spacing (16). Post yield forces and spacing were then combined into a single parameter, Fp, by dividing the dynamic post yield forces by the post spacing. CIP selection curves were then developed as a function of plastic moment of rail elements, M_p, and post yield force per unit length of barrier, F_p. Reference 16 contains a more detailed description of the development of CIP selection curves shown in Figures 3.7 through 3.14.

The plastic moment of a barrier rail element is merely the product of the beam's plastic section modulus and the material yield stress. Procedures for calculating plastic section modulus are presented in many textbooks on plastic design of steel structures (64). The plastic section modulus can be estimated with a reasonable degree of accuracy by multiplying the elastic section modulus by a form factor. Form factors for common beam shapes vary from a low of about 1.1 to a maximum of 2.0. As the fraction of a beam's cross section located near the neutral surface increases, the form factor of the cross section increases. Wide flange beams have very little material near the neutral surface and, as a result, generally have form factors less than 1.18 with an average near 1.14. Form factors for square box beams range from a low of 1.13 for a very thin-walled tube to a high of 1.5 for a solid rectangular rod. Form factors and plastic moments for some common barrier rail elements are shown in Table A3.1.

Barriers with multiple rail elements complicate the selection of an appropriate plastic moment for the barrier. When this type of barrier deflects during an impact, the upper rail deflection is much higher than that of lower rail elements. A simple energy analysis indicates that the total energy absorbed by each rail element is roughly proportional to the mounting height of the element. Equation 3.2 was then developed to estimate an equivalent plastic moment for multiple rail systems. A limited sensitivity study using Barrier VII revealed that

TABLE A3.1. PROPERTIES OF COMMON BARRIER RAIL ELEMENTS

Rail[a]	Elastic Section Modulus (cm^3)	Form Factor	Plastic Section Modulus (cm^3)	Plastic Moment (kN-m)
12 ga. W-Beam	22.5	1.41	31.6	10.9
10 ga. W-Beam	28.8	1.41	40.6	14.0
12 ga. Thrie-Beam	35.7	1.40	50.0	17.2
10 ga. Thrie-Beam	45.9	1.40	64.2	22.1
W6x15	.159	1.11	177	43.9
TS 6x6x3/16 Box Beam	134	1.16	156	49.5
TS 6x6x3/8 Box Beam	244	1.20	293	93.0
TS 8x6x1/4	257	1.19	306	97.1

[a] Post sizes are in English units.

the **CIP** determined by use of Equation 3.2 accurately estimates the CIP for most multiple rail barrier systems. This study indicated that the procedure was somewhat less accurate for barriers that have relatively stiff rail elements well above the impacting vehicle. For this situation, barrier posts will yield above the impacting vehicle and the upper rails will not deflect as much as the lower rails. Although the CIP selection procedures do give reasonable estimates of critical impact locations for most of these barriers, a simulation program should be used when possible to verify the findings.

Prior to determining F_p it is necessary to determine the dynamic yield force of the post. The post yield force will be governed by the smaller of two values: that necessary to yield the post itself assuming it is rigidly anchored at its base, or that necessary to yield the soil in which the post is embedded.

When barrier posts are rigidly anchored, yield forces are controlled by the material properties of the post. A dynamic magnification factor is normally applied to the plastic section modulus of metal posts to estimate the dynamic yield force for a post as given in Equation A3. 1.

$$F_y = D \left(\frac{\sigma_y Z_p}{H_r}\right) \qquad \text{(A3.1)}$$

where:

F_y = dynamic post yield force for a rigid anchor;
D = dynamic magnification factor;
ρ_y = post yield stress;
Z_p = post plastic section modulus; and
H_r= height of highest rail above base of post.

The accuracy of Equation A3.1 can be demonstrated by comparing a measured value of F_y for a rigidly anchored W6X9 steel post with the calculated value. A dynamic magnification factor of 1.5 is typically used for steel posts and a W6X9 beam has a plastic section modulus of 103 cm^3 and a yield stress of 248 MPa. For a 0.53 meter mounting height, Equation A3.1 gives an F_y of 71.9 kN compared to a measured value of 74.7 kN from reference 58.

Wood materials exhibit a brittle failure mechanism and therefore the plastic section modulus in Equation A3.1 is replaced by the elastic section modulus. Reference 58 reported that pendulum tests of a 6 inch X 8 inch (15.2 cm X 20.3 cm) Douglas Fir post have an average failure force of 72.1 kN when mounted in a rigid support. Southern Douglas Fir has an average modulus of rupture of 46.8 MPa (59). Using a dynamic magnification factor of 1.0, Equation A3.1 predicts failure forces of 91.9 kN and 74.0 kN for rough cut and finished posts with a nominal 6 inch X 8 inch (15.2 cm X 20.3 cm) size. Although it is unclear whether posts used in the pendulum tests were rough cut or finished size, the test results do indicate that the dynamic magnification factor from Equation A3.1 should be no more than 1.0 for wood materials. Table A3.2 shows the modulus of rupture for some common wood post materials.

Dynamic yield forces for posts embedded in soil are generally more difficult to estimate. Soil yield forces are usually measured through pendulum or instrumented cart testing at speeds

near 32 km/h. A number of guardrail posts have been tested for various soil embedment conditions (34,58,60,61,62,63). Dynamic yield forces for common guardrail posts embedded in strong soils are shown in Table A3.3. The testing programs referenced above have shown that post yield forces can be approximated as a linear function of the square of the embedment depth. Thus, yield forces from Table A3.3 can be extrapolated for other embedment depths by multiplying the forces shown by the square of the ratio of the two embedment depths as given in Equation A3.2.

$$F_s' = F_s \times \left(\frac{D_e'}{D_e}\right)^2 \qquad \text{(A3.2)}$$

where

$F_{s'}$ = soil dynamic yield force at alternate embedment depth, D_e';
F_s = soil dynamic yield force shown in Table A3.3;
D_e' = alternate embedment depth; and
D_e = post embedment depth shown in Table A3.3.

Some pendulum tests have been conducted in soft soils and are reported in reference 58. Analytical procedures for estimating the yield forces of other post sizes and soil conditions are discussed in reference 60.

The application of CIP selection curves is demonstrated in the following example:

Barrier	Rail	10 ga. thrie-beam mounted 0.58 m above ground
	Post:	W6X9 Steel with 1.5 meter embedment
	Spacing	2.5 meters
Test 3-11	Vehicle	2000P
	Impact Cond:	100 km/h, 25 deg

From Table A3.1 the plastic moment of a 10 ga. thrie-beam is found to be 22.1 kN-m. From Table A3.3 the dynamic yield force for a W6X9 steel post embedded 1.12 m in soil is approximately 55.2 kN. The approximate soil yield force for a W6X9 steel post embedded 1.5 m in soil can be estimated using Equation A3.2.

$$F_s' = 55.2\ KN \times \left(\frac{1.5\ m}{1.1\ m}\right)^2 = 103\ KN$$

The yield force for a rigidly anchored, W6X9 steel post can be calculated from Equation A3. 1. A W6X9 beam has a section modulus of 102 cm3 and a yield stress of 248 MPa (64). The post yield force then becomes:

TABLE A3.2. WOOD POST PROPERTIES

Wood	Modulus of Rupture (MPa)	Shear Strength (MPa)
Douglas Fir	46.8	6.6
Southern Yellow Pine	50.4	5.9
Redwood	40.8	6.2

TABLE A3.3. DYNAMIC YIELD FORCES OF POSTS EMBEDDED IN STRONG SOIL

Post Type[a]	Embedment Depth (m)	Maximum Soil Limit (kN)	Maximum Post Limit (kN)
6 inch x 8 inch Wood Post	0.91	50.2	72.1
8 inch x 8 inch Wood Post	0.91	55.2	101.0[b]
10 inch x 10 inch Wood Post	0.91	72.5	205.0[b]
W6x9 Steel Post	1.12	55.2	65.0
W6x15 Steel Post	1.12	81.4	105.2

[a] Post sizes are in English units.
[b] Estimated for Douglas Fir using Equation A3.1.

$$F_y = 1.5\ (\frac{248\ MPa\ 102\ cm^3}{0.58}) \times (\frac{1m}{100cm})^3 = 65\ KN$$

The numerator of F_p in this case is the lower of the above two values, or 65 kN. Th post yield force per unit length for this barrier then becomes:

$$F_p = \frac{65\ KN}{2.5\ m} = 26\ KN/m$$

The CIP distance, "x," for this test is found from Figure A3.1. For an M_p of 22.1 kN-m, "x" distances of 3.0 m and 5.5 m correspond to F_p values of 50 kN-m and 8 kNm, respectively. Linear extrapolation can be used to estimate "x" for this example as follows:

$$\frac{5.5 - 3.0}{50 - 8} = \frac{x - 3.0}{50 - 26}$$

$$x = 4.4\ m$$

Thus, the impact point for this test should be 4.4 m upstream from the reference post. Note that the reference post should be located at or just downstream from a rail splice.

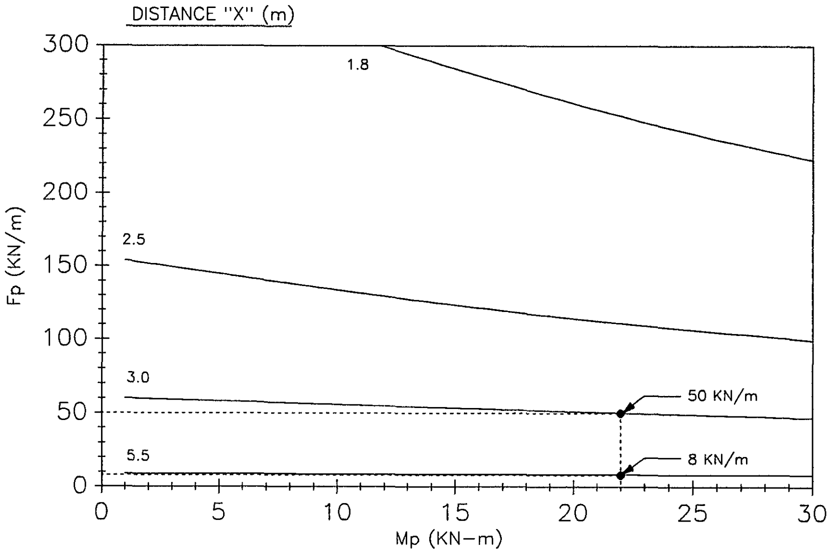
A3.4.2.2

Connection loading is the test parameter of primary importance for selecting impact points for heavy vehicle crash tests. Impact point selection guidelines presented in Section 3.4.2.1 are based on the distance from initial contact to the location of maximum lateral force. When possible, the impact point should be selected to generate maximum lateral loading at all important connection points including rail splices, rail-to-post connections, and post-to-base or post-to-deck connections. If the primary concern is for the truck to roll over the top of the barrier, the impact point should be selected to maximize lateral loading at midspan where the top barrier rail would be expected to deflect downward and increase rollover potential. Note that since heavy trucks spread impact loads over a larger area, a single test can usually be devised to apply near maximum loadings on all critical connections and adequately investigate the potential for post failure as well as rollover.

CHAPTER FOUR

A4.1

Proper documentation of key test details is often missing in a test report. For those not directly involved in the test program, assessment of a test and its results and development and implementation of standards for the test article cannot easily be done without good documentation. Sections 4.2, 4.3, and 4.4 describe important pretest, test, and post-test parameters.



SEE FIGURE 3.1 FOR "X".

FIGURE A3.1. EXAMPLE OF CRITICAL IMPACT POINT SELECTION

A4.3.2

Although not required at this time, the testing agency is encouraged to develop the capability to determine the six components of accelerations for the sprung mass (assumed to be a rigid body): translational accelerations in the x, y, and z vehicular axes and angular accelerations about these axes. These data, as well as corresponding velocities and displacements, should be shown in the report in plots or tables as a function of time.

High-speed cine is essential for study of crash dynamics to determine behavior of the test vehicle and the test article. In addition, high-speed cine has been used by some agencies as a backup system for determining vehicular accelerations and kinematics. Guidance for this secondary system consists of (1) minimum film speed (see Table 4.1), (2) internal or external timing device, and (3) stationary references located in the field of view of at least two cameras positioned 90 degrees apart. Layout and coordinates of references, camera positions, and impact point should be reported. Reference targets should be located on the side and the top of the test vehicle and should be of sufficient size and distance apart to allow accurate interpretation of the film. The instant of impact should be denoted by a flash unit placed in view of data cameras. The instant of impact should also be recorded on the electronic recording device(s).

A4.3.3

Vehicular accelerations are used in the assessment of test results through the occupant flail space model. Accelerations may also be used to estimate impact forces between the vehicle and the test article.

Implicit in the flail space model is the assumption that accelerations are measured at the center of mass of the vehicle. NCHRP Report 230 recommended that a set of accelerometers be placed at or near the center of mass. However, experience has shown that this cannot always be done due to physical constraints within the vehicle. As a result, actual placement of the set of accelerometers may be offset a significant distance from the center of mass. Depending on the offset, major differences can occur between measured accelerations and those at the center of mass for redirection impacts (such as impacts with a longitudinal barrier) or impacts which cause angular vehicular motions. The following procedure is recommended if accelerometers cannot be placed within +5 cm of the center of mass as measured in the x-y plane. Although roll motions (rotations about the vehicle's x-axis) of the vehicle are not accounted for, the method has been shown to give acceptable levels of accuracy even for moderate roll motions.

Procedure:

(1) A triaxial set of accelerometers, set 1 in Figure A4.1, is mounted on a common block and placed as close to the vehicle's center of mass as practical with their positive directions corresponding to the positive sign convention given in Figure 4.6. Measurement of the vertical (z direction) acceleration is optional, but preferred. The set must be mounted along the fore-aft centerline (along x axis) of the vehicle. Theoretically, it is not necessary that set 1 be placed near the center of mass; however, this is recommended in the event accelerometer set 2 malfunctions. It is preferable that distance h_1 be within ±3 cm of distance H.

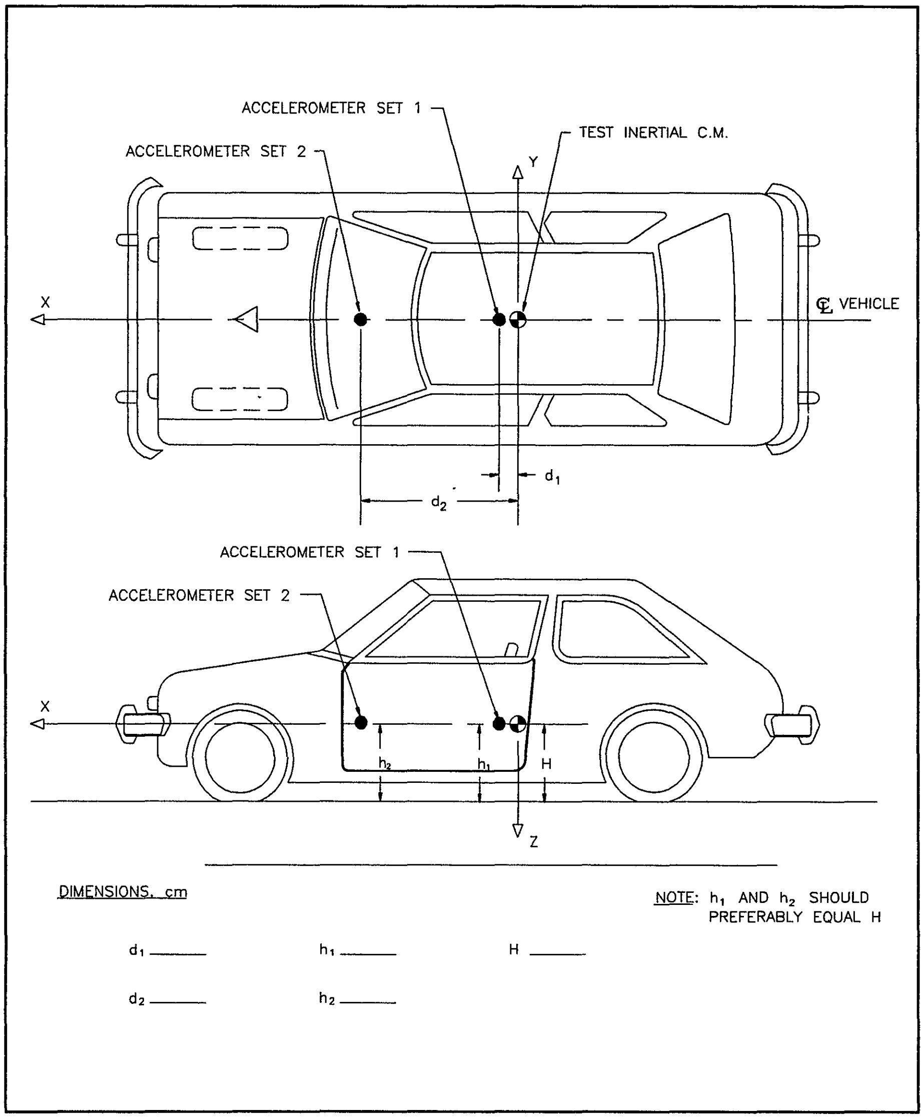


FIGURE A4.1 ACCELEROMETER PLACEMENT

(2) A triaxial set of accelerometers, set 2 in Figure A4. 1, is mounted as far as practical from set 1, preferably 60 cm or greater, either in front of or behind set 1. Note that both sets must be mounted forward of the cab/bed interface for the 2000P vehicle. The separation distance of the two sets should be as large as practical to reduce computational errors provided the accelerometers are not placed in an area that would be expected to undergo significant local dynamic deformations. Set 2 must also be mounted along the fore-aft centerline of the vehicle. It is preferable that distance h_2 be within +2 cm of distance h1.

(3) Using output from the above two accelerometer sets and distances d_1 and d_2, lateral, longitudinal, and vertical accelerations at the center of mass are computed by Equations A4.3, developed below. Note that d_1 and d_2 and their signs are measured with respect to the origin of the x,y,z axes located at the center of mass. For positions shown in Figure A4.1, both d_1 and d_2 are positive. However, it is not necessary that either be positive.

(4) Values of d_1, d_2, h_1, h_2, and H should be recorded and reported as shown in Figure A4.1.

<u>Derivations of Equations:</u>

Accelerations in the longitudinal direction a_x, lateral direction a_y, and vertical direction a_z measured by accelerometers located on the x axis a distance d forward from the center of mass are given by

$$a_x = a_{xg} - d(\omega_y^2 + \omega_z^2)$$

$$a_y = a_{yg} + d\dot{\omega}_z$$

$$a_z = a_{zg} - d\dot{\omega}_y$$

where, a_{xg}, a_{yg}, a_{zg} = longitudinal, lateral, and vertical accelerations at the center of mass; and
ω_y, ω_z, $\dot{\omega}_y$, $\dot{\omega}_z$ = pitch and yaw rates, and pitch and yaw accelerations.

Thus, the accelerations at points 1 and 2 of Figure A4. 1 are given by

$$a_{x_1} = a_{xg} - d_1(\omega_y^2 + \omega_z^2)$$
$$a_{y_1} = a_{yg} + d_1\dot{\omega}_z$$
$$a_{z_1} = a_{zg} - d_1\dot{\omega}_y \qquad \text{(A4.2)}$$
$$a_{x_2} = a_{xg} - d_2(\omega_y^2 + \omega_z^2)$$
$$a_{y_2} = a_{yg} + d_2\dot{\omega}_z$$
$$a_{z_2} = a_{zg} - d_2\dot{\omega}_y$$

Equatioons A4.2 can be solved to obtain the desired accelerations at the center of mass,a_{xg},.a_{yg}, and a_{zg} as follows:

$$a_{xg} = \frac{d_2 a_{x1} - d_1 a_{x2}}{d_2 - d_1}$$
$$a_{yg} = \frac{d_2 a_{y1} - d_1 a_{y2}}{d_2 - d_1} \qquad \text{(A4.3)}$$
$$a_{zg} = \frac{d_2 a_{z2} - d_1 a_{z1}}{d_2 - d_1}$$

Note that the second and fifth equations and the third and sixth equations of set A4.2 can be solved to yield an explicit solution for pitch and yaw acceleration as follows:

$$\dot{\omega}_y = -\frac{a_{z1} - a_{z2}}{d_1 - d_2}$$
$$\dot{\omega}_z = \frac{a_{y1} - a_{y2}}{d_1 - d_2} \qquad \text{(A4.4)}$$

Pitch rate ,ω_y, at any time T after impact can be obtained by adding the pitch rate at impact to the integral of the first equation of set A4.4 with respect to time from impact to time T. Yaw rate, ω_z, can be similarly computed using the second equation of set A4.4

A4.4

Measuring and recording both the vehicle damage scale (VDS), formerly the traffic accident data scale (TAD), and the collision damage classification (CDC) are recommended for the following reasons. First, VDS has been in use for a number of years by various accident

investigation agencies, and a considerable bank of data exists relating VDS to occupant injuries. Hence, by not reporting VDS, the tie of future tests with these historical data would be lost. And second, the National Highway Traffic Safety Administration (NHTSA) has standardized on the CDC for its multidisciplinary accident investigations. Therefore, CDC is needed to tie test vehicle damage (in which vehicle accelerations are measured) to real accidents in which occupant injury is documented.

CHAPTER FIVE

A5.1

Recommended evaluation criteria are limited to appraising safety performance of highway features for idealized vehicle crash test conditions. The basic purpose of crash tests is to screen out those candidate systems with functional deficiencies and to compare the relative merits of two or more promising candidate safety features. The test results are insufficient to project the overall performance of a safety feature for in-service use or in an actual collision situation. Final evaluation of a safety feature should be based on carefully documented in-service use.

Criteria for evaluating a vehicular crash test of a safety feature are patterned after those in Report 230 and consist of three interrelated factors: structural adequacy, occupant risk, and vehicle trajectory. In comparison to Report 230, the present criteria presented in Table 5.1 incorporate the following changes and/or modifications (further discussion of these items are given in following sections):

(a) Item D was moved from the "Structural Adequacy" category to the "Occupant Risk" category.

(b) Item E was added for evaluation of work zone traffic control devices.

(c) Item G was added for evaluation of heavy vehicle tests and test level 1 terminals and crash cushions.

(d) Under item H in the upper part of the table, the lateral occupant impact velocity limit was set equal to the longitudinal limit.

(e) The Hybrid III dummy is recommended as an optional measure of occupant risk for frontal impacts.

(f) Item L replaced item I of Report 230.

A5.2

The "structural adequacy" factor essentially assesses the feature from a structural and mechanical aspect. Depending on the feature, conditions to be examined include:

1. *Strength*. For longitudinal barriers, this requires containment and redirection of the design vehicles. Terminals and redirective crash cushions should develop necessary anchoring forces for anticipated site conditions.

2. *Geometry*. Longitudinal barrier rail members should engage the colliding vehicle at proper height to prevent the vehicle from underriding or overriding the installation. As a general rule, the vehicle-barrier contact surface should facilitate a smooth redirection. However, controlled stopping of the vehicle in a safe manner while the vehicle remains in contact with the rail is also satisfactory performance.Rail discontinuities such as splices and transitions and other elements such as support posts should not cause snagging to the extent that occupant risk criteria would not be met, or another failure mode would occur. Shaped rigid barriers, such as the New Jersey concrete barrier, should be designed to consider the stability of design vehicles.

3. *Mechanisms*. Stiffness, deformation, yielding, fracture, energy absorption and/or dissipation, etc., are characteristics of a feature that should be verified over the range of design vehicles.

In general, a safety feature should perform its function of redirecting, containing, or permitting controlled penetration of the test vehicles in a predictable and safe manner. Violent roll or rollover, pitching, or spinout of the vehicle reveal unstable and unpredictable dynamic interaction, behavior that is unacceptable.

A5.3

Relationships between occupant risk and vehicle dynamics during interaction with a high-way safety feature are extremely difficult to quantify because they involve such important by widely varying factors as occupant physiology, size, seating position, attitude and restraint, and vehicle interior geometry and padding. Advances have been made in recent years in better defining these relationships through development and application of sophisticated analytical and experimental tools, such as the collision victim simulation (CVS) computer program (66) and the Hybrid III dummy. Use of these tools would undoubtedly enhance assessment of occupant risk in tests of safety features. However, for the present document this was ruled unfeasible because of (a) costs associated with their purchase and/or use, (b) level of instrumentation and expertise needed, and (c) the absence of experience by testing agencies involved in evaluating highway safety features. Studies are needed to better define feasibility and effectiveness of tools of this type in improving occupant risk assessment in crash tests.

Flail-Space Model

Report 230 adopted the simplified point mass, flail-space model for assessing risks to occupants within the impacting vehicle due to vehicular accelerations. Two measures of risk are used; (1) the velocity at which a hypothetical occupant impacts a hypothetical interior surface and (2) "ridedown" acceleration experienced by the occupant subsequent to contact with the interior surface. Reference should be made to Report 230, the section on "Occupant Risk" in Chapter Four, in particular, for the underlying reasons for its adoption and its description, limitations, and assumed limiting risk factors. Based in part on reasons given in Section A5.3, it was concluded that the flail-space model should be retained for the present document.

Furthermore, it has served its intended purpose well and there are no indications that features designed and assessed thereby have performed adversely in service. Consideration was given to upgrading the flail-space model to better track the "occupant" as it flailed about the "occupant compartment." Assumptions made in the current model were:

(a) Occupant positioned at the vehicle's center of mass;

(b) Yaw motions of vehicle are ignored and, consequently, motion of the occupant in the lateral direction is completely independent of motion in the longitudinal direction,

(c) Vehicular and occupant motion is planar (in x-y plane); and

(d) Occupant contained in a compartment such that ± 0.3 m lateral movement can occur before impact with the sides of the compartment (idealized vehicular side structure), and 0.6 m longitudinal (forward) movement can occur before impact with the front of the compartment (idealized instrument panel/dash/windshield).

Options considered in updating the model all concerned changes that would affect results of redirection impacts. These included (a) positioning the occupant at the driver's and/or right-front passenger's seated position, (b) properly accounting for yaw motion of vehicle, and (c) changing the dimensions of the compartment to better represent the actual occupant compartment, e.g., this would allow the driver to flail 0.3 m to the left and in excess of 1.0 m to the right. After further study and careful review, it was concluded that the current model would be retained without changes for the following reasons:

(a) For typical redirection impacts, incorporation of options a and b, while effecting noncontrolling factors, would not have significant effects on controlling factors.

(b) If option c were incorporated, practically all redirection features would not meet limiting risk factors. This could be interpreted to mean one of several things including: most in-service redirection features developed according to Report 230 guidelines are unsafe; limiting occupant impact velocities and ridedown accelerations are too low; impact conditions of most accidents are not as severe as test conditions; occupants do not flail about the seats as would be assumed by option c; or a combination of these and/or other things. Since most redirection features designed according to Report 230 appear to be performing satisfactorily and since the flailspace model is actually an index or measure of occupant risk as opposed to an absolute measure, incorporation of option c does not appear warranted.

(c) Incorporation of these options would require use of a rather complex, standardized computer program and standardized input.

(d) A problem to date with determination of occupant risks through the flail-space model has been inconsistencies in positioning accelerometers used in measuring accelerations, i.e., they are not being placed at the vehicle's center of mass.

Recommendations contained in Section 4.3.3 should greatly reduce or eliminate this problem.

In the flail-space approach, lateral and longitudinal but not vertical vehicular accelerations measured at the vehicle's center-of-mass are used. By requiring that the vehicle in the occupant risk test remain upright throughout the collision, it is believed that the vertical component of vehicle acceleration becomes of secondary importance with regard to occupant kinematics for the level terrain tests described in this document and for most roadside features. Consequently, the vertical acceleration is considered an optional factor at present and has been neglected in the flail-space calculations.

The performance design strategy for a feature should be to (1) keep the occupant-vehicle interior impact velocity low by minimizing average vehicle accelerations or vehicle velocity change during the time the occupant is traveling through the occupant space and (2) limit peak vehicle accelerations during occupant ridedown.

Limiting Values for Impact Velocity and Ridedown Acceleration

The following items are to be noted:

(a) Report 230 presented "threshold" values and suggested feature-dependent factors of safety to apply to the threshold values. Table 8 of Report 230 contains values thusly obtained. In the present document, two sets of limiting values are given in Table 5.1: "preferred," which with some exceptions correspond to values in Table 8, and "maximum," which with some exceptions correspond to the threshold values.

(b) Based on consultations with biomechanics experts in the automotive industry and based on a review of the literature (67,68,69), it was concluded that Report 230 threshold values for occupant longitudinal impact velocity, and lateral and longitudinal ridedown accelerations should be retained. Based on information from these same sources, it was concluded that the threshold value for lateral occupant impact velocity should be increased to equal the value used for the longitudinal component. Note that reference 68 reported on a study that addressed the efficacy of the flail-space model and limiting values used therein. Among other things, this study found that recommended limiting occupant risk values of Report 230 were conservative, i.e., they overstated the risk level.

(c) Report 230 does not have a criterion that corresponds to the "preferred" limit for occupant impact velocity for support structures and work zone traffic control devices. The preferred limiting value of 3 m/sec and the maximum limiting value of 5 m/sec are approximately the same as those adopted by AASHTO (40). The maximum limiting value is slightly higher than the recommended value of Report 230.

(d) Due to conversions to the SI system, limiting occupant impact velocities and ridedown accelerations were rounded and consequently are not precisely the same as those in Report 230 or AASHTO.

"Maximum" limiting values of Table 5.1 should be treated as threshold limits. Test results should fall below these limits and desirably should not exceed the "preferred" values to promote safer performing features. In developing appropriate acceptance values, consideration should be given to the art-of-the-possible (i.e., can a device be made, regardless of cost, to perform to the requirements?) and cost effectiveness (i.e., can the increase in safety performance level justify the added cost?). Establishment of acceptance values is a policy decision and, therefore, beyond the purview of this report.

Procedures for acquiring and reducing vehicular accelerations used in determining occupant risk should follow recommended specifications given in Sections 5.3.2 and 5.3.3.

Calculation Procedures

The expression for occupant impact velocity is

$$V_{I_{x,y}} = \int_0^{t*} a_{x,y}\, dt \qquad \text{(A5.1)}$$

Where $V_{1_{xy}}$ is occupant-car interior impact velocity in the x or y directions, $a_{x,y}$ is vehicular acceleration in x or y direction, and t* is time when the occupant has traveled either 0.6 m forward or 0.3 m lateral, whichever is smaller. Time t* is determined by incremental integration as follows:

$$X, Y = \int_0^{t*} \int_0^{t*} a_{x,y}\, dt^2 \qquad \text{(A5.2)}$$

where, X = 0.6 m and Y = 0.3 m. Acceleration in the x direction is integrated twice with respect to time to find the value of time, t_x*, at which the double integration equals 0.6 m. Acceleration in the y direction is integrated twice with respect to time to find the value of time, t_y*, at which the double integration equals 0.3 m. Time t* is the smaller of t_x* and t_y*.

In tests of breakaway features the impulse on the vehicle may be relatively small and of short duration. It is not unusual in such tests for X and Y to be less than 0.6 m and 0.3 m, respectively, during the period in which accelerations are recorded or up to the time brakes are applied to the test vehicle. In such cases it is recommended that the occupant impact velocity be set equal to the vehicle's change in velocity that occurs during contact with the test article, or parts thereof. If parts of the test article remain with the vehicle after impact, the vehicle's change in velocity should be computed at the time the vehicle clears the footing or foundation of the test article.

For the ridedown acceleration to produce occupant injury, it should have at least a minimum duration ranging from 0.007 to 0.04 sec, depending on body component (70). Thus, vehicular acceleration "spikes" of duration less than 0.007 s are not critical and should be averaged from the pulse. An arbitrary duration of 0.010 s has been selected as a convenient and somewhat conservative time base for averaging accelerations for occupant risk assessment. This is accomplished by taking a moving 10-ms average of vehicular "instantaneous" accelerations in the x and y directions, subsequent to t*.

The occupant impact velocity and the highest 10-ms average acceleration values are then compared to recommended limits; it is desirable that both values be below the "preferable" limits; values in excess of the "maximum" limits are considered to be unacceptable.

Recommendations relative to the measurement of accelerations are given in Section 4.3.3 and in Appendix C. Further, for purposes of standardization of occupant risk calculation procedures, the following are recommended:

(1) Prior to integration using above formulas, accelerometer analog data should be digitized at 1,500 samples per second. This is consistent with recommendations of Appendix C, Section 9.2. It is recommended therein that the sample rate be, at a minimum, eight times F_h, where F_h = 180 for measurement of vehicular response. Note that F_h X 8 = 1,440, which is rounded to 1,500 for convenience and ease of integration.

(2) It is recommended the "linear acceleration" assumption or the equivalent "trapezoidal rule" be used to integrate the digitized accelerometer data. As such, accelerations are assumed to vary linearly over each time step t_i to t_{i+1} . Description of the trapezoidal rule can be found in most numerical methods textbooks.

A5.4

In general the ideal after-collision vehicular trajectory performance goal for all features should be that the vehicle trajectory and final stopping position should not intrude into the adjacent or opposing traffic stream. For breakaway or yielding supports the trajectory of a vehicle after it has collided with a test article that satisfies structural adequacy and occupant risk requirements is generally away from the traffic stream and, hence, is normally noncritical. For end-on impacts into crash cushions and barrier terminals that function as crash cushions, preferably the final position of the vehicle should be next to the test device.

For redirectional performance tests of length of need, transitions, terminals and redirective crash cushions, the after-collision trajectory is more difficult to assess. The after-collision trajectory may be one of the least repeatable performance factors because of variation in method and timing of brake application. Further, variables that are in part related to the specific model of vehicle selected for tests such as damage to vehicle suspension, tires, etc., may alter the vehicle's stability and path. Moreover, because driver response in avoiding secondary collisions is not simulated in the crash tests, it seems inappropriate to predict in-service performance based on the complete test trajectory. For these reasons trajectory evaluation for the redirectional type of tests is focused on the vehicle during contact (criterion L of Table 5.1). At the time it loses contact with the test article (criterion M of Table 5.1) and the subsequent part of the trajectory is only subjectively evaluated (criterion K of Table 5.1).

A study (71) conducted since publication of Report 230 found that risks to occupants of the impacting vehicle or to other motorists, as a consequence of the vehicle being redirected, are not as great as previously believed, provided the impacting vehicle does not collide subsequently with other roadside objects. The study pointed out that secondary collisions with roadside objects such as trees, other barriers, etc., is of major concern after a redirected impact. Hence,

the 24.2 km/h (15 mi/h) velocity change criterion of Report 230 (item I of Table 6) was not adopted in the present document. Criterion L of Table 5.1 is intended to allow controlled deceleration of the vehicle without excessive pocketing or snagging of the vehicle. Note that for most redirectional devices, a 12 m/sec occupant impact velocity equates to a vehicular velocity change of approximately the same magnitude or 43.2 km/h (26.8 mi/h).

While the above cited study suggests that trajectory of the vehicle into adjacent or opposing lanes may not be as critical as previously thought, it remains preferable that the vehicle exit the device at a low angle. Although ideal performance would be for the vehicle to exit with a path parallel to the installation, an upper limit of 60 percent of the impact angle is recommended.

A5.5

Specific test and evaluation guidelines for geometric features are not provided due to the largely nonstandard and variable nature of such features. However, it should be a goal of transportation agencies to design and implement geometric features that meet the spirit, if not the specifics, of safety recommendations for the more well-defined roadside safety features.

Evaluation guidelines given in this section were derived from a review of past practices and the collective expertise of those involved in preparing the document. They are, of necessity, general and may be amended as necessary to accommodate special designs or test conditions.

CHAPTER SIX

(No commentary is provided for this chapter)

CHAPTER SEVEN

A7.1

In-service evaluation guidelines are intended to encourage a cautious, systematic introduction of a new safety feature. With careful monitoring, unanticipated problems and design deficiencies can be identified before the feature has been installed in an excessive number of sites. Moreover, all the affected departments will have an opportunity to observe the performance of the device with respect to their operations. For instance there may be minor design changes recommended by the maintenance groups that may reduce normal maintenance or damage repair costs. Also, substitution of material or fasteners could ease the problem of a large inventory of spare parts. Care should be taken not to make changes in design details that could adversely affect safety performance without verification of adequate performance through full-scale crash testing or other acceptable means.

The in-service evaluation guidelines are intended to encourage a more consistent and thorough implementation of new devices and to promote a more direct and systematic process in demonstrating the operational status of ,safety features.

APPENDIX B

SOIL SPECIFICATIONS

APPENDIX B

PART 1

STANDARD SOIL

APPENDIX B

PART 2

WEAK SOIL

APPENDIX B

PART 3

COMPACTION GUIDELINES

PART 1

Standard Specification
for

Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses

AASHTO DESIGNATION: M 147-65 (1990)

1. SCOPE

1.1 This specification covers the quality and grading of sand-clay mixtures; gravel, stone or slag screenings; or sand, crusher run coarse aggregate consisting of gravel, crushed stone or slag with or without soil mortar or any combination of these materials for use in the construction of subbase, base and surface courses. The requirements are intended to cover only materials having normal or average specific gravity, absorption and gradation characteristics. Where other materials are to be used, appropriate limits suitable to their use must be specified.

2. GENERAL REQUIREMENTS

2.1 *Coarse Aggregate*:

2.1.1 Coarse aggregate retained on the 2.00 mm (No. 10) sieve shall consist of hard, durable particles or fragments of stone, gravel or slag. Materials that break up when alternately frozen and thawed or wetted and dried shall not be used.

2.1.2 Coarse aggregate shall have a percentage of wear, by the Los Angeles test, AASHTO T 96, of not more than 50.

NOTE 1-A higher or lower percentage of wear may be specified by the Engineer, depending upon the materials available for the work.

2.2 *Fine Aggregate*:

2.2.1 Fine aggregate passing the 2.00 mm (No. 10) sieve shall consist of natural or crushed sand, and fine mineral particles passing the 0.075 mm (No. 200) sieve.

2.2.2 The fraction passing the 0.075 mm sieve shall not be greater than two-thirds of the fraction passing the 0.425 mm (No. 40) sieve. The fraction passing the 0.425 mm sieve shall have a liquid limit not greater than 25 and a plasticity index not greater than 6

2.3 All material shall be free from vegetable matter and lumps or balls of clay. The soil-aggregate material shall conform to the grading requirements of Table 1. The grading requirements for composite aggregate material will be specified by the Engineer.

3. SUBBASE MATERIALS

3.1 Materials for subbase shall conform to the requirements of sections 2 and 3 for gradings A, B, C, D, E, or E The type and grading desired shall be specified.

NOTE 2-Where local experience has shown that lower percentages passing the 0.075 (No. 200) sieve than are required in Table 1 are necessary for subbase materials in order to prevent damage by frost action, the Engineer should specify such lower percentages.

4. BASE COURSE MATERIALS

4.1 Materials for base course shall conform to the requirements of section 2 for gradings A, B, C, D, E, or F The grading desired shall be specified.

NOTE 3-Where local experience has shown that lower percentages passing the 0.075 mm (No. 200) sieve than are required in Table 1 are necessary for base course materials in order to prevent damage by frost action, the Engineer should specify such lower percentages.

5. SURFACE COURSE MATERIALS

5.1 Materials for surface course shall conform to the requirements of sections 2 and 3 for gradings C, D, E, or F The gradings desired shall be specified.

NOTE 4-Where it is planned that the soil aggregate surface course is to be maintained for several years without bituminous surface treatment or other superimposed impervious surfacing, the Engineer should specify a minimum of 8 percent passing 0.075 mm (No. 200) sieve in lieu of the minimum percentages shown in Table I for grading C, D, or E, and should specify a maximum liquid limit of 35 and plasticity index range of 4 to 9 in lieu of the limits given in 2.2.2.

TABLE 1 Grading Requirements for Soil-Aggregate Materials

Sieve Designation		Mass Percent Passing					
Standard mm	Alternate	Grading A	Grading B	Grading C	Grading D	Grading E	Grading F
50	2 in.	100	100	—	—	—	—
25.0	1 in.	—	75-95	100	100	100	100
9.5	⅜ in.	30-65	40-75	50-85	60-100	—	—
4.75	No. 4	25-55	30-60	35-65	50-85	55-100	70-100
2.00	No. 10	15-40	20-45	25-50	40-70	40-100	55-100
0.425	No. 40	8-20	15-30	15-30	25-45	20-50	30-70
0.075	No. 200	2-8	5-20	5-15	5-20	6-20	8-25

6. MOISTURE CONTENT

6.1 All materials shall contain moisture equal to or slightly below the optimum necessary to insure that the design density requirements are obtained when materials are compacted.

7. ADMIXTURE

7.1 Calcium chloride used for the control of moisture shall meet the requirements of Standard Specifications for Calcium Chloride (AASHTO M 144).

8. METHODS OF SAMPLING AND TESTING

8.1 Sampling and testing shall be in accordance with the following standard methods of the American Association of State Highway and Transportation Officials:

Sampling	T 2
Sieve analysis	T 27 or T 88
Surveying and sampling soils for highway subgrades	T 86
Preparing samples	T 87
Liquid limit	T 89
Plastic limit and plasticity index	T 90
Percentage of wear	T 96
Passing 0.075 mm ..	T 11

PART 2

Standard Specification
for

Fine Aggregate for Portland Cement Concrete

AASHTO DESIGNATION: M 6-87

1. SCOPE

1.1 This specification covers the quality and grading of fine aggregate for port land cement concrete used in pavements or basics, highway bridges, and incidental
Structures.

1.2 *Units of Measurement:*

1.2.1 For sieve sizes and the size of aggregate as determined by the use of testing sieves, the values in inch-pound units are shown for the convenience of the user; however, the standard sieve designation shown in parentheses is the standard value as stated in AASHTO M 92.

1.2.2 For other units of measure, the values stated in inch-pound units are to be regarded as standard.

2. REFERENCED DOCUMENTS

2.1 AASHTO Standards:

- M 80 Coarse Aggregate for Portland Cement Concrete
- M 92 Wire Cloth Sieves for Testing Purposes
- T 2 Sampling Aggregates
- T 11 Amount of Material Finer Than 75-mu m Sieve in Aggregate
- T 21 Organic Impurities in Fine Aggregate for Concrete
- T 27 Sieve Analysis of Fine and Coarse Aggregates
- T 71 Effect of Organic Impurities in Fine Aggregate on Strength of Mortar
- T 103 Soundness of Aggregates by Freezing and Thawing
- T 104 Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
- T 112 Clay Lumps and Friable
- T 113 Lightweight Pieces in Aggregate
- T 161 Resistance of Concrete to Rapid Freezing and Thawing

Particles in Aggregate

3. ORDERING INFORMATION

3.1 The purchaser shall include the following information in the purchase order or contract when applicable:

3.1.1 Reference to this Specification, AASHTO M 6, and year of issue,

3.1.2 Grading requirements for No. 8 (2.36 mu m) and No. 30 (600 mu m) sieves, when required (5.1 and Note 1),

3.1.3 Whether the deleterious substances limits for Class A or Class B apply, and limits on other deleterious substances (7.1 and Note 3),

3.1.4 If the sulfate soundness requirement is waived (8.5),

3.1.5 In the case of the sulfate soundness test (8.1), which salt is to be used. If none is stated, either salt may be used.

3.1.6 If the supplementary requirement for reactive aggregates applies, (see S 1), and

3.1.7 Any exceptions or additions to this specification.

4. GENERAL REQUIREMENTS

4.1 Fine aggregate shall consist of natural sand or manufactured sand or combinations thereof, having hard, strong, durable particles.

4.2 Fine aggregate from different sources of supply shall not be mixed or stored in the same pile.

5. GRADING

5.1 Fine aggregate, when tested by means of laboratory sieves, shall conform
to the following requirements, except as provided in 5.2 and 5.3:

NOTE 1-The purchaser or specifier may insert specific values for percent passing the No. 8 and No. 30 sieves to further control the grading of the material.

Sieve		Mass Percent Passing
3/8 in.	(9.5 mm)	100
No. 4	(4.75 mm)	95-100
No. 8	(2.36 mm)	--
No. 16	(1.18 mm)	45-80
No. 30	(600 µm)	--
No. 50	(3(x) µm)	10-30
No. 100	(150 µm)	2-10

5.2 The minimum percent shown above for material passing the No. 50 (300-µm) and No. 100 (150-µm) sieves may be reduced to 5 and 0, respectively, if the aggregate is to be used in air-entrained concrete containing more than 400 lb of cement per cubic yard (237 kg/m^3) or in nonair-entrained concrete containing more than 500 lb of cement per cubic yard (297 kg/m^3) or if an approved mineral admixture is used to supply the deficiency in percent passing these sieves. Air-entrained concrete is here considered to be concrete containing air-entraining cement or an airentraining agent and having an air content of more than 3%.

5.3 The fine aggregate shall have not more than 45% passing any sieve and retained on the next consecutive sieve of those shown in 5. 1.

6. UNIFORMITY OF GRADING

6.1 The grading requirements given in 5.1 represent the extreme limits which shall determine suitability for use from all sources of supply. The grading from any one source shall be reasonably uniform and not subject to the extreme percentages

of grading specified above. For continuing shipments of fine aggregate from a given source, the fineness modulus shall not vary more than 0.20 from the base fineness modulus. The base fineness modulus shall be that value that is typical of the source. If necessary, the base fineness modulus may be changed when approved by the purchaser.

NOTE 2-The base fineness modulus should be determined from previous tests, or if no previous tests exist, from the average of the fineness modulus values for the first ten samples (or all preceding samples if less than ten) on the order. The proportioning of a concrete mixture may be dependent on the base fineness modulus of the fine aggregate to be used. Therefore, when it appears that the base fineness modulus is considerably different from the value used in selecting proportions for the concrete mixture, a suitable adjustment in the mixture may be necessary.

7. DELETERIOUS SUBSTANCES

7.1 The amount of deleterious substances shall not exceed the following limits (see table entitled "Deleterious Substances Limits"):

NOTE 3-The purchaser or specifier, due to knowledge of the requirements of the work and the constituents of locally available aggregate, should insert appropriate requirements when needed.

7.2 Organic Impurities:

7.2.1 Fine aggregate shall be free of injurious amounts of organic impurities. Except as herein provided, aggregates subjected to the test for organic impurities and producing a color darker than the standard shall be rejected.

7.2.2 A fine aggregate failing in the test may be used, provided that the discoloration is due principally to the presence of small quantities of coal, lignite, or similar discrete particles.

7.2.3 A fine aggregate failing in the test may be used, provided that, when tested for the effect of organic impurities on strength of mortar, the relative strength at 7 days calculated in accordance with AASHTO T 71 is not less than 95%.

8. SOUNDNESS

8.1 Except as provided in 8.2 through 8.5, fine aggregate subjected to five cycles of the soundness test shall have a weighted average loss not greater than 10% when sodium sulfate is used or 15% when magnesium sulfate is used.

8.2 Fine aggregate failing to meet the requirements of 8.1 may be accepted, provided that concrete of comparable properties, made from similar aggregate from the same source, has given satisfactory service when exposed to weathering similar to that to be encountered.

8.3 Fine aggregate not having a demonstrable service record and failing to meet the requirements of 8.1 may be accepted, provided it gives satisfactory results in concrete subjected to freezing and thawing tests. (See AASHTO T 161.)

8.4 Fine aggregate failing to meet the requirements given in 8.1 may, at the option of the purchaser or specifier, be subjected to an alternate freezing and thawing test of unconfined aggregate and may be accepted provided it gives satisfactory results.

NOTE 4-The purchaser or specifier should determine the details of the evaluation and criteria for determining satisfactory performance in 8.2, 8.3, and 8.4.

8.5 The requirements for soundness given in 8.1 may be waived in the case of aggregate for use in structures or portions of structures not exposed to weathering.

9. METHODS OF SAMPLING AND TESTING

9.1 Sampling and testing of fine aggregate shall be in accordance with the following methods of the American Association of State Highway and Transportation Officials:

9.1.1 Sampling-T 2

9.1.2 Sieve analysis and fineness modulus-T 27

9.1.3 Clay lumps and friable particles-T 112

9.1.4 Coal and Lignite-T 113, using a liquid of 2.0 specific gravity to remove the particles of coal and lignite. Only material that is brownish-black, or black, shall be considered coal or lignite. Coke shall not be classed as coal or lignite.

9.1.5 Material finer than No. 200 (75-µm)-T 11

9.1.6 Organic impurities-T 21

9.1.7 Effect of organic impurities on strength-T 71

9.1.8 Sulfate soundness-T 104

9.1.9 Soundness (unconfined freezing and thawing)-T 103

9.1.10 Freezing and thawing of concrete-T 161

SUPPLEMENTARY REQUIREMENT

The following supplementary requirement applies only when specifically stated in the order or contract.

S1. REACTIVE AGGREGATE

S1.1 Fine aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalies in the cement in an amount sufficient to cause

Deleterious Substances Limits

	Class A, max, Mass Percent	Class B, max, Mass Percent
Clay lumps and friable particles	3.0	3.0
Coal and Lignite	0.25	1.0
Material finer than No. 200 (75-µm) sieve:		
(a) In concrete subject to surface abrasion, not more than	2.0	4.0
(b) All other classes of concrete, not more than	3.0	5.0
Other deleterious substances (such as shale, alkali, mica, coated grains, soft and flaky particles)	Note 3	Note 3

excessive expansion of mortar or concrete, except that if such materials are present in injurious amounts, the fine aggregate may be used with a cement containing less than 0.60% alkalies calculated as sodium oxide equivalent ($Na_2O + 0.658K_20$) or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction. (See Appendix X1 of AASHTO M 80.)

NOTE SI-This supplementary requirement would normally be specified only in areas having a history of reactive aggregate, except for unusually critical structures, to save costs and delays due to unnecessary testing.

Guide Specifications for Highway Construction

Pay Item	Pay Unit
Liquid asphalt for road mix	
Bituminous base course	Ton or gallon
Emulsified asphalt for road mix	
Bituminous base course	Ton or gallon
Tar for road mix	
Bituminous base course	Ton or gallon

SECTION 303—RESERVED

SECTION 304—AGGREGATE BASE COURSE

304.01 Description. This work shall consist of furnishing and placing one or more courses of aggregate and additives if required, on a prepared foundation in accordance with these specifications, in reasonably close conformity with the lines, grades, thicknesses, and typical cross sections shown on the plans or established by the Engineer.

MATERIALS

304.02 Aggregate. The aggregates shall meet the requirements of *subsection 703.06.*

Acceptance will be based on random samples taken from the pug-mill output for *the stationary blend method or from the windrow after necessary* blending for a road mix method.

304.03 Calcium Chloride. Calcium chloride shall conform to subsection 714.02, except the requirements for total alkali chlorides and impurities shall not apply.

304.04 Sodium Chloride. Sodium chloride shall conform to subsection 714.04.

CONSTRUCTION REQUIREMENTS

304.05 Placing. If the required compacted depth of the base course exceeds 6 inches, the base shall be constructed in two or more layers of approximate equal thickness. The base material shall be laid by means of an approved mechanical spreader capable of placing the material to a uniform depth without segregation. The maximum compacted thickness of any one layer

shall not exceed 6 inches, except a single layer upon approval may be increased to a depth of 8 inches when vibratory equipment or special compaction equipment is used.

304.06 Mixing. Unless otherwise specified, the Contractor shall mix the base course by one of the following methods and incorporate any additives that may be required as shown on the plans.

(a) *Stationary Plant Method* — The material shall be mixed in an approved mixer and water added during the mixing operation to provide the optimum moisture content for compacting. Immediately after mixing, the base material shall be transported to the job site and placed on the roadbed by means of an approved aggregate spreader.

(b) *Travel Plant Method* — After the material has been placed through an aggregate spreader or windrow sizing device, the material shall be uniformly mixed by a traveling mixing plant and water added during the mixing operation to provide optimum moisture content for compacting.

(c) *Road Mix Method* — After the material has been placed, it shall be uniformly mixed by means of motor graders or other approved equipment and water added during the mixing operation to provide optimum moisture content.

304.07 Shaping and Compaction. The material shall be shaped to the required section and water applied or aerated as necessary to provide the optimum moisture content for compaction. Compaction shall continue until a density of not less than ..... percent (95 percent suggested) of the maximum density determined in accordance with AASHTO T 180 Method D has been achieved. The surface shall be maintained during the compaction operations in such a manner that a uniform texture is produced and the aggregates firmly keyed. Water shall be uniformly applied over the base materials during compaction in the amount necessary for proper consolidation.

In-place density will be determined in accordance with AASHTO T 191, T 205, or other approved method. The use of AASHTO T 224 (alternative) to correct for oversize particles may be required. AASHTO T 238 may be used if the limitations of the method as cited in the appendix to the standard are fully recognized.

304.08 Method of Measurement. Aggregate base course will be measured by the ton, cubic yard, or square yard in accordance with Section 109—Measurement and Payment. The weight of moisture (surface and hygroscopic) will be deducted when the aggregate is measured by weight.

APPENDIX C

ELECTRONIC AND PHOTOGRAPHIC INSTRUMENTATION SPECIFICATIONS

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SAE The Engineering Society For Advancing Mobility Land Sea Air and Space ®
400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096
HIGHWAY VEHICLE PRACTICE
Submitted for recognition as an American National Standard
SAE J211
Issued October 1970
Revised October 1988
Superseding J211 JUN80

Ø INSTRUMENTATION FOR IMPACT TEST

SCOPE:

This recommended practice outlines a series of performance recommendations which concern the whole data channel. These recommendations are not subject to any variation and all of them should be adhered to by any agency conducting tests to this practice. However, the method of demonstrating compliance with the recommendations is flexible and can be adapted to suit the needs of the particular equipment the agency is using.

It is not intended that each recommendation be taken in a literal sense, as necessitating a single test to demonstrate that the recommendation is met. Rather, it is intended that any agency proposing to conduct tests to this practice should be able to demonstrate that if such a single test could be and were carried out, then their equipment would meet the recommendations. This demonstration should be undertaken on the basis of reasonable deductions from evidence in their possession, such as the results of partial tests.

In some systems it may be necessary to divide the whole channel into subsystems, for calibration and checking purposes. The recommendations have been written only for the whole channel, as this is the sole route by which subsystem performances affect the quality of the output. If it is difficult to measure the whole channel performance, which is usually the case, the test agency may treat the channel as two or more convenient subsystems. The whole channel performance could then be demonstrated on the basis of subsystem results, together with a rationale for combining the subsystem results together.

Part 1 of this recommended practice covers electronic instrumentation and Part 2 covers photographic instrumentation.

PART 1 - ELECTRONIC INSTRUMENTATION

1. PURPOSE:

The purpose of this SAE Recommended Practice is to provide guidelines and recommendations for the techniques of measurement used in impact tests. The aim is to achieve uniformity in instrumentation practice and in reporting test results. Use of this recommended practice will provide a basis for meaningful comparisons of test results from different sources.

2. FIELD OF APPLICATION:

The instrumentation as defined in this recommended practice applies in particular to impact tests for road vehicles, including tests of their sub-assemblies, and occupant surrogates.

3. DEFINITIONS:

The definitions in 3.5 to 3.14 apply to the whole data channel, as defined in3.1.

3.1 Data Channel: All of the instrumentation from and including a single transducer (or multiple transducers whose outputs are combined in some specified way) up to and including any analysis procedures that may alter the frequency content or the amplitude content or the timing of data. It also includes all cabling and interconnections.

3.2 Transducer: The first device in a data channel, used to convert a physical quantity to be measured into a second quantity (such as an electrical voltage) which can be processed by the remainder of the channel.

3.3 Full Scale: The maximum usable linear range of a data channel.

3.4 Data Channel Full Scale: That value of a data channel determined by the component of the channel with the lowest full scale level. This is expressed in terms of the measured variable (input). For example, F.S.=50 G, 1000 N, 100 cm/s, etc.

3.5 Channel Amplitude Class, CAC: The designation for a data channel that meets certain amplitude characteristics as specified by this recommended practice.

The CAC number is numerically equal to the upper limit of the measurement range, (that is, equivalent to the data channel full scale).

3.6 Characteristic Frequencies, Fh, F1, Fn: These frequencies are defined in Fig. 1.

3.7 Channel Frequency Class, CFC: The channel frequency class is designated by a number indicating that the channel frequency response lies within limits specified by Fig. 1.

This number and the value of the frequency Fh in Hz are numerically equal.

3.8 Calibration Value: The value measured and read during the calibration of a data channel (see 4.6).

3.9 Sensitivity Coefficient: The slope of the straight line representing the best fit to the calibration values determined by the method of least squares within the channel amplitude class.

3.10 Calibration Factor of a Data Channel: The arithmetic mean of the sensitivity coefficients evaluated over frequencies which are evenly spaced on a logarithmic scale between Fl and Fh/2.5.

3.11 Linearity Error: The ratio, in percent, of the maximum difference between the calibration value and the corresponding value read on the straight line defined in 3.9 at the upper limit of the channel amplitude class (data channel full scale).

3.12 Sensitivity: The ratio of the output signal (in equivalent physical units) to the input signal (physical excitation), when an excitation is applied to the transducer. (Example: 10.24 mV/G/V for a strain gage accelerometer.)

3.13 Phase Delay Time: The phase delay time of a data channel is equal to the phase delay (in radians) of a sinusoidal signal, divided by the angular frequency of that signal (in radians per second).

3.14 Environment: The aggregate, at a given moment, of all external conditions and influences to which the data channel is subjected.

3.15 Transverse Sensitivity (of a rectilinear transducer): The sensitivity to excitation in a nominal direction perpendicular to its sensitive axis.

Note: The transverse sensitivity is usually a function of the nominal direction of the axis chosen.

3.16 Transverse Sensitivity Ratio (of a rectilinear transducer): The ratio of the transverse sensitivity to its sensitivity along its sensitive axis.

4. DATA CHANNEL PERFORMANCE REQUIREMENTS:

4.1 Linearity Error: The absolute value of the linearity error of a data channel at any frequency in the CFC, shall be less than or equal to 2.5% of the value of the CAC, through the whole measurement range. In general a sufficient number of measurements should be carried out in order to ensure the linearity in the range of interest, that is, between Fl and Fh. For a transducer, linearity at DC is sufficient.

4.2 Amplitude Against Frequency: The frequency response of a data channel shall lie within the limiting curves given in Fig. 1. The zero dB line is defined by the calibration factor.

4.3 Phase Delay Time: The phase delay time between the input and the output of a data channel shall be determined, and shall not vary more than 1/(lO*Fh) seconds between 0.03*Fh and Fh. This includes the transducer, that is the input is the excitation to the transducer.

4.4 Time:

4.4.1 Time Base: A time base shall give at least 1/100 second resolution with an error of less than 1/10000 seconds.

4.4.2 Relative Time Delay: The relative time delay between the signals of two or more data channels regardless of their frequency class, must not exceed 1 millisecond excluding phase delay caused by phase shift. Two or more data channels of which the signals are combined shall have the same frequency class and shall not have a relative time delay greater than l/(10*Fh) seconds.

This requirement applies to analog-signals as well as synchronization pulses and digital signals.

4.5 Transducer Transverse Sensitivity Ratio: The transverse sensitivity ratio of all transducers shall be less than 5% in any direction.

4.6 Calibration: Values in this section apply to reference equipment or "standards" against which a data channel is "calibrated", that is, its performance is determined.

4.6.1 General: A data channel shall be calibrated at least once a year against reference equipment traceable to known standards. The methods used to carry out a comparison with reference equipment shall not introduce an error greater than 1% of the CAC. The use of the reference equipment is limited to the range of frequencies for which they have been calibrated.

Subsystems of a data channel may be evaluated individually and the results factored into the accuracy of the total data channel. This can be accomplished for example by an electrical signal of known amplitude simulating the output signal of the transducer which allows a check to be made on the gain of the data channel, except the transducer.

4.6.2 Accuracy of Reference Equipment for Calibration: The accuracy of the reference equipment shall be certified or endorsed by an approved metrology service (for example, traceable to the National Bureau of Standards).

4.6.2.1 Static Calibration:

4.6.2.1.1 Accelerations: The error shall be less than 1.5% of the channel amplitude class.

4.6.2.1.2 Forces: The error shall be less than 1% of the channel amplitude class.

4.6.2.1.3 Displacements: The error shall be less than 1% of the channel amplitude class.

4.6.2.2 Dynamic Calibration:

4.6.2.2.1 Accelerations: The error in the reference accelerations expressed as a percentage of the channel amplitude class shall be less than 1.5% below 400 Hz, less than 2% between 400 and 900 Hz, and less than 2.5% between 900 Hz and the maximum frequency at which the reference acceleration is utilized (see 4.6.4).

4.6.2.2.2 Forces and Displacements: (No method for the evaluation of the dynamic response during calibration of data channels for forces and displacements is included since no satisfactory method is known at present.)

4.6.2.3 Time: The error in the reference time shall be less than 0.00001 seconds.

4.6.3 Sensitivity Coefficient and Linearity Error: The sensitivity coefficient and the linearity error shall be determined by measuring the output signal of the data channel against a known input signal, for various values of this signal. (The input signal is referenced to well known physical data, that is, a load or acceleration, but not voltage.)

The calibration of the data channel shall cover the whole range of the amplitude class. (This is between Fl and Fh/2.5.)

For bi-directional channels, both the positive and negative values shall be evaluated.

If the calibration equipment cannot produce the required input, due to excessively high values of the quantity to be measured, calibrations shall be carried out within the limits of these calibration standards and these limits shall be recorded in the report.

A total data channel shall be calibrated at a frequency or at a spectrum of frequencies with its significant values comprised between Fl and Fh/2.5.

4.6.4 Calibration of the Frequency Response: The response curves of phase and amplitude against frequency for the data channel shall be determined by measuring the output signals of the data channel in terms of phase and amplitude against a known input signal, for various values of this signal varying between Fl and 10 times the CFC or 3000 Hz whichever is the lower value.

4.7 Environmental Effects: The presence of any environmental effects shall be checked (that is, electric or magnetic flux, cable velocity, etc.). This can be done for instance by recording the output of spare channels equipped with dummy transducers.

If an output signal is greater than 2% of the expected data peak value, corrective action shall be taken, for instance re-allocation or replacement of cables.

4.8 Choice and Designation of the Data Channel: The CAC and CFC define a data channel.

A data channel consistent with the specifications of this recommended practice shall be designated according to the following codes:

SAE J211 XXXXX - (number of this recommended practice)
CAC ... - (channel amplitude class)
CFC ... - (channel frequency class)

If the calibration of the amplitude or frequency response does not cover the complete CAC or CFC owing to limited properties of the calibration equipment, then the CAC or CFC shall be marked with an asterisk.

Example, SAE J211 XXXX
CAC* 200 m/s^2
CFC 1000 Hz

means that:

-this measurement has been carried out according to this recommended practice:

-the channel amplitude class was 200 m/s^2;

-the channel frequency class was 1000 Hz;

-the calibration of the amplitude response did not cover the complete CAC.

The test report shall indicate the calibration limits.

5. DATA CHANNEL SELECTION:

The selection of a frequency response class is dependent upon many considerations, some of which may be unique to a particular test. The ultimate usage of the data and good engineering judgment will determine what portions of the frequency spectrum are significant or useful. The various classes of frequency response in Fig. 1 are intended to permit appropriate choices for different engineering requirements.

It is important to note that valid comparisons using different frequency response classes may be difficult to make. It is useful to establish specific frequency response classes when comparing test results from different sources. The frequency response classes in Table 1 are recommended for that purpose. These recommendations reflect current practices and equipment. However, it is recognized that other considerations (for example, biomechanics) may impose special instrumentation requirements.

5. DATA CHANNEL SELECTION: (continued)

The channel class recommendations for a particular application should not be considered to imply that all the frequencies passed by that channel are significant for the application. In several cases, such as occupant head accelerations, headform accelerations, and femur force, the recommendation may be higher than necessary, but current biomechanical knowledge will not permit a closer specification. All data is to be gathered at class lOO0 or higher, for any purpose.

TABLE 1 - Frequency Response Classes

Typical Test Measurements	Channel Class#
Vehicle structural accelerations for use in:	
Total vehicle comparison	60 (1)
Collision simulation input	60
Component analysis	600
Integration for velocity or displacement	180
Barrier face force	60
Belt restraint system loads	60
Anthropomorphic Test Device	
Head accelerations (linear and angular)	1000
Neck	
Forces	1000 (2,3)
Moments	600 (2,3)
Thorax	
Spine accelerations	180
Rib accelerations	1000 (2)
Sternum accelerations	1000 (2)
Deflections	180
Lumbar	
Forces	1000 (4)
Moments	1000 (4)
Pelvis	
Accelerations	1000 (2)
Forces	1000 (4)
Moments	1000 (4)
Femur/Knee/Tibia/Ankle	
Forces	600
Moments	600 (2)
Displacements	180 (2)
Sled acceleration	60
Steering column loads	600
Headform acceleration	1000

5. DATA CHANNEL SELECTION: (continued)

#Filtering can cause appreciable time lag (for example, approximately 2.5 ms
with class 60 channel). These effects should be considered when comparing film and electronic data, or when performing integration.

1. When overall acceleration of the frame or body in a given direction is desired and a higher frequency response class is used, readability of the data may be improved by averaging outputs of two or more transducers at different locations prior to recording of the output.

2. References are listed in Section A.4.

3. These classifications are needed to calculate head impact forces based n neck forces and head accelerations when using the Hybrid III crash test dummy.

4. No rationale for this classification. By default, class 1000 was chosen.

6. MOUNTING OF TRANSDUCERS:

Mechanical resonances associated with transducer mounting should not distort readout data.

Transducers should be mounted on dummies using a support specially provided for this purpose. In cases where properties of non-mechanical test subjects preclude rigid transducer mounting, an analytical or experimental evaluation of mounting effects on the data should be provided.

Acceleration transducers, in particular, should be mounted in such a way that the initial angle of the actual measurement axis to the corresponding axis of the reference axis system is not greater than 5 deg unless analytical or experimental assessment of the effect of the mounting on the collected data is made. When multi-axial accelerations at a point are to be measured, each acceleration transducer axis should pass within 10 mm of that point, and the center of seismic mass of each accelerometer should be within 30 mm of that point.

7. SIGN CONVENTION:

A standardized coordinate system and axes designation for major body segments of dummies or other test surrogates as well as for test vehicles and sleds is needed throughout the crash testing community. The results of computer modeling and biomechanical research have been hard to interrelate with test results due to different coordinate and sign conventions.

The sign convention for dummies and other test surrogates should be consistent with Fig. 2 for applicable instrumentation. Table 2 provides a method for determining positive output from dummy transducers when a force is applied to its various body segments.

TABLE 2

The directions are defined in relation to a seated dummy

Body Segment - Measured Force	Positive Output Direction
Neck - FX shear	Chest forward or Head rearward
FY shear	Chest right or Head left
FZ axial	Chest down or Head up
MX moment (roll)	Left shoulder to left ear
MY moment (pitch)	Chest to chin
MZ moment (yaw)	Left shoulder to chin
Femur - FX shear	Knee up
FY shear	Knee right
FZ axial	Knee forward (tension)
MX moment (roll)	Knee left
MY moment (pitch)	Knee up
MZ moment (yaw)	Knee rotated CCW when facing front of dummy
Knee clevis - FZ axial	Tibia down (tension)
Upper tibia - MX moment	Ankle left
MY moment	Ankle forward
Lower tibia - FX shear	Ankle forward
FY shear	Ankle right
FZ axial	Ankle down (tension)
MX moment	Ankle left
MY moment	Ankle forward
Chest displacement	Chest expansion (1)
Knee shear displacement	Pull tibia from femur (2)

(1) Chest is normally compressed for negative output.

(1) Chest is normally compressed for negative output.
(2) Push on tibia for negative output.

For vehicles and sleds the positive X-axis should be in the normal forward motion direction of the vehicle or sled. The positive Z-axis should be vertically downward (+G) and, following the right hand rule, the positive Y-axis should be towards the right.

Inertial coordinate systems should be chosen with positive Z-axis vertically downward (+G) and the positive Y-axis toward the right from the chosen
X-axis. The directional reference of the X-axis should be reported.

8. RECORDING:

8.1 Analogue Magnetic Recorder: Tape speed should be stable to within less than 0.5% of the tape speed used. The signal-to-noise ratio of the recorder should not be less than 42 dB at the maximum tape speed.

The total harmonic distortion should be less than 3% and the linearity error should be less than 1% of the measurement range.

It is suggested that standard tape speeds be used: 15/16, 1 7/8, 3 3/4, 1.5, 15, 30, 60, 120 ips. Conformance to Inter-Range Instrumentation Group (IRIG) specifications is desirable.

8.2 Digital Magnetic Recorder: Tape speed should be stable to within less than 10% of the tape speed used. It is suggested that standard tape speeds be used: 75 or 100 ips. Tapes should be 0.5 in wide and recorded at standard 800, 1600 or 6250 bpi on 7 or 9 track formats.

8.3 Paper Tape Recorder: In the case of direct data recording, the paper speed in millimeters per second should be at least 1.5 times the number expressing Fh in Hz.

In other cases, the paper speed should be such that an equivalent resolution should be obtained.

9.. DIGITAL DATA PROCESSING:

This section establishes guidelines for digital data processing equipment used by crash testing agencies.

9.1 Presample Filtering: Filtering corresponding to the frequencies of the data channel class may be carried out during processing of data.

However, before recording, analog filtering at a higher level than CFC-1O00 should take place in order to use at least 50% of the dynamic range of the recorder and to reduce the risk of high frequencies saturating the recorder. Since crash test data may have high-frequency components above the channel class Fh, presample filtering should be used to keep these components from causing aliasing errors in the sampling process. The user is cautioned to examine the unfiltered data for signal overloads, since the filtering process can mask certain overload conditions. Since Class 1000 data is generally the highest frequency data required in crash testing, many laboratories set the presample filter to Class 1000 and use digital filtering for lower classes. Digital filtering should only be done once per data channel; that is, do not digital filter a digitally filtered signal.

The maximum error induced by aliasing at the Fh frequency shall not exceed 0.1% of the CAC.

9.2 Sampling Rate: The minimum acceptable sampling rate is a function of many variables, particularly sophistication of the reconstruction method used in the processing software. For those installations utilizing only simple reconstruction software, the sample rate should be a minimum of eight times the Fh. In installations with Class lO00 presample filters, this corresponds to a minimum sampling rate of approximately 8000 samples per second per channel. In the case of analog recording, when the recording and playback speeds are different, the sampling frequency can be divided by the speed ratio.

9.3 Resolution: Digital word lengths of at least 10 bits (including sign) should be used to be assured of reasonable accuracy in processing. In those systems in which the dynamic range of the data is less than 5U% of the A/D converter full-scale, a higher resolution may be required. The least significant bit should correspond to approximately 0.2% of the CAC.

9.4 Data Processing: Processing software is typically used to scale and filter data, determine zero levels, perform mathematical operations and prepare data plot formats.

9.4.1 Digital Filtering: Filtering may be either phase-shifting or phaseless. Phase-shifting filters will cause time offsets and phaseless filters will cause time uncertainty; either of which will cause problems in comparing data to film, and comparing data to data if the class filters are different. Filtering should precede all non-linear operations, such as calculation of resultant vectors and injury indices. Any filtering algorithm can be used as long as the results conform to the data channel performance requirements as given in Section 4. The type of digital filter used should be reported.

9.4.2 Scaling and Zeroing: Software should be used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. Zero offset errors in orthogonal components cause comparable errors in resultant computation that are often difficult to detect.

9.4.3 Injury Index Calculations: Injury index calculations should use all sampled data points. Head Injury Criterion calculations should use all data points for the integration. However, the maximizing time intervals need be no more precise than 1 ms.

10. TIMING MARKS:

Timing marks are essential in data analysis and correlation of high-speed film to other data channels. Timing frequency error should be less than 1% of the chosen or designated frequency. Timing synchronization should be within +/-1 ms.

11. TIME OF CONTACT:

Time of initial contact (real or simulated) should be known within +/- 1 ms and can be accomplished by recording a switch actuated by the impact or by observing the instant the test acceleration exceeds a predetermined value (for example, 0.5 G). It should also be recorded in film data through strobe lights or timing mark channels.

12. PRESENTATION OF RESULTS:

In reporting results of tests, the following information should be provided with data tabulations, time history traces, etc.:

(a) The data channel designations.
(b) Description of designated reference points and locations of vehicle accelerations.
(c) Transducer mounting analysis, if required by Section 6.
(d) Type of digital filter used.
(e) Method of combining sub-systems for calibration.
(f) Inertial coordinate system definition.

12. PRESENTATION OF RESULTS: (continued)

The results should be presented on A4 (210 x 297 mm) size paper (ISO 216) or 8.5 x 11 n paper. Results presented as diagrams should have axes scaled with one measurement unit corresponding to a suitable multiple of the chosen unit (for example 1, 2, *5,* 10, 20 millimeters). SI units shall be used, except for vehicle velocity where km/h may be used and for accelerations due to an impact where G may be used (with G = 9.81 m/s/s).

ANNEX TO PART 1 - SPECIFIC MEASUREMENTS

A.1 Impact Velocity: This can be calculated by measuring the time required to traverse a known distance prior to impact. Determination of impact velocity should be with an error of less than 1% of the actual velocity.

A.2 Test Specimen Crush:

A.2.1 Residual Crush: Residual crush is specified by one or more single-valued data points, with respect to a designated reference points. Determination of residual crush should be with an error of less than 5% of the actual crush.

A.2.2 Dynamic Crush: Maximum dynamic crush is a measurement of the maximum deformation of the test specimen during the impact. This is also measured with respect to one or more designated reference points. Contingent on the size of the specimen and the magnitude of the expected dynamic crush, the following are possible measurement methods:

(a) High-speed motion picture photography.
(b) Double integration of acceleration data.
(c) Use of a specific displacement transducer.

The error should be less than 5% of the actual crush.

A.3 Steering Column Displacement: Displacements relative to designated reference points on the vehicle can be measured by various techniques. The coordinate system in which displacement is measured should be indicated. Determination of steering column displacement should be accurate to +/-0.5 in (+/-1.27 cm).

A.4 References: Information pertaining to the justification of some of the specified filter frequency classes is contained in the minutes of the SAE Safety Test Instrumentation Subcommittee meetings held on April 16, September 24, and November 21, 1986.

PART 2 - PHOTOGRAPHIC INSTRUMENTATION

1. SCOPE:

The purpose of this recommended practice is to define criteria of performance for an optical data channel when numerical time and space data are taken from the images to analyze impact test results.

The requirements are to facilitate comparison between results obtained by different laboratories.

2. DEFINITIONS:

2.1 Optical Data Channel: A system composed of an image taking device (for example, camera and lenses), a recording medium for these images (film, disc, magnetic tape . . .), an optical path (for example, fiber optic cable) and a system for analyzing the images including any analysis procedure that may modify the content of the data.

2.2 Distortion Index: The distortion index is a quality parameter of the optical data channel.

2.3 Analysis System: An analysis system is composed of a system for measuring and collecting the coordinates of image points as a function of time.

2.4 Time Base System: A device to enable the determination of the time interval elapsed between any two recorded events.

2.5 Time Origin Identification Device: A device for identifying the instant chosen as the time origin, usually the beginning of the impact.

2.6 Imaging Rate: This is the frequency of renewal of information for a given point expressed in renewals per second or in images per second when all the points of the image are renewed simultaneously.

3. PERFORMANCES:

The performances of the optical data channel should be evaluated initially to establish performance levels and repeated whenever the system is modified to an extent which could cause a change in accuracy.

The following measures of performance may be evaluated as detailed in the annex or in an equivalent manner.

3.1 Optical Performance: The optical performance is determined by analyzing the variation of apparent length of 40 diameters according to the annex.

3.1.1 Distortion Index: The distortion index is assessed by using the photographic target and procedure described in the annex. It shall be evaluated as detailed in the annex and shall not exceed 1%.

3.2 Time Base: A time base is required. It shall permit the determination of the time between recorded events with an error of less than the reciprocal of the imaging rate or 1% of the actual time, whichever is greater

3.3 Time Origin Identificaton Device: The accuracy of the device shall be equal to the value expressed in s of the inverse of the imaging rate.

3.4 Imaging Rate: The imaging rate shall be left to the user's initiative, taking account of the following main three factors:

- the goal to be attained
- the limitations due to the equipment, (blur, etc...)
- the need to combine data from several image taking devices and rom electronic recordings of the impact test.

The user's choice shall be guided by the distance the recorded point moves between two analyzed images. This distance should not exceed the accuracy required for its positional determination.

3.5 Length Reference: A length calibration shall be performed which permits the determination of lengths within any requirements there may be on their accuracies.

In lieu of such requirements it is recommended to be able to perform length determinations with an error of less than 1% of the diagonal of the picture.

ANNEX TO PART 2

Recommended procedure for determining the optical performance of an optical data channel.

A.1 <u>Test Equipment:</u> A rectangular target having dimensions in conformity with Fig. 3 shall be used.

This target shall be divided into four parts by joining the center points of two opposite sides. In each quadrant thus obtained and at the target center, circles 400 +/- 1 mm in diameter shall be drawn.

The five circles shall be marked on their circumference with sixteen equally spaced
reference marks, thus defining eight diameters for each, and hence forty diameters for the whole target.

A.2 <u>Test Procedure:</u> The target shall be exposed "full frame" by the camera forming one of the elements of the data channel to be tested.

The film or tape to be used for calibration shall be of the same type and quality as that used for impact testing. It shall be analyzed using the analysis system.

The coordinates of the marks of a diameter, d_{ij}, must be measured on the same frame while the coordinates of the marks of different diameters must be measured on consecutive analyzed images.

For each circle, j, j=l to 5, label the 16 marks, i, i=l to 16, consecutively around a circle. Then the forty diameters (d_{ij}) shall be measured as

$$d_{ij} = [(x_{ij} - x_{i+8,j})^2 + (y_{ij} - y_{i+8,j})^2]^{1/2},$$

where i=1,2...8 and j=1,2...5.

The mean diameter (D) and the standard deviation (S) shall be calculated taking the 40 diameter values (d_{ij}) into account:

$$D = \mathrm{sum}^{8}_{i=1} \; (\mathrm{sum}^{5=}_{j=1} d_{ij}/N) \qquad \text{with } N=40,$$

$$S = [\mathrm{sum}^{8}_{i=1} \; (\mathrm{sum}^{5}_{j=1} \; ((d_{ij} - D)^2 \;)/(N-1))]^{1/2}$$

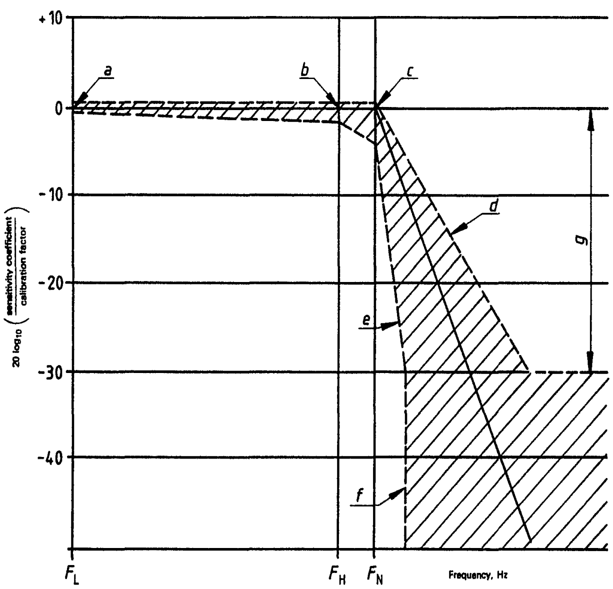
The distortion index is equal to the ratio (S/D) of the standard deviation (S) to the mean diameter (D).

A.3 <u>Alternate Procedure:</u> Other targets with different sizes or patterns of reference marks may be used, in which case the user has to determine the distortion index in an indirect way.

There is then also a need to show that the indirect method gives a result equivalent to the use of the pattern specified in this annex.

This may be of advantage when for instance a target with a rectangular pattern of reference marks is employed for the determination of lens corrections, which are needed in case of some wide angle lenses.

The phi (∅) symbol is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. If the symbol is next to the report title, it indicates a complete revision of the report.



CFC	F_L Hz	F_H Hz	F_N Hz
1 000	< 0,1	1 000	1 650
600	< 0,1	600	1 000
180	< 0,1	180	300
60	< 0,1	60	100

Logarithmic scale

a ± 0,5 dB
b + 0,5; − 1 dB
c + 0,5; − 4 dB
d − 9 dB/octave
e − 24 dB/octave
f ∞
g − 30 dB

FIGURE 1 - Data Channel Dynamic Accuracy

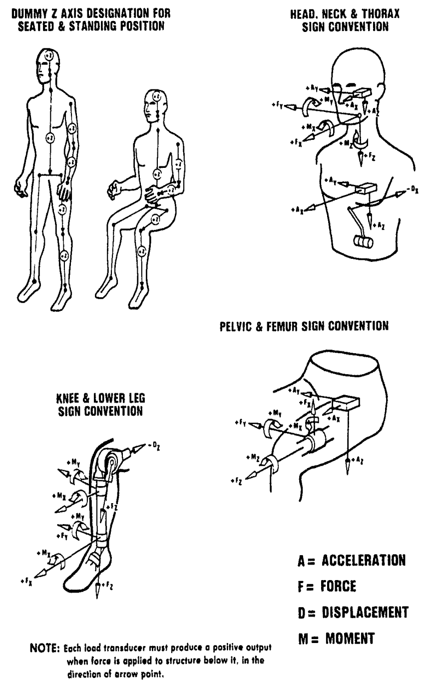


FIGURE 2 - Hybrid III Positive Sign Convention

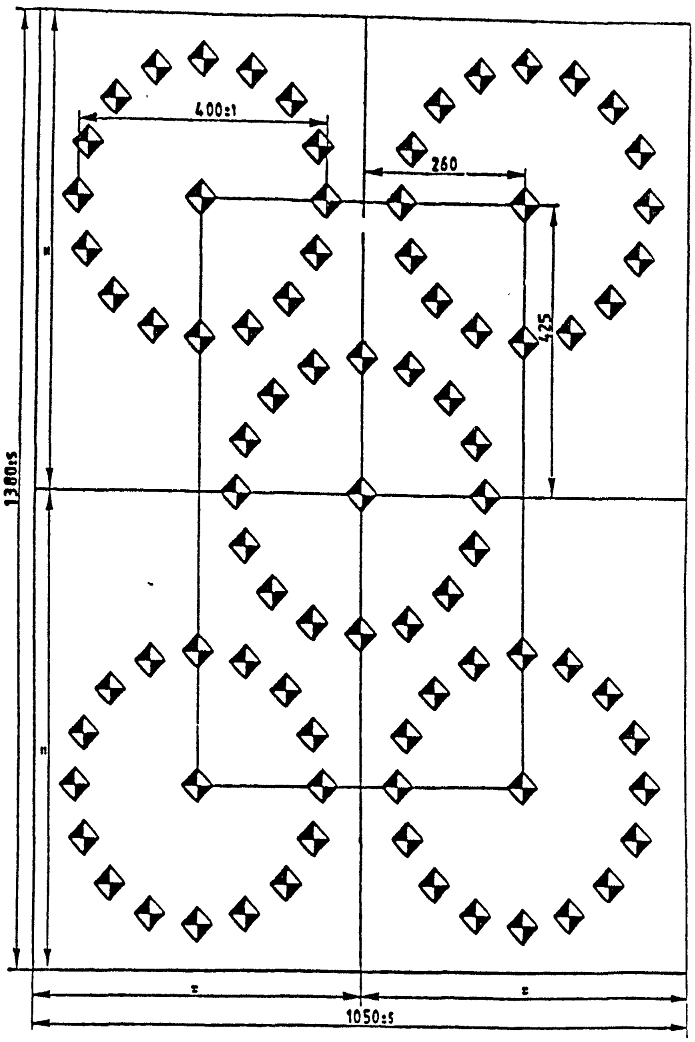


FIGURE 3

RATIONALE:

Not applicable.

RELATIONSHIP OF SAE STANDARD TO ISO STANDARD:

Not applicable.

REFERENCE SECTION:

Not applicable.

APPLICATION:

The purpose of this SAE Recommended Practice is to provide guidelines and recommendations for the techniques of measurement used in impact tests. The aim is to achieve uniformity in instrumentation practice and n reporting test results. Use of this recommended practice will provide a basis for meaningful comparisons of test results from different sources.

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APPENDIX D

ANALYTICAL AND EXPERIMENTAL TOOLS

Design, synthesis, and development of a new safety feature is not a straightforward procedure but is an iterative process requiring tradeoffs among sometimes conflicting safety performance requirements, environmental considerations, and costs. In this appendix, analytical and experimental tools (excluding full-scale crash tests) that are typically used in developing and evaluating new safety features are presented and discussed. Also, application and limitations of these techniques are presented.

D1 Useful Techniques

D1.1 Structural Design

The primary design objective of longitudinal barriers and crash cushions is the safety performance with errant vehicles, but there are other design considerations pertaining to economy, environment, maintenance, and operational needs.

On the other hand, safety performance during vehicle collision is not the reason for installing supports for signs and luminaires. If lighting or information for the motorist is not needed, the installation should not be located on the roadside. Hence, the primary design objective is to support the luminaire or sign blank for environmental loading, and safety performance is a secondary objective. Fortunately, engineers have been able to develop breakaway and yielding supports that will satisfy both the primary and secondary objectives.

Structural loading and design procedures are contained in civil engineering textbooks, AASHTO design manuals, and research publications. Primary references are given in Table D-l for each type of safety feature. The designer/developer should consult these references as a first step along with the appropriate safety feature manufacturer. These references will aid the developer in estimating design loads and proportioning a new design for subsequent evaluation steps.

1.2 Static Tests

During an early stage of development, certain critical details and connections of a safety feature may require strength/deflection evaluation. Safety features are often designed to function at or near ultimate capacity of the materials. Since the materials will be loaded well beyond typical design ranges such as elastic limits, these tests are often very specialized and do not conform to standard tests suggested by ASTM.

Most static tests will have one of the following objectives:

* Demonstrate safety feature performance under simulated environmental loading.
* Evaluate ultimate strength of critical connections.
* Develop load/deflection properties for subsequent computer model simulations.

TABLE D-1. SOURCES FOR SAFETY FEATURE INFORMATION

Feature	Principal Reference
I. Longitudinal Barriers	
A. Bridge Rails	17, 27, 28, 29, 30, 31, 32
B. Guardrails	27, 30, 31, 33, 34, 35, 36
C. Median Barriers	7, 27, 30, 31, 33, 34, 37
II. Crash Cushions and Terminals	27, 31, 37
III. Breakaway or Yielding Supports	
A. Luminaire	39, 40, 41, 42
B. Sign Supports	40, 43
C. Utility Poles	44, 45
IV. Truck Mounted Attenuators	46, 47, 48
V. Roadside Geometric Features	4, 5, 6, 7, 8, 18, 19, 27, 35

Static testing is often used to compare the performance of competing design details. When such tests are used to evaluate safety feature components that must perform under dynamic loading, developers should be aware of the many problems that can arise from material load rate sensitivity. A primary concern in the design of many roadside safety features is the energy absorbed as a component fails. Static testing generally allows a component to fail at the lowest possible load. However, the lowest failure load often will not correspond to the lowest energy failure mode. For example, wood posts embedded in soil seldom fracture under static loading and energy dissipation is usually high as the post rotates in the soil. Under dynamic loading, soils can generate much higher loadings and a wood post can fracture prematurely with little energy dissipation.

In general it is anticipated that quality control of materials used in the operational system may vary extensively. Where possible, safety performance behavior should not rely heavily on material properties that cannot be carefully controlled. For instance, energy to fragment a frangible transformer base can vary more than 100 percent with even minor changes in heat treatment of the aluminum alloy. Soil conditions can exhibit even wider seasonal variations as a soil goes through saturated, dry, and frozen situations. In contrast, tensile strength and elastic modulus of wire rope vary within a narrow performance band.

Even at this stage the developer should be aware of value engineering by avoiding overspecifying materials, especially components that are noncritical. Moreover, he should ensure that materials used in the prototypes are typical and routinely acquired materials and not "Sunday samples." Where possible, the developer should use standard hardware elements for initial economy and to minimize costs associated with inventory maintenance (31).

D1.3 Computer Simulations

A number of computer programs have been developed that simulate vehicle dynamics and kinematics during interactions with highway safety features. Also, several models have been developed to simulate occupant dynamics during impact. These models vary in complexity of mathematical analog, type of safety feature investigated, and class of vehicle. Simulation results are sensitive to vehicle parameters that are sometimes difficult to obtain or approximate. Vehicle moments of inertia, crush properties, and suspension stiffness properties are generally not published and must be determined experimentally. Moreover, barriers often exhibit large deflections that are difficult to predict because of uncontrolled features such as joint slack, soil variation, and unstable structural behavior.

Most of the available simulation programs have been correlated to some degree with crash tests. For the validated cases, simulation results can be most helpful to the safety feature designer by providing sometimes unique insight into the collision event. Where the program has been validated for multiple impact conditions, it can be used with some confidence in investigating conditions that are bracketed by the validated conditions. Although investigation of impact conditions outside the validated range can provide some insight, the engineer should use care in these extrapolations and view the findings with caution. The most important simulation programs are given in Table D-2 and are described below.

TABLE D-2. SUMMARY OF HIGHWAY SAFETY COMPUTER PROGRAMS

Name	Developer/Date of Last Mod.	Principal Application	Model	Validation	Documentation Availability	Comment
HVOSM	CALSPAN/1989	Simple vehicle/rigid directive barrier	3D Lump Mass Vehicle	Extensive	FHWA (R & D)	Excellent wheel/suspension system analog; simplified vehicle body crush analog
BARRIER VII	Univ. of Cal./1973	Simple vehicle/flexible redirective barrier	2D Finite Element Model (FEM)	Extensive	FHWA (R & D	For cases where roll and pitch of vehicle are negligible.
GUARD	HTRI/1989	Simple vehicle with detailed bumper modeling capability; flexible or rigid barrier systems	3D FEM Vehicle and Barrier Model	Limited	FHWA (R & D)	Developed in part from CRUNCH program--simplistic wheel/suspension model
NARD	HTRI/1989	Articulated vehicle/flexible or rigid barrier capabilities	3D FEM	Limited	FHWA (R & D)	Similar to GUARD program but with articulated vehicle
SMAC	CALSPAN/1975	Rigid body motion--2D vehicle (no barrier)	Vehicle	Limited	NHTSA	Model used for accident reconstruction

HVOSM - The Highway Vehicle Object Simulation Program (HVOSM) (6,7) is a very sophisticated and widely used vehicle handling model. HVOSM incorporates an 11 degree of freedom (DOF) vehicle model with relatively sophisticated suspension and tire models. This program has been extensively validated against a wide variety of crash tests involving many different terrain configurations. The program has demonstrated validity for modeling vehicle traversals of ditches, driveways, and a variety of roadside slopes. HVOSM is especially suited for evaluation of roadway and roadside geometrics where vehicle stability is a primary concern.

This program has also been successfully used for simulating rigid barrier impacts (7). This version of the program incorporates a relatively sophisticated sheet metal crush model and barrier/vehicle interaction routines. However, the program continues to be limited by its thin disk tire model and an inability to adequately predict or model suspension and wheel damage. Nonetheless, HVOSM is the best available model for simulating rigid barrier impacts.

Barrier VII - Barrier VII program *(49)* is a widely used model for simulating impacts with flexible barriers. This program incorporates a beam and column finite element model (FEM) of the barrier and a two-dimensional vehicle model. The FEM code incorporates both geometric and material nonlinearities as well as a number of specialized barrier elements including nonlinear springs and dashpots. Although the vehicle model incorporates relatively simple bilinear spring elements and is limited to three degrees of freedom (DOF), this program has been successfully validated for a wide variety of flexible barriers and a number of different vehicles. The primary limitation of this program is that it cannot be used to predict vehicle stability. However, the program is especially suited for use as a tool for barrier design in predicting maximum loads on and strains in barrier components. Further, the program has proven useful for identification of critical impact locations as well as predicting vehicle snagging and pocketing.

GUARD - The GUARD program (50) utilizes a three dimensional finite element barrier model and a 6 DOF vehicle model. The finite element barrier model incorporates both translational and rotational degrees of freedom for all elements. Although this feature makes the program versatile and should improve accuracy for many structures, the low rotational stiffnesses of many barrier elements, such as W-beam guardrail, tend to destabilize the solution routine. As a result, this program is very difficult to use and has not been adequately validated for very many barriers or impact conditions. The program is also severely handicapped by the limited number of barrier nodes and elements that can be accommodated. GUARD's sheet metal crush model incorporates deformable panels that interact with predescribed lines on the barrier surface. Special care must be taken when describing panel surfaces to make sure that panel contact lines are properly positioned relative to barrier contact lines. Further, GUARD's suspension and tire models are relatively crude and severely limit the program's usefulness for modeling safety-shaped barrier impacts.

GUARD has yet to be adequately validated for any general class of simulations. Although the program is ostensibly capable of simulating impacts with virtually any barrier, it is best suited for relatively strong beam barriers where torsional stiffnesses are high. This program is not recommended for the inexperienced user and even experienced users should view simulation findings with extreme caution.

NARD - The Numerical Analysis for Roadside Design (NARD) program (51) has evolved from **GUARD**. The program is designed to be both a handling and impact model and can simulate a variety of vehicles including passenger cars, single unit trucks, and combination trucks with as many as three trailers. The program is also capable of simulating impacts with a variety of roadside objects including breakaway devices and crash cushions as well as longitudinal barriers. Unfortunately, **NARD** incorporates the same basic program structure as the GUARD program from which it evolved. As a result, NARD suffers from virtually all of the same problems as **GUARD**. Nard does incorporate a relatively sophisticated suspension and tire model similar to **HVOSM** that should allow it to simulate safety-shaped barrier impacts.

Like **GUARD**, the **NARD** program is both unvalidated and very difficult to use. After proper validation, the program should offer a reasonably accurate handling model for automobiles and trucks. However, an extensive effort is required before the program can be considered to be validated for barrier impacts. Users are cautioned against using NARD without proper validation.

SMAC - The Simulation Model for Automobile Collisions (**SMAC**) (52) is a two dimensional program for modeling two car collisions. The vehicles are modeled as uniformly crushable blocks with linear stiffness coefficients. Although this program was designed as a tool for reconstructing traffic accidents, the program has proven to be quite useful for analyzing impacts with crash cushions and barrier end treatments. For this purpose a roadside object can be modeled as one of the two vehicles. The program has been shown to be capable of predicting the extent of vehicle crush and planar rotations during impacts with guardrail terminals and roadside poles. The gross vehicle model incorporated by the program and problems associated with modeling roadside objects as a vehicle are significant limitations of this program. Nonetheless, SMAC can be a useful design tool that merits further consideration.

D1.4 Laboratory Dynamic Tests

In addition to full-scale crash tests procedures presented elsewhere in this report, there are four types of dynamic test methods to evaluate and study safety features: gravitational pendulum, drop mass/dynamic test device, scale model, bogie vehicle.

D1.5 Gravitational Pendulum

The facility is characterized by a striking mass that swings in a circular arc suspended by cables or by rigid arms from a main frame. The specimen is generally mounted in an upright manner. Mass velocity at impact is governed by the formula

$$V_i = \sqrt{2gh}$$

subject to minor corrections due to friction and aerodynamic losses, where h is the drop height of the mass. As an example, for an impact speed of 35 km/h (9.7 m/s), a drop height of 4.8 m is required. The swing radius is usually considerably larger than the drop height. Gravitational pendulums are commonly used to evaluate performance at impact speeds of

approximately 40 km/h or less. A gravitational pendulum capable of high speed impacts would be very large and unwieldy.

A primary problem associated with this type of testing is the type of impact surface or crushable nose used on the pendulum. A rigid nose greatly increases the impact forces applied to the pendulum while reducing the energy dissipation during the test. An excessively soft nose will minimize impact forces and maximize energy dissipation associated with the tested feature. Although simulated soft noses have been developed for subcompact and minisize vehicles (2,30), these devices were developed to simulate vehicle models that are well over 10 years old. Nose assembly systems must be revalidated periodically if pendulum testing is to yield accurate predictions of safety feature performance during full-scale testing.

Pendulum testing is frequently used to evaluate the performance of breakaway structures such as luminaire and sign supports. Such systems often absorb more impact energy during low speed crashes than during high speed impacts. As a result, pendulums are an inexpensive method for evaluating the low-speed performance of prototype design alternatives. Some breakaway systems have been placed into service based solely on pendulum testing. As discussed in Section 2.4.1.2, the acceptance of safety features based on such testing is left to the discretion of the user agency.

Pendulums can also be used for dynamic testing of various safety feature components. For example, pendulums are often used for dynamic testing of barrier posts embedded in soil and crash cushion attenuator elements. This type of testing is not sensitive to the design of the pendulum's crushable nose and can yield valuable information with a rigid impact surface.

D1.6 Drop Mass/Dynamic Test Device

These facilities generally involve a rigid striking mass or plate that strikes a test specimen at prescribed velocities. Drop mass devices can be used to test large components and assemblies under low-speed dynamic conditions. Dynamic test devices are not limited to low test speeds, but specimen sizes are generally very limited. As a result, these devices are limited to tests of scale models or relatively small components of a safety feature. Although these test methods have proven to be quite valuable, developers should be aware of the problems associated with both test methods. Low test speeds associated with drop test facilities can lead to the same strain rate sensitivities associated with static testing. Further, since dynamic testing devices accelerate and decelerate the impact plate over relatively short distances, the velocity of the strike plate can vary significantly during the test event. In this case, strain rate sensitivities can make test results virtually useless since the test velocity is no longer constant.

D1.7 Scale Model

Scale model testing involves constructing models of safety features and test vehicles to a reduced scale. The complexity of modeling automobile sheet metal crush, tire-pavement interaction, and suspension behavior has limited the application of these procedures for development of most roadside safety features. However, scale modeling can be useful during the development phases of safety features where most vehicle properties are of secondary importance, such as impact attenuation devices (73). This technique may yield useful

information about the gross motion of a vehicle during impact with selected safety features. Uncertainties associated with modeling of connection designs and material properties have continued to limit the usefulness of these procedures.

D1.8 Bogie Test

The bogie vehicle is defined as a structure mounted on four wheels and with mass equivalent to that of a selected passenger vehicle. The bogie vehicle is steered by rails, guide cable, remote control, or other means to strike the specimen. The bogie vehicle may be accelerated to impact speed by a push or tow vehicle, by self power, or by stationary windlass. A crushable or otherwise deformable nose is mounted on the front of the bogie.

As discussed in Section 2.4.1.2, bogie vehicles must be revalidated periodically if the devices are to be representative of modern vehicles. Existing bogies have been designed to replicate vehicular crush characteristics and inertial properties. Such a bogie has been shown to be capable of simulating impacts with breakaway structures. However, significant improvements to the vehicle crush and suspension models must be made before existing bogies can be expected to replicate impacts with other safety features such as longitudinal barriers.

D2.0 Comparison of Techniques

Applications and limitations of safety feature development techniques are given in Table D-3.

TABLE D-3. APPLICATIONS AND LIMITATIONS OF SAFETY FEATURE DEVELOPMENT TECHNIQUES

Development Technique	Principal Areas of Application	Possible Limitations
1. Structural Design Methods	• Preliminary and final design of feature for environment and non-collision performance • Preliminary design of feature for vehicle collision performance • Analysis of connections, material properties requirement and foundation design	• Dynamics and kinematics of feature and collision vehicle are not addressed • Collision severity in terms of occupant injuries and fatalities is not addressed
2. Static Tests (quasi-static)	• Mechanical properties of unique shapes, connections, new materials • Validation of structural design features • Quality control of critical material properties • Develop input values for computer programs	• Dynamic properties not examined • Generally applicable to samples, connections, and small subassemblies; entire system is not accommodated
3. Computer Simulations	• Study interrelations of feature and vehicle dynamics and kinematics • Study interrelations of vehicle dynamics and occupant dynamics • Study sensitivity of feature, vehicle and site conditions on vehicle/feature dynamic interactions	• Program should be validated by full-scale crash tests for specific conditions that bracket the conditions under study • Input parameters are sometimes not available and must be estimated • For practical and economic reasons, programs model only major feature/vehicle properties • Sometimes minor features decide the performance
4. Laboratory Dynamic Tests		
A. Gravitational Pendulum	• Compliance test for luminaire and single-leg sign breakaway supports • Evaluation of breakaway mechanisms • Force/deformation properties of guardrail post/soil interaction • Dynamic strength of anchor systems • Dynamic properties of barrier subsystems	• Impact speed 40 km/h or less • For dual-leg supports, upper-hinge mechanism are not examined • Does not simulate off-center impacts • Trajectory of article not reproduced • Base-bending support not applicable • Crushable nose must be tuned for type and width of specimen and recalibrated periodically • Cannot properly evaluate criterion D, Table 5.1
B. Drop Mass	• Quality control test of breakaway component • Test can be performed in a confined, indoor space	• Same limitations as for pendulum • For breakaway base, attached pole introduces artifact moment into base due to gravity
C. Scale Model	• Development testing of feature	• Difficulties and uncertainties in modeling vehicle and safety feature components
C. Bogie Vehicle Test	• Compliance test for single or multi-leg breakaway support • Repeatable test vehicle suspension, nose crash, and other dynamic properties • Low-cost, high-speed (0-60 mph) experiments	• Must be carefully designed and calibrated to represent vehicle characteristic of interest, which is often a long and expensive process • Designs have been appropriate for testing only limited variations in feature • Must be updated and recalibrated periodically.
D. Vehicle Crash Test	• Compliance test for all features • Investigation of unusual conditions • Most direct tie to actual highway collisions • Final proof test	• Relatively expensive to perform • Requires extensive capital facilities • Deliberate and slow to perform • Test results pertain to the specific vehicle model tested and may not be applicable to other vehicles

APPENDIX E

OCCUPANT COMPARTMENT DEFORMATION INDEX

El. Definition

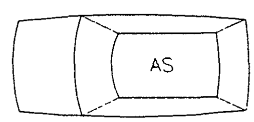
The Occupant Compartment Deformation Index (OCDI) described herein was taken from reference 77, and modified slightly. As recommended herein, it will be used by the European Committee for Normalization (CEN) for information purposes only and for the purpose of creating a data base from which future indices can be developed. It is referred to as the Vehicle Cockpit Deformation Index in reference 77.

This index designates both location and extent of deformation of the occupant compartment. It consists of two alphabetic characters plus seven numeric characters, in the form:

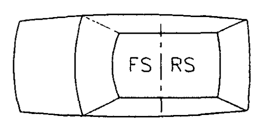
XXabcdefg

E2. Location of the Deformation

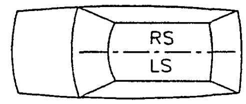
The location of occupant compartment deformation is indicated by two alphabetic characters XX, as follows:



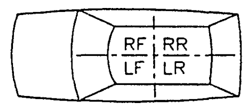
All Seats: XX = AS



Front Seats: XX = FS   Rear Seats: XX = RS



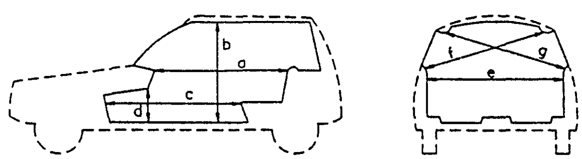
Right Seats: XX = RS Left Seats: XX = LS



Right Front: XX = RF Right Rear: XX = RR
Left Front: XX = LF Left Rear: XX = LR

E3. Extent of the Deformation

The seven subindices a, b, c, d, e, f and g indicate the percentage of reduction of seven interior dimensions shown on the following figure:



where,

a = distance between the dashboard and a reference point at the rear of the occupant compartment, such as top of rear seat, or the rear part of the cab on a pickup;

b = distance between the roof and the floor panel;

c = distance between a reference point at the rear of the occupant compartment and the motor panel;

d = distance between the lower dashboard and the floor panel;

e = interior width;

f = distance between the lower edge of right window and the upper edge of left window; and

g = distance between the lower edge of left window and the upper edge of right window.

All pre-impact reference points used in the above measurements should be marked and documented so that post-impact measurements can be made between the same points. To the extent possible, pre-impact measurements should be made in the area where maximum occupant compartment deformations are expected to occur. For example, the right-front part of the occupant compartment has the highest potential for damage from an impact with a longitudinal barrier, when the right-front part of the vehicle makes initial contact. In such a case, a set of a, b, c, and d measurements should be made on the right side of the occupant compartment, near the right door. Another set should probably be made midway between the sides of the occupant compartment. The value of each subindex should be based on the greatest reduction in each respective set of values. For example, the greatest reduction in c may occur at the center of the compartment and the greatest reduction in d may occur at the right side of the compartment. For the above longitudinal barrier impact, measurements e, f, and g should be made at the front windows of the vehicle.

Pre-impact reference points may not always coincide with the area of maximum compartment damage. In such a case it is recommended that pre-impact measurements be made on a vehicle of the same make and model year as the one tested. If this is not practical, estimates can be made from pre-impact measurements.

If resources permit, accurate measurements can be obtained by making sets of pre-impact subindices measurements along several planes that dissect the occupant compartment as one moves from the front to the rear of the compartment, and as one moves from one side of the compartment to the other.

The value of each of the seven numeric subindices is determined by the following scale:

0 - If the reduction is less than 3%
1 - If the reduction is more than 3% and less or equal to 10%
2 - If the reduction is more than 10% and less or equal to 20%
3 - If the reduction is more than 20% and less or equal to 30%
4 - If the reduction is more than 30% and less or equal to 40%, etc.

E4. Examples

(1) If an impact causes deformations to the right side of the occupant compartment, wherein e and f are reduced by 14% and g by 7% for the right seats (deformation centered approximately midway between the front and rear seats), the reduction of all the remaining dimension being below 3%, the OCDI will be: RS0000221.

(2) If in an impact distance a is reduced by 8% and c by 12% at the right front seat, all other reductions remaining below 3%, the OCDI will be: RF1200000.

APPENDIX F

DETERMINATION OF THE THIV, THE PHD, AND THE ASI

Fl. Introduction

The European Committee for Normalization (CEN) has adopted the Theoretical Head Impact Velocity (THIV) and associated Post-Impact Head Deceleration (PHD), and the Acceleration Severity Index (ASI) as measures of occupant risks for purposes of evaluating results of a crash test (77). They are presented herein with the hope and expectation that U.S. testers will determine and report these indices. The goal of this effort is to (a) develop a data base from which comparisons can be made between the THIV, ASI, the flail space indices recommended herein, and other measures of occupant risk, and (b) to provide a basis from which future test and evaluation procedures can be formulated by and harmonized between the U.S., CEN, and other countries.

F2. A Guide to the Measurement of the Theoretical Head Impact Velocity (THIV) and the Post-Impact Head Deceleration (PHD)

F2.1 General

The Theoretical Head Impact Velocity (THIV) concept has been developed for assessing occupant impact severity for vehicles involved in collisions with road vehicle restraint systems (78). The occupant is considered to be a freely moving object (head) that, as the vehicle changes its speed during contact with the safety feature, continues moving until it strikes a surface within the interior of the vehicle. The magnitude of the velocity of the theoretical head impact is considered to be a measure of the impact severity.

The head is presumed to remain in contact with the surface during the remainder of the impact period. In so doing it experiences the same levels of acceleration as the vehicle during the remaining contact period (Post-impact Head Deceleration - PHD) (79).

F2.2 Theoretical Head Impact Velocity (THIV)

It can be assumed that at the beginning of vehicular contact with the test article, both the vehicle and the theoretical head have the same horizontal velocity V_O, vehicular motion being purely translational.

During impact, the vehicle is assumed to move only in a horizontal plane, because high levels of pitch, roll, or vertical motion are not of prime importance unless the vehicle overturns. This extreme event does not need to be considered, as in this case the decision to reject the candidate system will be taken on the basis of visual observation or photographic recording.

Two reference frames are used, as indicated in Figure F2.1. The first of these is a vehicular reference Cxy, x being longitudinal and y transversal; the origin C is a point at or near the vehicle's center of mass, where two accelerometers and a rate gyroscope are typically

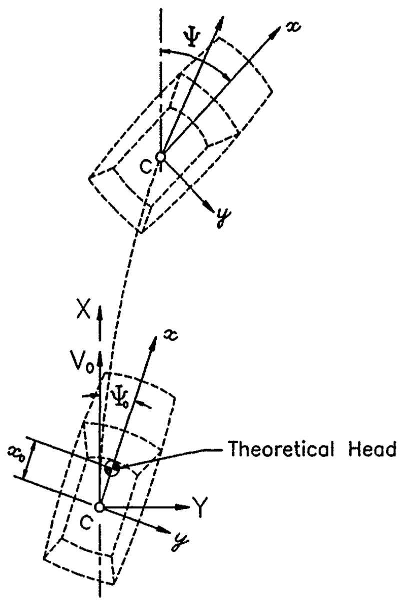


FIGURE F2.1: VEHICLE AND GROUND REFERENCE FRAMES

installed (see Section 4.3.3 for recommended procedures to determine accelerations and yaw rate at C if the instrumentation cannot be placed at or near the center of mass). Let $\ddot{x}_c$ and $\ddot{y}_c$ be the accelerations of point *C* (in m/s^2), respectively, along the x and y vehicle axes, recorded from the two accelerometers, and $\dot{\Psi}$ the yaw rate (in radians per second), recorded from the gyroscope ($\ddot{x}$ positive forward, $\ddot{y}$ positive to right hand side and $\dot{\Psi}$ positive clockwise looking from above).

The second reference frame is a ground reference *OXY,* with the X axis aligned with the initial vehicular velocity V_O, and the origin O coinciding with the initial position of the vehicular datum point C.

$X_c(t)$, $Y_c(t)$ are the ground coordinates of the vehicle reference *C,* while $X_b(t)$, $Y_b(t)$ are the ground coordinates of the theoretical head (see Figure F2.2).

With these definitions and simplifying hypotheses, vehicle and theoretical head motion can be computed as follows.

VEHICULAR MOTION

Initial conditions:

$$\text{at time } t = 0, \quad \begin{cases} X_c = 0 & Y_c = 0 & \Psi = \Psi_0 \\ \dot{X}_c = V_0 & \dot{Y}_c = 0 & \dot{\Psi} = 0 \end{cases} \tag{F2.1}$$

The yaw angle Ψ is computed by integration of the yaw rate $\dot{\Psi}$:

$$\Psi(t) = \int_0^t \dot{\Psi}\, dt + \Psi_0 \tag{F2.2}$$

Then, from the components of vehicular acceleration in ground reference,

$$\begin{cases} \ddot{X}_c = \ddot{x}_c \cos\Psi - \ddot{y}_c \sin\Psi \\ \ddot{Y}_c = \ddot{x}_c \sin\Psi + \ddot{y}_c \cos\Psi \end{cases} \tag{F2.3}$$

Vehicular velocity and position are computed by integration:

$$\begin{cases} \dot{X}_c = \Delta\dot{X}_c + V_0 & \Delta\dot{X}_c = \int_0^t \ddot{X}_c dt \\ \dot{Y}_c = \Delta\dot{Y}_c & \Delta\dot{Y}_c = \int_0^t \ddot{Y}_c dt \end{cases} \tag{F2.4}$$

$$\begin{cases} X_c = \int_0^t \Delta\dot{X}_c dt + V_0 t \\ Y_c = \int_0^t \Delta\dot{Y}_c dt \end{cases} \tag{F2.5}$$

THEORETICAL HEAD MOTION RELATIVE TO GROUND

Initial condition: time=0

$$\begin{cases} X_b = x_0 \cos\Psi_0 = X_0 & Y_b = x_0 \sin\Psi_0 = Y_0 \\ \dot{X}_b = V_0 & \dot{Y}_b = 0 \end{cases} \tag{F2.6}$$

Then, if the theoretical head continues its uniform motions:

$$X_b = V_0 t + X_0 \qquad Y_b = Y_o \tag{F2.7}$$

THEORETICAL HEAD MOTION RELATIVE TO VEHICLE

Vehicular components of the relative velocity of the theoretical head are:

$$\begin{cases} v_x(t) = -\Delta\dot{X}_c\cos\Psi - \Delta\dot{Y}_c\sin\Psi + y_b\dot{\Psi} \\ v_y(t) = \Delta\dot{X}_c\sin\Psi - \Delta\dot{Y}_c\cos\Psi - x_b\dot{\Psi} \end{cases} \qquad \text{(F2.8)}$$

Coordinates of the theoretical head with respect to the vehicle's frame can be computed by the formula:

$$\begin{cases} x_b(t) = \Delta X_b\cos\Psi + \Delta Y_b\sin\Psi \\ y_b(t) = -\Delta X_b\sin\Psi + \Delta Y_b\cos\Psi \end{cases} \quad where \quad \begin{matrix} \Delta X_b = X_0 - \int_0^t \Delta\dot{X}_c\, dt \\ \Delta Y_b = Y_0 - \int_0^t \Delta\dot{Y}_c\, dt \end{matrix} \qquad \text{(F2.9)}$$

TIME OF FLIGHT

Notional impact surfaces inside the vehicle are assumed to be flat and perpendicular to the x and y vehicular axes (see Figure F2.2). The distances of such surfaces from the original head position (flail distances) are D_x forward and D_y laterally on both sides.

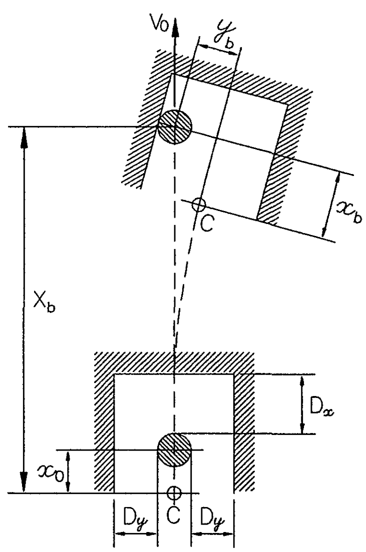


FIGURE F2.2: IMPACT OF THE THEORETICAL HEAD ON THE LEFT SIDE

The time of flight of the theoretical head is the time of impact on one of the three notional surfaces in Figure F2.2, i.e., the shortest time T when one of the three following equalities is satisfied:

$$x_b(T) = D_x + x_0; \quad or \quad y_b(T) = D_y; \quad or \quad y_b(T) = -D_y \qquad \text{(F2.10)}$$

The standard values of the flail distances are:

$$D_x = 0.6 \text{ m} \qquad D_y = 0.3 \text{ m}$$

<u>THIV</u>

Finally, the Theoretical Head Impact Velocity is the relative velocity at time T, i.e.:

$$THIV = \left[v_x^2(T) + v_y^2(T)\right]^{1/2}$$

THIV shall be reported in m/s.

F2.3 Post-Impact Head Deceleration (PHD)

Post-impact Head Deceleration (PHD) is the maximum value of the acceleration filtered by a 10 Hz low-pass filter, occurring after the time T of the collision of the theoretical head. If $\mathscr{F}_{10}$ represents the filtering, then:

$$PHD = MAX\left(\mathscr{F}_{10}(\ddot{x}_c^2 + \ddot{y}_c^2)^{1/2}\right) \qquad (for\ t > T)$$

PHD shall be reported in g units

F2.4 Summary of Procedure to Compute THIV and PHD

1. Record vehicular accelerations and yaw rate, and store in digital form at the sample rate S; let the data in the three record files be ${}^k\ddot{x}_c$, ${}^k\ddot{y}_c$, ${}^k\dot{\Psi}$ $(k = 1,2,...,N)$. The time interval between two subsequent data in the record file is $h = {}^k t - {}^{k-1}t = 1/S$. For example, if S = 500 samples per second, h = 2 ms.

2. Integrate the yaw rate by the recurrent formula (from Equation F2.2):

$${}^1\Psi = \Psi_0; \quad {}^2\Psi = {}^1\Psi + h\frac{{}^1\dot{\Psi} + {}^2\dot{\Psi}}{2} \quad ;...; \quad {}^{k+1}\Psi = {}^k\Psi + h\frac{{}^k\dot{\Psi} + {}^{k+1}\dot{\Psi}}{2}$$

3. Compute vehicular acceleration in ground reference (from Equation F2.3):

$${}^k\ddot{X}_c = {}^k\ddot{x}_c\cos{}^k\Psi - {}^k\ddot{y}_c\sin{}^k\Psi \qquad {}^k\ddot{Y}_c = {}^k\ddot{x}_c\sin{}^k\Psi + {}^k\ddot{y}_c\cos{}^k\Psi$$

4. Integrate vehicular acceleration in ground reference (from Equations F2.4 and F2.9)

$$\begin{cases} {}^{1}\Delta\dot{X}_c = 0; \quad {}^{k+1}\Delta\dot{X}_c = {}^{k}\Delta\dot{X}_c + h\,\dfrac{{}^{k}\ddot{X}_c + {}^{k+1}\ddot{X}_c}{2}; \\ {}^{1}\Delta\dot{Y}_c = 0; \quad {}^{k+1}\Delta\dot{Y}_c = {}^{k}\Delta\dot{Y}_c + h\,\dfrac{{}^{k}\ddot{Y}_c + {}^{k+1}\ddot{Y}_c}{2}; \end{cases}$$

$$\begin{cases} {}^{1}\Delta X_b = X_0; \quad {}^{k+1}\Delta X_b = {}^{k}\Delta X_b - h\,\dfrac{{}^{k}\Delta\dot{X}_c + {}^{k+1}\Delta\dot{X}_c}{2} \\ {}^{1}\Delta Y_b = 0; \quad {}^{k+1}\Delta Y_b = {}^{k}\Delta Y_b - h\,\dfrac{{}^{k}\Delta\dot{Y}_c + {}^{k+1}\Delta\dot{Y}_c}{2}; \end{cases}$$

5. Compute relative position and relative velocity of the theoretical head as functions of time (from Equations 8 and 9):

$$\begin{cases} {}^{k}x_b(t) = {}^{k}\Delta X_b \cos {}^{k}\Psi + {}^{k}\Delta Y_b \sin {}^{k}\Psi \\ {}^{k}y_b(t) = -{}^{k}\Delta X_b \sin {}^{k}\Psi + {}^{k}\Delta Y_b \cos {}^{k}\Psi \end{cases}$$

$$\begin{cases} {}^{k}v_x = -{}^{k}\Delta\dot{X}_c \cos {}^{k}\Psi - {}^{k}\Delta\dot{Y}_c \sin {}^{k}\Psi + {}^{k}y_b\,{}^{k}\dot{\Psi} \\ {}^{k}v_y = {}^{k}\Delta\dot{X}_c \sin {}^{k}\Psi - {}^{k}\Delta\dot{Y}_c \cos {}^{k}\Psi - {}^{k}x_b\,{}^{k}\dot{\Psi} \end{cases}$$

6. Find the minimum value of j for which one of the three equalities is satisfied.

$${}^{j}x_b = D_x + X_0; \qquad or\ {}^{j}y_b = D_y; \qquad or\ {}^{j}y_b = -D_y$$

7. Compute

$$THIV = \left[{}^{j}v_x^2 + {}^{j}v_y^2\right]^{1/2}$$

8. Compute the resultant vehicular acceleration in g as a function of time

$${}^{k}A = \frac{1}{g}\left({}^{k}\ddot{x}_c^2 + {}^{k}\ddot{y}_c^2\right)^{1/2}$$

9. Filter the sequence ${}^{k}A$ with a digital Butterworth low-pass filter, having a cut-off frequency of 10 Hz and a roll-off of 48 dB/octave; PHD is the maximum of such filtered sequence.

F3. A Guide to the Measurement of the Acceleration Severity Index (ASI)

F3.1 Procedure

The Acceleration Severity Index (ASI), developed by TTI (80), is a function of time, computed with the following formula:

$$ASI(t) = [(\bar{a}_x / \hat{a}_x)^2 + (\bar{a}_y / \hat{a}_y)^2 + (\bar{a}_z / \hat{a}_z)^2]^{1/2} \qquad (F3.1)$$

where $\hat{a}_x$, $\hat{a}_y$, *and* $\hat{a}_z$, are limit values for the components of the acceleration along the body axes x, y, and z; $\bar{a}_x$, $\bar{a}_y$, *and* $\bar{a}_z$ are the components of the acceleration of a selected point P of the vehicle, averaged over a moving time interval delta δ = 50 ms, so that:

$$\bar{a}_x = \frac{1}{\delta}\int_t^{t+\delta} a_x dt; \quad \bar{a}_y = \frac{1}{\delta}\int_t^{t+\delta} a_y dt; \quad \bar{a}_z = \frac{1}{\delta}\int_t^{t+\delta} a_z dt \qquad (F3.2)$$

The index ASI is intended to give a measure of the severity of the vehicular motion during an impact for a person seated in the proximity of point P.

Averages computed in Equations F3.2 are equivalent to what would be obtained by a low pass filter, and take into account the fact that vehicular accelerations can be transmitted to the occupant body through relatively soft contacts which cannot pass the highest frequencies. Direct use of vehicular accelerations, even if averaged, implies that the parts of occupant body than can be injured are continuously in contact with some part of the vehicle.

Note that Equation F3.1 is a basic interaction formula of three variables. If any two components of vehicular acceleration are null, ASI reaches its limit value of 1 when the third component reaches its limit acceleration. When two or three components are non null, ASI may be 1 with the single components well below the relevant limits. Limit accelerations are interpreted as the values below which occupant risk is very small (light injuries, if any).

In Europe (France, Germany, and Netherlands), for occupants wearing safety belts, the generally used limit accelerations are:

$$\hat{a}_x = 12g, \ \hat{a}_y = 9g, \ \hat{a}_z = 10g \qquad (F3.3)$$

where g = 9.81 ms^{-2} is the acceleration of Earth gravity at sea level.

With the above definition ASI is a nondimensional quantity, which is a scalar function of time and, in general, of the selected vehicular point, having only positive values. Occupant risk is assumed to be proportional to ASI. Therefore, the maximum value attained by ASI in a collision is assumed as a single measure of the severity, or:

$$ASI = \max[ASI(t)] \qquad (F3.4)$$

Vehicular accelerations in the x, y, and z directions are measured at or near the center of mass of the vehicle (see Section 4.3.3 for recommended procedures to determine accelerations

in the x and y directions at the center of mass if the accelerometers cannot be placed at or near the center of mass).

F3.2 Summary

In summary, the following steps are used to compute the ASI.

1. Record vehicular accelerations in the x, y, and z directions at or near the vehicle's center of mass (see Section 4.3.3 if accelerometers can not be placed at or near the center of mass). In general, accelerations are stored on a magnetic tape as three series of N numbers, sampled at a certain sampling rate S (samples/sec).

For such three series of measures,

$$
\begin{aligned}
&{}^{1}a_x, {}^{2}a_x, \ldots, {}^{k-1}a_x, {}^{k}a_x, {}^{k+1}a_x, \ldots, {}^{N}a_x \\
&{}^{1}a_y, {}^{2}a_y, \ldots, {}^{k-1}a_y, {}^{k}a_y, {}^{k+1}a_y, \ldots, {}^{N}a_y \\
&{}^{1}a_z, {}^{2}a_z, \ldots, {}^{k-1}a_z, {}^{k}a_z, {}^{k+1}a_z, \ldots, {}^{N}a_z
\end{aligned}
$$

where acceleration of gravity g is the unit of measurement.

2. Find the number m of samples in the averaging window delta o = 0.05s: m = INT(o *S) =INT(.05*S), where INT(R) is the integer nearest to R. For example, if S = 500 samples per sec., m = 25.

3. Compute the average accelerations from Equation F3.2:

$$
\begin{aligned}
{}^{k}\bar{a}_x &= \frac{1}{m}\left({}^{k}a_x + {}^{k+1}a_x + {}^{k+2}a_x + \ldots + {}^{k+m}a_x\right) = \frac{1}{m}\sum_{j=k}^{k+m} {}^{j}a_x \\
{}^{k}\bar{a}_y &= \frac{1}{m}\left({}^{k}a_y + {}^{k+1}a_y + {}^{k+2}a_y + \ldots + {}^{k+m}a_y\right) = \frac{1}{m}\sum_{j=k}^{k+m} {}^{j}a_y \\
{}^{k}\bar{a}_z &= \frac{1}{m}\left({}^{k}a_z + {}^{k+1}a_z + {}^{k+2}a_z + \ldots + {}^{k+m}a_z\right) = \frac{1}{m}\sum_{j=k}^{k+m} {}^{j}a_z
\end{aligned}
$$

Functions of time ${}^{k}t$ = h (k+m/2).

4. Compute ASI as a function of time from Equation F3. 1:

$$
{}^{k}ASI = [({}^{k}\bar{a}_x/12)^2 + ({}^{k}\bar{a}_y/9)^2 + ({}^{k}\bar{a}_z/10)^2]^{1/2}
$$

5. Find ASI as the maximum of the series of the ^{k}ASI.

APPENDIX G

SIDE IMPACT TEST AND EVALUATION PROCEDURES FOR ROADSIDE STRUCTURE CRASH TESTS

Concurrent with the effort to prepare an update to *NCHRP Report 230,* an FHWA-sponsored study was being conducted to examine the side impact problem and to develop tentative side impact test procedures for sign and luminaire support structures. This appendix contains a report, copied verbatim, from that study describing recommended test and evaluation procedures for side impact testing. It is included for information purposes only because no recommendations are made relative to the impact performance requirements of a safety feature for side impacts (see discussion in Section 3.5). Until these or other guidelines are nationally accepted, developers of safety features for side impact capabilities may use guidelines presented therein.

Note that references cited in the appendix refer to the list of references given at the end of the Appendix G.

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16 Abstract

The report contains recommendations for performing and evaluating side impact crash tests of roadside structures like luminaire supports, guardrail terminals, and utility poles. A 50 km/h full broadside test using a small car is recommended. Evaluation criteria include recommendations for structural adequacy, occupant risk, and post collision trajectory. The occupant risk criteria use indicies obtained using anthropometric dummy test devices.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

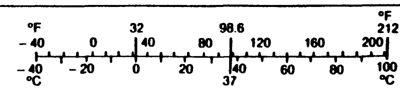
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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1 Introduction

Side impact collisions involving fixed roadside objects like utility poles, trees and luminaire supports account for about 1600 fatalities and 60,000 injured vehicle occupants each year in the United States [28] [31]. This type of collision appears to cause a disproportionate number of fatalities and serious injuries [16][28] [31].

Many of the fixed objects struck on the roadside are intentionally placed there to provide lighting, power transmission, or to convey information. While usually serving a benign purpose, these objects can become a hazard if they are not designed to breakaway, collapse, or fracture in an impact with an errant vehicle. This report recommends testing conditions and evaluation criteria for side impact full-scale crash tests of structures placed on the roadside.

These recommendations supplement guidelines published by the National Cooperative Highway Research Program (NCHRP) [19] [29]. Where a particular guideline is not specifically addressed herein, the more general NCHRP guidelines should be applied. For example, test documentation is not specifically addressed so all documentation items recommended in the NCHRP guidelines should be included in a complete side impact test report. These recommendations are organized much like the latest NCHRP guidelines [29].

This document is based largely on research described in several other reports and papers [32] [27] [28] [31] [14]. The Fatal Accident Reporting System (FARS) and National Accident Sampling System (NASS) were investigated to learn about the characteristics of side impacts with fixed roadside objects [32] [28]. A number of side impact crash tests of luminaire supports and guardrail terminals were performed by the Federal Highway Administration (FHWA) during the past decade [27] [12] [10]. More information on particular aspects of these recommendations can be found in these other documents.

The National Highway Traffic and Safety Administration (NHTSA) has published rules on performing vehicle-to-vehicle side impact crash tests to evaluate the crashworthiness of production automobiles and light trucks [23] [21] [22]. Although there are important differences between the objectives of these NHTSA tests and the tests addressed by this report, the proposed NHTSA rules were used as a guide wherever possible in formulating these recommendations [24]. Any linkage that can be forged between NHTSA and FHWA side impact crash tests would be beneficial in the future as more is learned by both research communities about side impact collisions.

2 Test Parameters

2.1 Test Facilities

Side impact crash tests are significantly more difficult to perform than typical safety appurtenance crash tests. Accelerating the vehicle laterally requires test facilities that are not commonly found in the roadside research community. Side impact crash tests have been performed using:

- A differentially braked vehicle on a slick pavement [9].
- A cable-guided cable-towed carriage with the vehicle mounted sideways [2].
- A cable-towed wooden pallet with the vehicle resting sideways [33].
- A monorail and outrigger assembly with the vehicle resting on casters [11].

The Federal Outdoor Impact Laboratory (FOIL), shown in figure 1, was used for most of the side impact crash tests performed to assess the performance of roadside structures. The vehicle is transported on a monorail. A stabilizing outrigger rail runs parallel to the monorail. Rolling carriages are mounted on the underside of the vehicle body. The monorail and outrigger rail end approximately 2 m from the test device. The vehicle is brought up to the desired test speed using a drop-weight accelerator. The vehicle, with the attached roller carriages, drops off the rails and slides the remaining distance to the test device. Information about the construction, capabilities, and operation of the FOIL can be found elsewhere [11].

Test devices should be mounted in as realistic a manner as possible. Some objects like foundation mounted luminaire supports may be rigidly connected to a universal foundation if they are normally supported on a rigid foundation in the field. Soil mounted structures like guardrail terminals, utility poles and signs should be mounted in a soil representative of the soil type typically found in the field.

The vehicle should slide laterally at least two vehicle track widths to allow the vehicle to stabilize after dropping off the monorail. The sliding should occur on pavement or wood since soft earth may trip a vehicle sliding broadside over a large distance. Wetting down the approach area with water just prior to the test will help reduce friction between the surface and the vehicle tires. Accidents certainly occur on dry non-paved surfaces but experimental difficulties with the stability of the vehicle and repeatability of the test make reducing the sliding friction advisable.

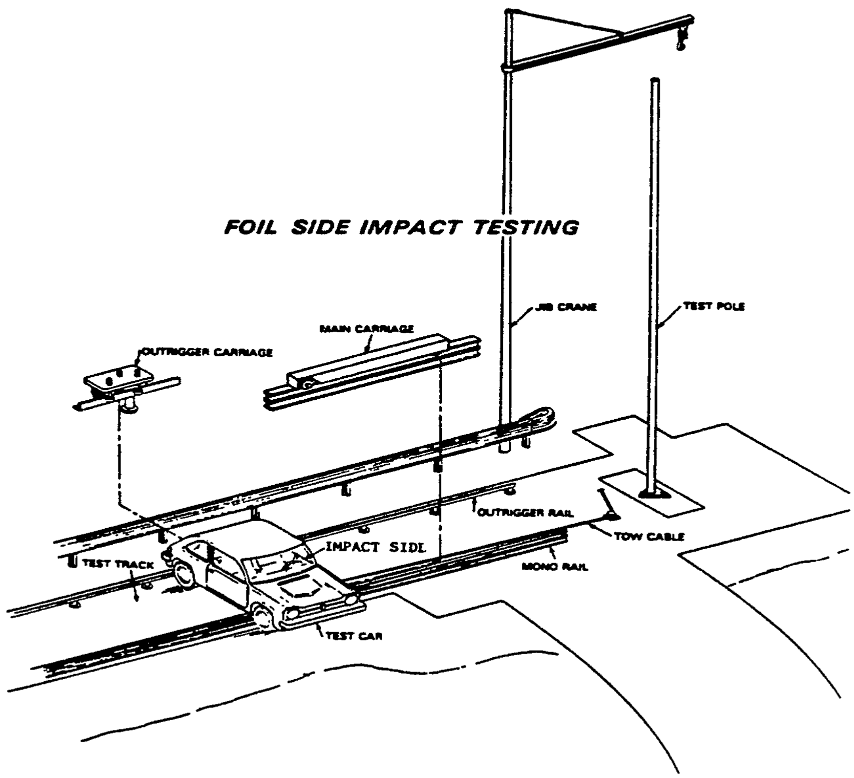


Figure 1: Federal Outdoor Impact Laboratory [11].

2.2 Test Articles

An investigation of the Fatal Accident Reporting System (FARS) and National Accident Sampling System (NASS) showed that narrow objects accounted for 60 percent of the accidents but 80 percent of the fatalities in side impact accidents involving fixed roadside objects. Narrow objects subject the side of a vehicle to highly concentrated loadings that are difficult to resist without extensive vehicle deformation.

Highway safety appurtenances in the narrow-object category (table 1) include luminaire supports, utility poles, sign supports, guardrail terminals and narrow crash cushions. These recommendations should be used during an assessment program after all the applicable frontal tests have been performed. The side impact test is much more demanding than the frontal tests. After successful performance is observed in the frontal tests, the side impact test should be performed.

Table 1. Test devices appropriate for side impact crash testing.

Luminaire Supports
Large and Small Sign Supports
Guardrail Terminals Narrow Crash Cushions
Breakaway Utility Poles

2.3 Vehicle

A two-door 820-kg small vehicle should be used in side impact crash testing of roadside hardware. This vehicle is identical to the 820C vehicle recommended in the NCHRP guidelines with the exception that only two-door models should be used [29]. All the requirements for mass tolerances, vehicle age and condition recommended in the NCHRP guidelines should also be satisfied for side impact crash tests as should recommended vehicle dimensions.

Examination of the **FARS** accident data has shown that the fatality rate in smaller vehicles is no different than for larger vehicles in side-impact fixed-object accidents [28]. Partyka has shown that, in general, the fatality rate is not a function of weight in single-vehicle accidents where rollover does not occur [25]. The choice of a lighter test vehicle, therefore, cannot be justified on the grounds that the occupant is more at risk.

Instead, the lighter vehicle was chosen in order to (1) minimize the kinetic energy available for device activation and (2) maximize the probability of vehicle instability during the post collision trajectory. Most of the devices targeted by these recommended procedures function by breaking away, collapsing, yielding or fracturing. T1 e 820C vehicle provides a reasonable minimum amount of kinetic energy in an impact.

While vehicle stability was not normally a problem in side impact crash tests with fixed objects, smaller vehicles tend to be less stable than larger vehicles because of narrower track widths, smaller masses, and the position of their centers of gravity. Stability problems like rolling over are more easily identified when smaller vehicles are used so their use is recommended.

The door on a two-door vehicle spans a larger distance than in comparable four-door models. This larger span on two-door models makes the door inherently weaker than the four-door model. The two-door small car minimizes the side impact resistance of the vehicle.

Side impact crash tests of narrow fixed objects sponsored by the FHWA have been performed using the Honda Civic Si, the Dodge Colt, the Plymouth Champ and the Volkswagen Rabbit [27]. All the vehicles used were two-door models manufactured between 1978 and 1986 and conform to the requirements shown in table 2.

Table 2. Side impact test vehicle.

Vehicle Type	NCHRP 820C	
Test Inertial - kg	820	± 25
Dummy - kg	75	
Max. Ballast - kg	50	
Gross Static - kg	915	± 25
Engine Location	Front	
Drive Axle Location	Front	
Number of Doors	Two	

3 Test Conditions

3.1 General

Side impact tests will be supplementary to the usual frontal crash tests specified in *NCHRP Report 230.* The standard frontal matrix of tests includes a 30 km/h test of the breakaway mechanism. Since this frontal test examines the breakaway mechanism at the 30 kJ level, there should be no need to retest in a side impact configuration. In frontal tests, the amount of kinetic energy transformed to vehicle deformation is usually a relatively small percentage of the total energy; most of the energy can be used to activate the device. In side impacts, vehicle deformation accounts for a much larger proportion of the initial kinetic energy. It cannot be assumed a *priori,* then, that a device that activates in a low speed frontal collision will activate in a side impact collision. While testing at a lower speed would produce a more demanding test in terms of device activation, it may not by satisfactory for evaluating the risk to vehicle occupants. The side impact test

recommended herein will focus on the response of the hypothetical occupant.

Impact conditions for full-scale crash tests have generally been designed to represent the practical worse-case impact scenario [19]. With this perspective in mind, accident data from the Fatal Accident Reporting System (FARS) and the National Accident Sampling System (NASS) Continuous Sampling System (CSS) were investigated to examine the characteristics of side impact fixed object accidents [32] [28] [31].

The following recommended test conditions for side-impact fixed object collisions are a compromise between the most realistic conditions and those easiest to obtain in controlled experiments. The accident data provides indications of the speeds and orientations common in side impact collisions. Because of the shortcomings of accident data the estimates of impact conditions must be viewed as tentative. The accident data does, however, provide the only view of the real-world accident problem. It appears that most side impacts occur at relatively low lateral speeds and high angles.

Table 3 shows the recommended impact conditions for side impact testing of roadside structures. A collision between a fixed roadside object and the center of the driver's side door is recommended. The lateral impact speed for test SI- should be 50 km/h. Test SI-2 is an optional higher velocity test that can be included when the performance of a device is expected to degrade at higher velocities. While real accidents involve longitudinal and angular velocity components, experimental limitations often preclude testing with these additional velocity components. These impact conditions are suggested as a reasonable set of experimentally achievable test conditions for exploring the performance of roadside hardware in side impact collisions.

Table 3. Side impact test conditions.

	SI-1		SI-2 (optional)	
Lateral Velocity	50	km/h	60	km/h
Longitudinal Velocity	0	km/h	0	km/h
Yaw Angle	90	degrees	90	degrees
Yaw Rate	0	degrees/sec	0	degrees/sec
Impact Point	Center of Door		Center of Door	

3.2 Vehicle Orientation

Side impacts have been shown to be associated primarily with narrow fixed objects such as utility poles and luminaire supports [28] [31]. The impact angle is usually defined in a crash test as the angle between the longitudinal axis of a device and the approach path of the vehicle. Since many narrow objects have no longitudinal axis the impact angle is technically undefined. The vehicle orientation and yaw angle can be defined instead in

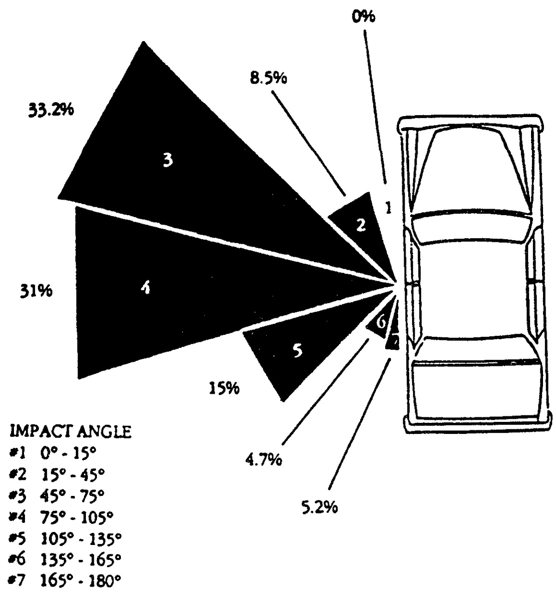


Figure 2. Directions of force in side impact collisions with fixed roadside objects involving the passenger compartment (1982 - 1985 NASS) [32].

terms of the orientation of the traveled way as shown in figure 3. This ensures that the basic accident scenario being investigated is the same even if the devices are different.

There is no direct measure of the yaw angle given in the NASS-CSS accident data. An estimate of these quantities can be made, however, using the direction-of-force variable and the longitudinal and lateral changes in velocity. The yaw angle is the angle between the longitudinal direction of the vehicle and the direction of the velocity vector.

The direction-of-force (DOF variable is an estimate of the orientation of the resultant force during the collision. A DOF of 0 indicates that the force interaction was parallel with the center line of the vehicle whereas a DOF of 90 would indicate a perpendicular force. Figure 2 shows the direction of force distribution for side impacts with fixed objects from the 1982 through 1985 NASS-CSS data [32]. The mean direction of force was found to be 56 degrees and the median value was 60 degrees. The most frequently observed direction of force was 90 degrees, a full broadside collision. Figure 2 also shows that the vehicle had a forward component of velocity in more than 80 percent of the impacts. Angles between 45 and 105 degrees accounted for almost 50 percent of the side impact yaw impact angles.

Another rough estimate of the yaw angle can be obtained by calculating the arctangent of the longitudinal and lateral change in velocity. These estimates are very approximate because of the uncertainties in calculating the two velocity values [30]. The mean yaw

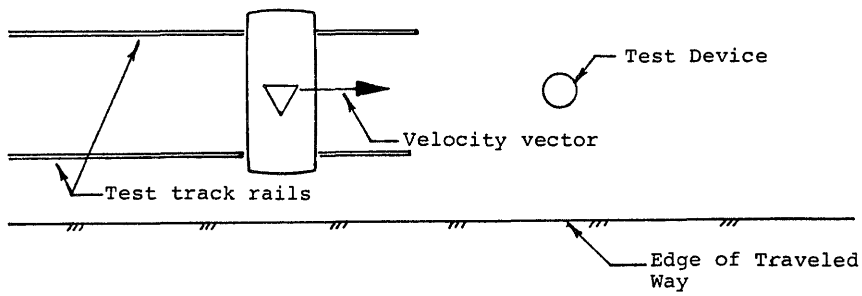


Figure 3. Vehicle orientation for side impact crash tests.

angle was found to be 57 degrees with a standard deviation of 19 degrees [32]. Both estimates of the yaw angle, then, indicate that the mean yaw angle is approximately 60 degrees. The final rule on side impact testing published by NHTSA specifies a test with a crabbed impactor bogie. The principal direction of force on the test vehicle is 63 degrees. This choice of a crabbed vehicle was based on NHTSA's analysis of vehicle-to-vehicle side impact collisions.

Performing tests with a yaw angle of 60 degrees was considered but abandoned in favor of a 90-degree orientation for several reasons:

- Mounting a vehicle on a carriage with a 60 degree yaw angles causes some experimental problems in balancing the vehicle on the guidance rails and mounting the carriages under the vehicle. In NHTSA tests the impacted vehicle is stationary so it does not have to balanced and accelerated. The impactor bogie, though yawed, is a tracking vehicle since the wheel are attached at an angle.

- When a yawed vehicle releases from the carriage it will tend to roll ahead making the vehicle difficult to control. Obtaining repeatable impact locations would be impossible with a yawing vehicle.
- A full broadside orientation constitutes a reasonable worst-case (possible unsurvivable) scenario in terms of the side-door strength of the vehicle. The side of the vehicle is relatively weak and the perpendicular orientation maximizes the loading in the weak direction.

Side impact crash tests of roadside structures should be performed with the vehicle perpendicular to the traveled way with the front of the vehicle facing the traveled way.

This orientation, shown in figure 3, represents the common accident scenario of leaving the road on the wrong side, partially recovering and striking a fixed object nearly broadside.

3.3 Velocity

The velocity change values reported in the 1982 through 1985 NASS-CSS data for side impact fixed objects accidents centered on the occupant compartment were used to estimate the impact velocity [32]. The change in velocity can be assumed to be close to the impact velocity if it is assumed that the vehicle was brought to rest as a result of the collision. The most frequently struck objects in the NASS-CSS data are trees, utility poles and other narrow objects. While some of these objects, like sign supports and delineator posts, do break away or yield the majority of collisions are with objects that do not break away such as trees and utility poles. When the fixed object does not break away, the vehicle must come to rest. The assumption that the changes in lateral velocity can be used to represent lateral impact velocities, then, seems to be a reasonable first approximation for side impacts with fixed roadside structures.

The mean lateral change in velocity, as shown in table 4, was 24 km/h. The maximum lateral velocity observed in this sample was 63 km/h. If the distribution of lateral velocities is assumed to be exponential, 85 percent of the cases would occur at less than 45 km/h and 70 percent of the cases would occur at less than 30 km/h. An exponential distribution is a reasonable assumption since the most common lateral velocity should be zero and large lateral velocities should be quite rare. An exponentially distributed lateral velocity distribution is suggested by the NASS data [27].

Table 4. Change in velocity statistics for side impact accidents with fixed objects (1982-1985 NASS) [32].

Velocity Direction	Maximum Velocity (km/h)	Mean Velocity (km/h)	Standard Deviation (km/h)
Lateral	63	24	16
Longitudinal	38	11	10
Total	67	29	18

Table 5 illustrates the increasing severity of injury with increasing total velocity change. More than 60 percent of all minor injuries occurred in accidents where the lateral change in velocity was less than 10 km/h. In contrast 75 percent of the severe and fatal injuries occurred in accidents where the lateral change in velocity was greater than 31 km/h. Clearly, the amount of energy dissipated is related to the severity of injury experienced by the vehicle occupants. It has been suggested that injury can be defined as exposure to energy [4]; more energy should be correlated with a higher proportion of severe injuries. The proportion of severe and moderately injured occupants increases as the lateral change in velocity increases.

Table 5. Injury as a function of lateral change in velocity for side ipacts centered on the passenger compartment [32].

ΔV_{total}	Minor $0 \leq AIS < 2$		Moderate $2 \leq AIS < 3$		Severe $AIS \geq 4$		Unknown	Total	
(km/h)	(no.)	(%)	(no.)	(%)	(no.)	(%)	(no.)	(no.)	(%)
0-10	34	65	7	33	2	25	2	44	54
11-20	4	8	1	5	0	0	0	5	6
21-30	9	17	0	0	0	0	0	9	11
31-40	2	4	6	29	1	12	0	9	11
41-50	3	6	1	5	1	13	0	5	6
51-60	0	0	5	23	3	38	0	8	10
60 >	0	0	1	5	1	12	0	2	2
Total	52	100	21	100	8	100	2	83	
Missing								23	

Severe injuries *(AIS* > 3) can be observed across the range of impact speeds but 75 percent occur at velocities greater than 30 .km/h. The mean velocity for occupants who received *AIS* > 3 injuries was approximately 40 km/h. Impacts occurring in the 30 to 60 km/h range resulted in 1 chance in 18 of sustaining an *AIS* > 3 injury. A test velocity of 50 km/h was selected since successful performance at this speed would imply protection for nearly 90 percent of the vehicle occupants in this sample. Specifying a higher test velocity would probably exceed the point of diminishing returns.

3.4 Impact Point

The impact point for side impact crash tests of roadside structures should be at the center of the driver's side door on a small 2-door passenger vehicle. This location is near the longitudinal center of gravity of the 820C vehicle and about 250 mm in front of the dummy shoulder. The door is weakest at the center so the maximum amount of intrusion should be observed when the impact is located at this point.

One of the CRASH3 data items collected in the NASS data is the distance from the vehicle center of gravity to the centroid of the damaged area. Nearly 60 percent of the side impacts in the study sample occurred between the A and B pillar [32]. Impacts that occur between the A and B pillars will be located on the front door, very close to the front seat occupant.

Earlier tests [12] have used an impact point centered on the front seat occupant. While this orientation represents a practical worst case scenario, recent testing has indicated that obtaining useful anthropometric dummy responses is very difficult when the dummy directly contacts the intruding object [27]. Accidents where the occupant's head directly contacted an intruding pole are not difficult to find in the literature or in the accident data.

When this occurs the occupant is nearly always severely injured, even when the lateral impact velocity is very low. The absence of any protection between the head and the window makes protection of the occupant in this situation nearly impossible.

The recommended impact location is slightly in front of the dummy shoulder. This location, while not the worst, subjects the dummy to large impact loadings but is far enough removed to yield more repeatable and meaningful dummy responses.

3.5 Anthropometric Dummy Position

NHTSA vehicle-to-vehicle side impact tests require the use of an instrumented Part 572 Subpart F side impact dummy (SID) [24]. The side impact tests performed at the FOIL since 1985 have all used this type of dummy. The long-term objective of this research is to specify criteria that will allow side impact crash tests to be evaluated without dummies. There are several reasons for not including dummies in crash tests of safety appurtenances. A recent FHWA staff studies found that in most typical appurtenance crash tests, the data obtained from the anthropometric dummy was rarely used and the responses were often subcritical [17].

The use of dummies in the early stages of side impact research, however, is inescapable. Judging the performance of a test article ultimately involves judging the risk of serious injury to vehicle occupants in real accidents. The anthropometric dummy is the best available device that, at least in principal, links the performance of the device on the test pad to the performance in the real world. Instrumented side impact dummies should, therefore, be used in the side impact crash tests of roadside objects for the foreseeable future.

The Part 572 dummy is recommended primarily because all previous side impact crash tests of roadside structures have used this device, and it is unlikely that newer side impact anthropometric devices like the EuroSID or BioSID will be made available to roadside appurtenance researchers in the near future.

The seat should be positioned as far to the rear as the normal seat adjustment will allow in order to fit both the anthropometric test device and the displacement transducer in the occupant compartment (see section 4.3). The displacement transducer includes a string that stretches from the impact-side door to the non-impact-side door. If the dummy is not position far enough back the string could interfere with the dummy response.

The dummy was placed in the driver's position in all the side impact tests performed at the Federal Outdoor Impact Laboratory. The dummy should be placed in the front seat position on the impact side on the vehicle. Although many injuries in real accidents result from an unrestrained non-impact-side occupant flailing across the passenger compartment, the impact-side occupant is always at greater risk of injury.

Table 6. Anthropometric side impact test dummy.

Type	Part 572 Subpart F (SID)
Seating Position	Impact Side (Driver-side preferable)
Seat Adjustment	Maximum rearward position
Seat Back Position	Normal upright position
Restraint	Available restraints

The seat back should be positioned in the "normal," unadjusted position. This is usually the most vertical orientation. Some recent research has suggested that ensuring the head is relatively level is an important factor in obtaining repeatable HIC values in side impacts [24]. While explicit leveling of the head is not necessary, the upright position of the seat back will result in a more level head form.

Traditionally, restraints have not been used in full-scale crash tests of safety hardware. Seat belts are not effective in side impacts when the impact is on the same side as the occupant. The lap belt restrains the pelvis but not the upper body, allowing the head and thorax to contact the side structure of the vehicle. Seat belts do, however, help keep the dummy in-position as the vehicle is being transported down the test track. Prior research has indicated that all occupant response measures are extremely sensitive to the position of the dummy at impact. The seat belts help keep the dummy from bouncing out of position during the acceleration and sliding phases prior to impact. All available restraints should be used in side-impact fixed object crash tests.

4 Data Acquisition

4.1 General

Side impact crash tests require the same types of vehicle data as more traditional full-scale crash tests [29]. The vehicle should be instrumented with accelerometers to measure all six degrees of freedom of the vehicle. Photographic coverage should conform to the usual practice in appurtenance tests. Film analysis of the vehicle motions should be performed as well as analyses of the vehicle accelerometer outputs. An on-board high-speed camera is useful for understanding the response of the vehicle occupants and possible sources of injury and is essential for determining the pre-impact position of the dummy.

Relating observable results of crash tests and the risk of severe injury in such collisions is the long-term goal of side impact crash testing. Table 7 shows the data elements that should be calculated, collected, recorded and reported in side impact crash tests. To date there are relatively few side impact crash tests available for analysis. These data elements

Table 7. Data elements required in side impact crash tests.

Parameter	Symbol	Acquisition Device
Impact Velocity	V_i	Film
Actual Dummy Impact Velocity	V_{occ}	Calculations
Maximum static vehicle crush (exterior)	c_e	NHTSA 6-point sketch
Area of crush (exterior)	C_{area}	NHTSA 6-point sketch
Maximum dynamic intrusion (interior)	c_i	Displacement Transducer
Average intrusion rate (interior)	$\dot{c}_i$	Displacement Transducer
Maximum 10-msec vehicle acceleration prior to dummy contact with interior.	a_{pc}	Vehicle accelerometers
Maximum 10-msec vehicle acceleration during dummy contact with interior.	a_{dc}	Vehicle accelerometers
Maximum 10-msec vehicle acceleration after dummy contact with interior.	a_{rd}	Vehicle accelerometers
Thoracic Trauma Index	TTI	Anthropometric Dummy
Head Injury Criteria	HIC	Anthropometric Dummy
Maximum pelvis acceleration	a_p	Anthropometric Dummy
Longitudinal distance from the center of the dummy head to impact point	r	Onboard Film
Lateral distance from the left side of the dummy head to edge of passenger compartment	s	Onboard Film
Distance from impact point to front axle	D	Post Test Measurement

are thought to be important characteristics of the collision that might be useful in building models that predict the risk of severe occupant injury. Collecting these data will allow a data base of important side impact parameters to be assembled. Table 7 also shows the data acquisition device needed to obtained each parameter. Most involve typical acquisition methods like vehicle accelerometers and film analysis. In addition to the usual data acquisition methods, a fully instrumented anthropometric dummy and a displacement transducer to measure the deformation of the door should be used.

4.2 Anthropometric Dummy

While anthropometric dummies were routinely used in the past in full-scale safety appurtenance crash tests, they did not provide much useful information [17]. The forces in most longitudinal barrier tests are well below the level necessary to result in significant dummy responses. In recent years anthropometric dummies have been included in most crash tests only to represent the occupant's inertia and to enhance the on-board photographic record.

The severity of the crash loading in side impacts, however, places the dummy in a much more extreme environment and meaningful dummy responses can be obtained. An instrumented SID should be used in side impact crash tests with roadside structures.

The dummy should be instrumented so that the Thoracic Trauma Index (TTI), the Head Injury Criteria (HIC) and the maximum pelvis accelerations *(a_p)* can be calculated. Calculation of the TTI requires accelerometers located on the impact-side ribs and T12 segment of the spine. The HIC is calculated based on the resultant of a triaxial accelerometer mounted in the head form of the Part 572 dummy [24].

4.3 Displacement Transducer

The intrusion of the door into the passenger compartment is one of the most hazardous characteristics of side impact accidents. The occupant strikes the intruding door structure in a typical side impact event. Penetration of the passenger compartment has long been recognized as a very hazardous event in roadside collisions. Any significant penetration or deformation of the passenger compartment is disallowed in all other types of full-scale appurtenance crash tests. The severity of side impact collisions, however, makes this an unreasonable and unobtainable restriction. In order to determine the effect of the intrusion and more particularly the intrusion rate, the use of a displacement transducer is recommended.

A Celesco PT510 string pot transducer has been used successfully in several side impact crash tests of guardrail terminals [27]. This device can accurately record distances between 0 and 2 m. Devices of this type are readily available, inexpensive and very robust. Figure 4 shows how the transducer was mounted in several recent tests. The transducer unit was attached to the inner window sill of the non-impact side door. The end of the string was stretched across the passenger compartment and screwed into the structure of the impact-side door. The string should be perpendicular to the door. The transducer measures the instantaneous width of the passenger compartment and the slope of this line represents the velocity of the inner surface of the intruding door. Figure 5 shows the output of a string pot transducer in a side impact test of a guardrail terminal.

5 Evaluation Criteria

5.1 General

Using standard testing conditions ensures that different tests performed by different testing agencies can be compared directly. Standardizing test conditions does not indicate how well a device performs; evaluation criteria do. Evaluation criteria are a set of quantifiable

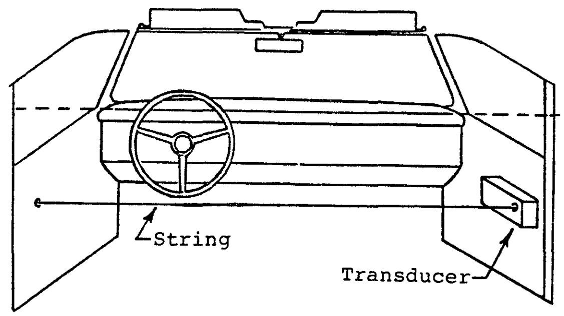
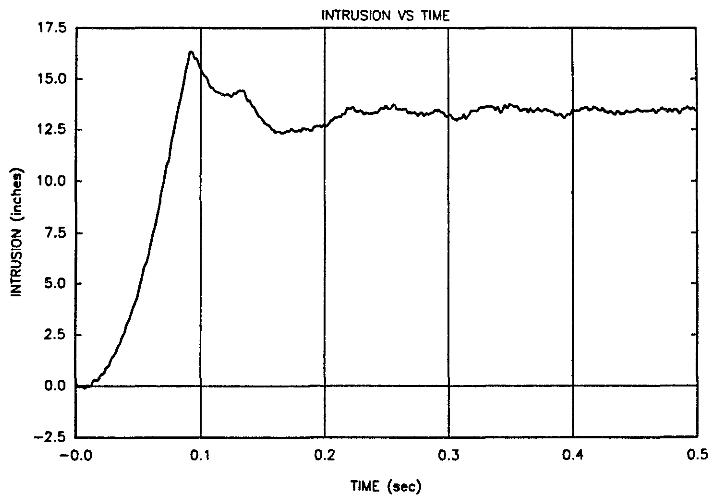


Figure 4. Displacement transducer.



1 in = 25.4 mm

Figure 5. Example Displacement Transducer Output.

limits that, taken together, suggest how well a roadside structure can be expected to perform in real-world impacts.

The NCHRP guidelines recommend three separate criteria for evaluating crash tests: structural adequacy, occupant risk, and vehicle trajectory. These three criteria have evolved over the years to ensure that hardware performs as designed (structural adequacy criteria), it does so without undue risk to vehicle occupants (occupant risk criteria), and the probability of subsequent accident events is minimized (vehicle trajectory). Although past criteria have not addressed side impacts specifically, the three general criteria are as applicable to the side impact scenario as other, more typical accident scenarios. The three general NCHRP evaluation criteria are used as a framework for developing side impact crash test evaluation procedures.

5.2 Structural Adequacy Criteria

The structural adequacy criteria requires that a roadside structure be structurally capable of accomplishing its primary purpose. For longitudinal barriers, this primary structural purpose is preventing the vehicle from crossing the barrier line; for breakaway hardware the primary purpose is to yield or breakaway without penetrating the passenger compartment or scattering debris onto the roadway.

In side impacts, roadside structures should be expected to breakaway, fracture, collapse or yield allowing the vehicle to either pass by or stop. The suggested structural adequacy criteria for side impacts are shown in table 8. Italicized text represents an addition to NCHRP criterion B

5.3 Occupant Risk Criteria

The occupant risk criteria have evolved into the most important single evaluation criteria in testing roadside hardware. The ultimate objective of all safety hardware is to prevent or minimize the potential for injury to occupants of vehicles that leave the traveled way.
Unfortunately, establishing a linkage between parameters measured in crash tests and real occupants of vehicles in accidents has been an extraordinarily difficult task.

Report 230 introduced the concept of the flail space occupant risk criteria. The flail space method calculates the hypothetical impact velocity of an occupant head with the interior of the vehicle. The impact velocity between the occupant and the vehicle interior did not prove to be a good predictor of dummy response even when the flail space method was modified to account for the intrusion rate of the door.

Relating the forces experienced by anthropometric test devices to the potential for

Table 8. Side impact crash test evaluation criteria.

Structural Adequacy	NCHRP-B.	The test article should readily activate in a predictable manner by *collapsing*, breaking away, fracturing or yielding.
Occupant Risk	NCHRP-F	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.
	SI-H	The Head Injury Criteria (HIC) measured using a side impact dummy (part 572 subpart F) should be less than 1000. If the dummy was not in the normal seating position at the time of impact, the HIC may be normalized using the following expression: $HIC_{norm} = HIC_{obs}\ 0.9925^{r}\ 0.9883^{s}$ where $r =$ Longitudinal distance from dummy shoulder to impact point (mm). $s =$ Lateral distance from the left side of the dummy head to door window (mm).
	SI-T	The Thoracic Trauma Index (TTI) measured using a side impact dummy (part 572 subpart F) should be less than 90. If the dummy was not in the normal seating position at the time of impact, the TTI may be normalized using the following expression: $TTI_{norm} = TTI_{obs}\ 0.9960^{r}\ 0.9975^{s}$ where $r =$ Longitudinal distance from dummy shoulder to impact point (mm). $s =$ Lateral distance from the left side of the dummy head to door window (mm).
	SI-P	The pelvic acceleration measured using a side impact dummy must be less than 130 g's.
Vehicle Trajectory	SI-V.	After collision the vehicle trajectory should not intrude into adjacent traffic lanes.

serious injury is a challenging area of research that has been pursued by NHTSA, the military and the automotive design communities for decades. The measures of injury promoted by NHTSA are recommended since that agency has the most expertise and ability in the area of biomechanics and human tolerance. Conforming to the NHTSA recommendations will allow the roadside safety community to take advantage of a wealth of biomechanics experience while also facilitating the exchange of information between these two agencies in the future. While the HIC and TTI could certainly be improved, they have a better linkage to real human trauma than the flail space for side impacts.

The recommended occupant risk criteria, discussed below, is composed of four subcriterion: a vehicle stability criterion, a thoracic trauma criterion, a head injury criterion and a pelvis acceleration criterion.

5.3.1 Vehicle Stability Criterion

Roll over of the vehicle has long been recognized has a very hazardous event in single vehicle accidents [25]. Roadside structures should breakaway, collapse or yield in an impact without causing the vehicle to rollover or completely loose contact with the ground.

5.3.2 Head Injury Criterion

The Head Injury Criteria (HIC) evolved from several earlier techniques for measuring the resultant accelerations experienced by the head form of the Part 572 dummy [18]. The HIC has been used for many years in frontal barrier crash tests by NHTSA as well as by the roadside design community. A HIC of 1000 has generally been considered the threshold for severe injury.

The purpose of any occupant response measure is to estimate the risk to occupants in real accidents. A cumulative probability density function relating the probability of sustaining an $AIS > 3$ injury based on the observed HIC has been developed from the results of cadaver testing [26]. According to this curve, a $HIC = 1000$ implies a risk of $AIS > 3$ injury of 0.18: 18 percent of occupants with a $HIC = 1000$ will be severely injured.

Unfortunately, the HIC was not developed to measure head injury potential in side impacts. The differences between longitudinal and lateral head impact tolerance and the degree to which the Part 572 head form predicts human injury have been debated but no consensus has been reached [18]. It is widely agreed, however, that the head is probably *less* tolerant in lateral impacts than in frontal impacts so the HIC should certainly be no greater than 1000. There is a great need for the biomechanics research community to address the issue of an appropriate lateral HIC limit or, more generally, head injury criteria

for the side of the head. A *HIC* = 1000 has been used in a recent study of head form impacts with upper vehicle-interior structures like the A-pillar, roof rails and B-pillar [6]. A limit of 1000 appears to be the best available link between the dynamics of an impacting head and the potential for serious injury.

Anthropometric dummies should be used in side impact crash tests of roadside structures as long as the possibility of serious damage to the dummy is minimal. The *HIC* should be evaluated in the same manner typically used for frontal collisions. Details on computationally efficient *HIC* algorithms can be found in a variety of papers in the literature [18] [3] [13].

The exact location of the dummy at the time of impact has been a problem in performing side impact crash tests of roadside structures. Dummies in vehicle-to-vehicle crash tests do not move prior to the impact because the struck vehicle is stationary so correct dummy position can be guaranteed. In roadside structure crash tests the vehicle and dummy must be accelerated to the desired impact velocity since the structure is fixed and the vehicle is accelerated. Ideally, the dummy should be in the "normal" seating position. This would correspond to a location about 250 mm behind the impact point and 165 mm from the head to the side window.

When the dummy is not in the correct position at impact, the HIC can be normalized using the following expression:

$$HIC_{norm} = HIC_{obs}\ 0.9925^{r}\ 0.9883^{s} \qquad (1)$$

where
r = Longitudinal distance from dummy shoulder to impact point in mm.
s = Lateral distance from dummy shoulder to impact point in mm.

This expression was derived from a regression analysis of 15 side impact crash tests of poles. The HIC appears to decay exponentially as the distance between the head and the impact point increases. The worst-case impact location is one that is centered on the occupant's head when the occupant is in contact with the door window (r = 0, *s* = 0). Figure 6 shows the definition of the coordinates for equation 1.

It is very important to normalize the HIC when different tests are being compared since a large HIC may be due to the head impact being too close to the intruding object rather than a difference in performance between one device and another.

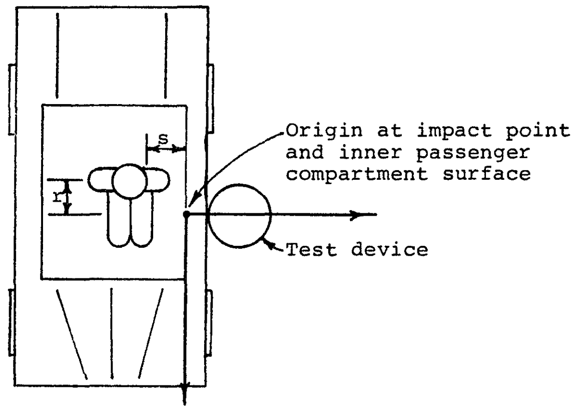


Figure 6. Coordinates for occupant position in side impact crash tests.

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5.3.3 Thoracic Trauma Criterion

The thoracic trauma index (TTI) was developed by NHTSA to measure the chance of severely injuring the human thorax during a collision [20] [5] [8] [7]. The formulation of TTI has gone through several revisions, the most recent being found in the 1990 final amendment for Federal Motor Vehicle Safety Standard 214 [24]. The TTI is the average acceleration experienced by accelerometers located on the left upper rib (LURY) and the twelfth spinal segment (T12P) as shown in equation 2. The accelerations should be filtered using the FIR100 finite impulse response filter as specified in FMVSS No. 214 [24].

$$TTI = \frac{G_R + G_{LS}}{2} \tag{2}$$

where
G_R = The greater peak acceleration of either the upper or lower rib in g's, and
G_{LR} = The peak acceleration of the lower spine (T12) [24].

The TTI is not the only possible measure of thoracic trauma. Researchers at General Motors Research Laboratory, for example, developed a competing injury scale, the viscous criteria (VC) [34] [15]. Unfortunately, the data required to calculate VC are only obtainable using BioSID dummies which were not available in any of the side impact crash tests performed to date at the FOIL. In contrast, the TTI can be calculated using the more common Part 572 SID. Since most of the FHWA tests and all of the NHTSA tests contained data that could be used to calculate the TTI, the TTI was preferred as a measure of thoracic occupant trauma.

Instrumented anthropometric dummies should be used in side impact crash tests of roadside structures. The TTI for the in-position dummy should be less than 90 g's. NHTSA, in its 1990 final rules on side impact, requires the TTI be less than 90 g's in tests of 2-door passenger cars. The recommended criteria therefore conform to the NHTSA design limits. The TTI has been related to the probability of various levels of injury using the Abbreviated Injury Score (AIS) [1]. The cumulative density function of TTI was found to be a Weibull extreme value distribution [20]. A $TTI = 90$ corresponds to a 0.16 probability of an $AIS > 3$ injury. This level of risk is roughly the same used for the HIC so these criteria represent an internally consistent risk of trauma for evaluating side impact tests.

Maintaining correct dummy position, as discussed earlier, is often very difficult in a crash test where the vehicle and dummy must be accelerated up to a target test speed. If the dummy is out of position (i.e. $r \neq 250$ mm and $s \neq 165$ mm) the TTI should be normalized to the hypothetical in-position response using equation 3. The coordinate system for occupant motions is shown in figure 6. This expression is based on the empirical observation that the TTI, like HIC, seems to decay exponentially as the distance from the occupant increases.

$$TTI_{norm} = TTI_{obs}\ 0.9960^{r}\ 0.9975^{s} \qquad (3)$$

where
r = Longitudinal distance from dummy shoulder to impact point in mm
s = Lateral distance from dummy shoulder to impact point in mm.

5.3.4 Pelvis Acceleration Criterion

Although no side impact crash tests of roadside hardware have collected the pelvic acceleration, it is a component of the NHTSA final rules on FMVSS-214 [24]. The pelvis accelerations should be filtered using the FIR100 finite impulse response filter as specified in FMVSS No. 214. This rule specifies that the pelvic must not experience an acceleration greater than 130 g's during the test.

$$a_p \leq 130$$

Where a_p, is the maximum acceleration of the pelvis of the side impact dummy. The probability of experiencing a fatal fracture is relatively low at this level. Including the pelvis acceleration also helps to ensure that improvements in the TTI and HIC do not come at the expense of shifting the load path through lower parts of the vehicle.

5.4 Vehicle Trajectory Criterion

The purpose of the vehicle trajectory criteria is to reduce the chance of a subsequent harmful event after the appurtenance collision. Since the vehicle is sliding sideways in a side impact it will usually loose speed rapidly and come to rest near the first impact point. Sometimes, after the collision, the laterally sliding tires may begin to rotate causing the vehicle to roll forward. Since the front of the vehicle is pointing toward the traveled way in the standard orientation (figure 3) there is a danger that the vehicle can reenter the roadway or even travel completely across it. Reentry of the vehicle into the roadway, especially at the high angles resulting from a side impact, is not acceptable.

Criteria SI-V, shown in table 8, is very similar to NCHRP evaluation criteria K [29] except more restrictive language is used. This slightly more stringent criteria is recommended because, after a side impact, a vehicle could reenter the roadway at a high angle, perhaps even perpendicular to the roadway. After the vehicle comes to rest it will probably require towing since vehicle damage is usually extensive in a side impact.

6 Estimating Dummy Responses

6.1 General

Ultimately anthropometric dummies should be eliminated from full scale tests. The environment in many full scale crash tests of roadside safety appurtenances is so severe it is often not advisable to place dummies in the vehicle. Good dummy results require careful and frequent calibration which has traditionally been a problem for roadside safety applications. Since the response of the vehicle can be easily measured in a full-scale test, vehicle-based evaluation parameters that estimate the response of hypothetical humans are preferable to the use of fully instrumented anthropometric dummies.

As discussed earlier, there are three primary injury mechanisms that are active in side impact collisions: thoracic trauma, head injury and pelvic fracture. Data from 15 previous crash tests were analyzed to determine if there were any relationships between the observed vehicle-based parameters and the vales of TTI and HIC. Pelvic acceleration was not modeled since there has been no data collected as yet. The same type of modeling activity could be performed to estimate the accelerations of the pelvis based on vehicle-based parameters once sufficient data has been collected. The 15 tests used represent all the tests that used instrumented SID dummies. The following sections summarize the findings of these investigations [27].

6.2 Thoracic Trauma Index

A multiple linear regression analysis was performed on 15 tests of small cars side impacting a variety of poles. Values for all the parameters listed in table 7 were collected and entered into a data base of values. A variety of regression models were evaluated. Models that included the effect of occupant position (parameters *r* and s) and impact velocity were required. Beyond these three basic parameters the model with the fewest predictors and highest R^2 were preferred. The best five parameter model was:

$$TTI = 0.5(10)^{-3}\left\{0.9960^{r}0.9975^{s}\right\} V_i^{2.5}\left\{\frac{c_i^{1.25}}{\sqrt{\dot{c}_i}}\right\} \qquad (5)$$

$R^2 = 0.90$

where r = Longitudinal distance from occupant head to impact point in mm.

s = Lateral distance from occupant head to the impact point in mm.

V_i = Vehicle impact velocity in m/sec.

c_i = Maximum static passenger compartment crush in mm.

c_i = Average passenger compartment intrusion rate in m/sec.

The coefficient of regression squared *(R^2)* for this model was quite good for this type of experimental data. The components of this model seem reasonable: severity should increase as the occupant gets closer to the impact point *(r* and *s)* and severity should be a function of the impact velocity (V_i) since this is a measure of the total amount of kinetic energy at the start of the impact event. Passenger compartment crush and crush rate were also thought to be directly related to the TTI since thoracic injuries are caused by contact with the side door panels.

In a test with no dummy, three of these parameters (r, *s,* and V_i) are specified. Only crush and crush rate are measurable results of the test. The desirable, in-position location of an occupant is at r = 250 mm, s = 165 mm and the standard impact speed is 50 km/h (14 m/sec). The maximum allowable TTI from table 8 is 90 g's. These values can be substituted into equation 5 and solved for the quantity $\left\{\frac{c_i^{1.25}}{\sqrt{\dot{c}_i}}\right\}$. Doing so results in a criterion for allowable thoracic trauma.

$$1000 \geq \frac{c_i^{1.25}}{\sqrt{\dot{c}_i}}$$

If the crush and crush rate result in a value less than 1000, the probability of observing a TTI greater than 90 is relatively small.

This expression was developed using the results of 15 side impact tests of slip-base and ESV poles. The degree to which this expression will predict TTI scores for other types of devices is not known. The range of crush and crush rate in these tests was between 200 and 900 mm and 1 and 10 m/sec, respectively. These expressions might not yield

appropriate estimates for tests where the crush or crush rate was substantially more than the tested range. These expressions should be used as a guide when direct measures of the TTI are not available.

6.3 Head Injury Criteria

The same type of stepwise regression analysis was performed to find models for the HIC. The results of this analysis were not as attractive as the TTI model described in the previous section. It is presented here to serve as an approximate guide for tests where no dummies were included.

Most of the 15 tests were conducted with the dummy head aligned with the impacting pole. This caused exceptionally high HIC values since there was often direct contact between the pole and the head. This extreme test condition may be more demanding than the SID dummy capabilities. For this reason, a longitudinal impact point (r) of 250 mm is recommended for future tests. The severity of the loading caused problems in developing a model for HIC. The $r = 0$ position appears to represent a singularity in the response of the dummy. Future research with dummies at positions other than r = 0 should help to refine the model presented herein. Equation 7 represents the model with the best R^2 value which included terms for occupant position *(r* and *s).*

$$\mathrm{HIC} = 280\left\{0.9925^{r}\ 0.9883^{s}\right\}\left\{\frac{c_i^{1.64}}{\dot{c}\,V_{occ}^{\ 0.15}}\right\} \qquad (7)$$

$R^2 = 0.56$

where r = Longitudinal distance from occupant head to impact point in mm.
s = Lateral distance from occupant head to the impact point in mm.
V_{occ} = Occupant impact velocity with intruding vehicle interior in m/sec
c_i = Maximum static passenger compartment crush in mm.
c_i = Average passenger compartment intrusion rate in m/sec.

When there is no dummy in the test vehicle, the above expression can be solved for limiting values of the quantity . $\left\{\frac{c^{1.64}}{\dot{c}\,V_{occ}^{\ 0.15}}\right\}$. Substituting HIC=1000, r=250 , and s=165, yields a value of 165.An approximate criteria that would predict acceptable HIC values could be stated as :

$$165 \geq \left\{\frac{c^{1.64}}{\dot{c}\,V_{occ}^{\ 0.15}}\right\} \qquad (8)$$

As with the TTI model described above, this model may not be appropriate for devices that are not breakaway poles and for impacts outside the range of typical values used in building the regression models. Equation 7 is presented as a guide for tests where it is not possible to use a dummy in the test vehicle. This model, due to the underlying data. should only be used in tests where there is a possibility of direct contact between the head

and the intruding object. In tests of guardrail terminals, for example, there is no possible contact between the head and the terminal so the HIC should not be evaluated. The HIC should always be evaluated for tall, narrow objects like luminaires, utility poles and signs.

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APPENDIX H

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APPENDIX I

GLOSSARY

AASHTO American Association of State Highway and Transportation Officials.ACI American Concrete Institute.
AISC American Institute of Steel Construction.
AISI American Iron and Steel Institute.
ASI Acceleration Severity Index.
ASTM American Society for Testing and Materials.
Ballast Mass added to vehicle, other than simulated occupant(s) and instrumentation, to simulate cargo and/or to achieve desired test inertial mass.
Bogie A device used as a surrogate for a production model test vehicle. Existing bogies are four-wheeled devices that are towedinto the test article. They are typically designed to replicate the dynamic response of a vehicle for specific tests, e.g., tests of breakaway features. Bogies typically can be used for both lowand high-speed tests.
Center of Mass (c.m.) Point within test vehicle at which its total mass can be assumed to be concentrated.
Clear Zone The total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles. This area may consist of a shoulder, a recoverable slope, a nonrecoverable slope, and/or a clear run-out area. The desired width is dependent on the traffic volumes and speeds and on the roadside geometry.
Crash Cushion A device designed primarily to safely stop a vehicle within a relatively short distance. A *redirective crash cushion* is designed to contain and redirect a vehicle impacting downstream from the nose of the cushion. A *nonredirective crash cushion* is designed to contain and capture a vehicle impacting downstream from the nose of the cushion.
Crash Test A test in which a production model test vehicle or a surrogate test vehicle impacts or traverses a highway feature. **Critical Impact Angle (CIA)** For a given test and the attendant range of vehicular impact angles, the CIA is the angle within
this range judged to have the greatest potential for causing a failure when the test is assessed by the recommended evaluation criteria. For most tests, impact angles can range from 0 up to 25 degrees.
Critical Impact Point (CIP) For a given test, the CIP is the initial point(s) of vehicular contact along the longitudinal dimension of a feature judged to have the greatest potential for causing a failure when the test is assessed by the recommended evaluation criteria.
Curb Mass Mass of test vehicle with standard equipment, maximum capacity of engine fuel, oil and coolant and, if so equipped, air conditioning and additional optional mass engine. It does not include occupants or cargo.
Device Refers to a design or a specific part thereof, such as a breakaway device. Note that the terms "device" and "feature"are often synonymous.
Evaluation Criteria Criteria used to assess the results of a crash test or to assess the in-service performance of a feature.
Feature Refers to a specific element of a highway. It may be a hardware item and its associated foundation, such as a sign orbarrier installation, or it may be a geometric element, such as a side slope or a ditch cross section.
FHWA Federal Highway Administration.
Flail Space Hypothetical space in which a hypothetical occupant is permitted to move during impact.
Gating Device (Feature) A device designed to allow controlled penetration of a vehicle when impacted upstream of the beginning of the length of need (LON). Note there is some distance between the end of a gating device and the beginning of the LON of the device.
Geometric Feature A roadside cross section element such as a ditch section, an embankment, a driveway or a median crossover, or a curb. It also includes drainage structures such as inlets and culvert ends and devices such as grates used to enhance safety of these features.
Gross Static Mass Sum of test inertial mass and mass of surrogate occupant(s).
HVOSM Highway-Vehicle-Object-Simulation-Model computer program.
Hybrid III Dummy An anthropomorphic dummy, representing the 50th percentile male, the specifications of which are contained in part 572, Subpart E, Title 49 of the Code of Federal Regulations, Chapter V-(10-1-88 Edition).
Impact Angle (Θ) Angle between normal direction of traffic and approach path of test vehicle into the test article. The test article should be oriented as it would typically be in service with respect to the normal direction of traffic.
Impact Point The initial point on a test article contacted by the impacting test vehicle.
Impact Severity (IS) A measure of the impact severity of a vehicle of mass M, impacting at a speed V, at an impact angle Θ. It is defined as follows: $IS = 1/2M(V \sin \Theta)^2$
Length of Need (LON) That part of a longitudinal barrier or terminal designed to contain and redirect an errant vehicle.
Longitudinal Barrier A device whose primary functions are to prevent vehicular penetration and to safely redirect an errant vehicle away from a roadside or median hazard. The three types of longitudinal barriers are roadside barriers, median barriers, and bridge rails.
Nongating Device A device with redirectional capabilities along its entire length. Note that the end of a nongating device is the beginning of the length of need for the device.
Occupant Impact Velocity Velocity at which a hypothetical "point mass" occupant impacts a surface of a hypothetical occupant compartment.

Pendulum A device used as a surrogate for a production model test vehicle. A mass is attached to cables, which are in turn suspended from a fixed point. The mass is raised to a selected height and released, allowing gravity to accelerate the mass as it swings into the test article. The structure of the mass can be designed to replicate the dynamic crush properties of a produc tion model test vehicle. It is basically a low-speed test device.

Permanent Feature (Device) A feature with an anticipated long duration of service, as opposed to those used in a work or construction zone having a relatively short duration of service.

Pocketing If, on impact, a redirective device undergoes relatively large lateral displacements within a relatively short longitudinal

distance, pocketing is said to have occurred. Depending on the degree, pocketing can cause large and unacceptable vehicular decelerations.

PHD Post-Impact Head Deceleration.

Production Model Test Vehicle A commercially available vehicle with properties matching those required in a given test. Ridedown Acceleration Acceleration experienced by a hypothetical "point mass" occupant subsequent to impact with a hypothetical occupant compartment.

SAE Society of Automotive Engineers.

Sprung Mass All mass that is supported by a vehicle's suspension system, including portions of the mass of the suspensionmembers.

Snagging When a portion of a test vehicle, such as a wheel,engages a vertical element in a redirective device, such as apost, snagging is said to have occurred. The degree of snagging depends on the degree of engagement. Snagging may cause large and unacceptable vehicular decelerations.

Support Structure A system used to support a sign panel, chevronpanel, luminaire, utility lines, mailbox, or emergency call box.The system includes the post(s), pole(s), structural elements, foundation, breakaway mechanism if used, and accompanying hardware used to support the given feature.

SI International System of Units.

Surrogate Occupant A dummy, set of sand bags, or other artifact used to simulate the effects and/or to study the dynamic responseof an occupant in a vehicle.

Surrogate Test Vehicle A bogie, pendulum device, or other substitute device designed to replicate the dynamic response of aproduction model vehicle when in collision with a roadside feature.

Temporary Feature (Device) A feature used in a work, construction, or maintenance zone. Its duration of use is normally relatively short, usually one year or less.

Terminal A device designed to treat the end of a longitudinal barrier. A terminal may function by (a) decelerating a vehicle to a safe stop within a relatively short distance, (b) permitting controlled penetration of the vehicle behind the device, (c) containing and redirecting the vehicle, or (d) a combination of a, b, and c.

Test Article (Test Feature) All components of a system, including the foundation as relevant, being evaluated in a crash test. Notethat the system may be a geometric feature such as a ditch or driveway slope.

Test Inertial Mass Mass of test vehicle and all items rigidly attached to vehicle's structure, including ballast and instrumentation. Mass of surrogate occupant(s), if used, is not included in test inertial mass.

Test Level (TL) A set of conditions, defined in terms of vehiculartype and mass, vehicular impact speed, and vehicular impact angle, that quantifies the impact severity of a matrix of tests.

Test Vehicle A commercially available, production model vehicle or an approved surrogate vehicle used in a crash test to evaluate the impact performance of a test article.

THIV Theoretical Head Impact Velocity.

Track Width Center-of-tire-to-center-of-tire distance for a givenaxle of a vehicle.

Transition That part of a longitudinal barrier system between and connecting sections of differing lateral stiffness and/or sectionsof differing design or geometry.

Truck-Mounted Attenuator (TMA) An energy-absorbing deviceattached to the rear of a truck or utility vehicle. A TMA isdesigned to provide a controlled stop of a vehicle impacting the rear of the truck.

Unsprung Mass All mass which is not carried by the suspensionsystem but is supported directly by the tire or wheel and considered to move with it.

Utility Pole A support structure used to support power transmission lines or communication lines.

Work Zone Traffic Control Device A device used in a work zone to regulate, warn, and guide road users and advise them totraverse a section of highway or street in the proper manner. Work zone traffic control devices of interest herein include signs, plastic drums, and lights that may be used thereon; cones, barricades, chevron panels, and their support system; and any other such device(s) commonly exposed to traffic that may pose a hazard to occupants of a vehicle and/or to work zone personnel.

APPENDIX J

SI CONVERSIONS

To convert from	To	Multiply by[1]
	ACCELERATION	
Meter per second squared (m/s^2)	ft/s^2	3.280 840 E+00
	AREA	
Square meter (m^2)	ft^2	1.076 391 E+01
	ENERGY	
Joule (J)	ft-lbf	7.375 621 E-01
	FORCE	
Newton (N)	pound-force (lbf)	2.248 089 E-01
	LENGTH	
Meter (m)	ft	3.280 840 E+00
Meter (m)	in	3.937 008 E+01
Centimeter (cm)	in	3.937 008 E-01
	MASS	
Kilogram (kg)	pound (lb avoirdupois)	2.204 623 E+00
	PRESSURE OR STRESS	
Pascal (Pa)	psi	1.450 377 E-04
	VELOCITY	
Kilometer per hour (km/h)	miles per hour (mi/h)	6.213 712 E-01
Kilometer per hour (km/h)	ft/s	9.113 444 E-01
Meter per second (m/s)	ft/s	3.280 840 E+00

[1] Numbers to the left of "E" are multiplied by 10 raised to an exponent equal to the number, and accompanying sign, to the right of "E."

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

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