Appendix D

Analytical and Experimental Tools

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he design, synthesis, and development of a new safety feature is not a straightforward procedure but is an iterative process requiring tradeoffs among sometimes conflicting impact performance requirements, environmental considerations, and costs. This appendix summarizes some common analytical and experimental tools that can be used to support the development and evaluation of new safety features. Applications and limitations of these techniques are also discussed.

D1 Useful Techniques

D1.1 Structural Design

Most roadside safety features require significant structural capacity in order to achieve their desired performance. For example, longitudinal barriers must have sufficient structural capacity to resist the lateral impact loads from an impacting vehicle. Other roadside features, such as structural supports for signs and luminaires, must have sufficient structural capacity to resist environmental loadings as well as accommodating impacts. Virtually all roadside safety features are required to sustain some minimum structural capacity, and assuring that a device can resist the applied loading is an important part of the development process.

Structural loading and design procedures are contained in numerous civil engineering textbooks, AASHTO design manuals, and research publications. References containing recommendations for design loadings and analysis procedures for each type of safety feature are listed in Table D-1. Designers/developers should consult these references to estimate design loads and proportion a new design for subsequent evaluation steps. Static and/or dynamic testing and computer simulation should be implemented whenever necessary to assure that features have sufficient structural capacity.

TABLE D-1. Sources for Safety Feature Information

|  |  |
| --- | --- |
| **Feature** | **Principal Reference** |
| I. | Longitudinal Barriers |   |
|   | A. Bridge Rails | 4, 5, 9, 13, 23, 27, 48, 49, 68, 82, 100 |
|   | B. Guardrails | 4, 9, 20, 24, 26, 28, 37, 46, 47, 50, 63, 94, 100, 108, 139 |
|   | C. Median Barriers | 4, 9, 21, 27, 84, 100, 131 |
| II. | Crash Cushions and Terminals | 4, 9, 21, 67, 80, 124, 126 |
| III. | Breakaway or Yielding Supports |   |
|   | A. Luminaire Supports | 3, 6, 8, 17, 34, 43, 105 |
|   | B. Sign Supports | 3, 6, 16, 51, 57, 83, 91, 102, 106, 121, 122, 123, 138 |
|   | C. Utility Poles | 12, 55, 72, 77 |
| IV. | Truck-Mounted Attenuators | 30, 32, 33, 58, 135, 148 |
| V. | Roadside Geometric Features | 4, 38, 40, 69, 101, 127, 130, 152, 160 |

D1.2 Static Tests

During an early stage of development, certain critical details and connections of a safety feature may require an evaluation of structural capacity or force deflection characteristics. Safety features are often designed to function at or near ultimate capacity which means that materials are often loaded well beyond elastic limits and in many cases materials are intended to rupture in a sequential process and in a controlled manner. As a result, specialized static tests are often necessary that 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.

Evaluate failure mode(s).

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 may 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 there are significant variations in the mechanical properties of most materials. Further, the mechanical characteristics of many materials are specified only in terms of minimum values, and actual material strengths can be almost double the rated minimum. If a safety feature relies on the controlled bending or fracture of a material, excessive material strength may be just as dangerous as a strength that is below the minimum. For example, research has shown that the energy required to fragment a frangible transformer base can vary more than 100 percent with even minor changes in heat treatment of the aluminum alloy. Further, soil conditions can exhibit even wider seasonal variations as a soil goes through saturated, dry, and frozen situations. Designers should utilize static and/or dynamic testing to evaluate safety feature performance over the expected range of variation in material properties.

Even at this stage, the developer should be aware of value engineering by avoiding over specifying materials, especially components that are not critical to system performance. Where possible, the developer should use standard hardware elements for initial economy and to minimize costs associated with inventory maintenance (9).

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, analysis procedures, and type of safety feature and vehicle classes that can be investigated. LS-DYNA (82) has become the analysis program of choice for most safety feature development while MADYMO (151) is widely used to model occupant motions. Although the roadside safety community has been migrating to explicit finite element analysis tools, many of the older programs, especially HVOSM (136) and Barrier VII (111), provide cost-effective tools for identifying vehicle trajectories, critical impact points, and expected barrier–rail loadings.

Most of the available simulation programs have been correlated to some degree with crash tests. For the validated cases, simulation results can be very helpful to the safety feature designer by providing unique insight into the collision event. Where the program has been validated for multiple impact conditions, it can sometimes accurately predict behavior for impact conditions that are bracketed by the validated conditions. Although computer simulations have proven to be invaluable in the development of new roadside safety features, the accuracy of these programs has not yet reached a point that required compliance tests can be replaced by computer modeling. 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 Model** | **Principal Application** | **Model** | **Validation** | **Documentary Availability** | **Comment** |
| HVOSM | CALSPAN/1989 | Vehicle handling and stability | 3D Lump Mass Vehicle | Extensive | FHWA (R&D) | Excellent wheel/suspension system; simplified vehicle body crush analog. |
| Barrier VII | University 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. |
| LS-DYNA | Livermore Software Technology Corp./2006 | Nonlinear, explicit finite element program | Detailed Finite Element Models | Extensive  | LSTC  | Detailed models can provide very accurate predictions of safety hardware performance. |

**HVOSM**—The Highway Vehicle Object Simulation Program (HVOSM) (136) 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 (127). HVOSM is especially suited for evaluation of roadway and roadside geometrics where vehicle stability is a primary concern. Although this program has also been used for simulating rigid barrier impacts (104), it has now been superseded by LS-DYNA.

**Barrier VII**—The Barrier VII program (111) 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 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 (18, 137).

**LS-DYNA**—This program is a highly sophisticated, nonlinear finite element computer program (82). The program is commonly used to model vehicular impacts with virtually any roadside safety feature. Although this program has proven to be capable of accurately predicting the behavior of vehicles and roadside safety features during high-speed impacts, some significant limitations remain. LS-DYNA’s primary limitations are related to failure of barrier and vehicle components. Finite element modeling of metal rupture has not progressed to the point that it can be reliably predicted. Dynamic rupture of metal components has proven to be very mesh dependent. A developer can sometimes tune a particular model to fail at the appropriate time in a dynamic test, but even minor changes in the load orientation or model mesh configuration can destroy the program’s accuracy. As a result, LS-DYNA’s ability to accurately predict vehicle suspension failure or barrier component rupture is very limited.

D1.4 Laboratory Dynamic Tests

In addition to the full-scale crash test 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, and bogie vehicle.

D1.5 Gravitational Pendulum

A pendulum 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:



Where:

*Vi* = velocity at impact

*g* = acceleration due to gravity

*h* = drop height of mass

The above formula ignores speed losses due to friction and aerodynamic drag and therefore should be corrected to more accurately assess the actual pendulum impact speeds. As an example, for an impact speed of 32 mph (9.7 m/s), a drop height of 15.7 ft (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 25 mph (40 km/h) or less. A gravitational pendulum capable of high-speed impacts would require very high drop heights and is impractical.

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 (19, 85), these devices may be out of date. Nose assembly systems should be evaluated to ensure that they accurately replicate modern vehicles.

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. 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 not 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 (31). 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

A bogie vehicle is 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 can be mounted on the front of the bogie.

Bogie vehicles may be used to simulate impacts with breakaway structures, work-zone traffic control devices, longitudinal barriers, or components of such systems. As discussed in Section 4.2.2, bogie vehicles must be revalidated periodically to ensure that the devices are representative of modern vehicles.

D2 Comparison of Techniques

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

TABLE D-3. 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 performancePreliminary design of feature for vehicle collision performanceAnalysis of connections, material properties requirements, and foundation design | Dynamics and kinematics of feature and collision vehicle are not addressedCollision severity in terms of occupant injuries and fatalities is not addressed  |
| 2 | Static Tests (quasi-static) | Mechanical properties of unique shapes, connections, new materialsValidation of structural design featuresQuality control of critical material properties Develop input values for computer programs | Dynamic properties not examinedGenerally applicable to samples, connections, and small subassemblies; entire system is not accommodated |
| 3 | Computer Simulations | Study interrelations of feature and vehicle dynamics and kinematicsStudy interrelations of vehicle dynamics and occupant dynamicsStudy 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 estimatedFor practical and economic reasons, programs model only major feature/vehicle properties Sometimes minor features decide the performance |
|  |  |  |  (Continued on next page) |

TABLE D-3. Safety Feature Development Techniques (continued)

|  |  |  |
| --- | --- | --- |
| **Development Technique** | **Principal Areas of Application** | **Possible Limitations** |
| 4 | Dynamic Tests |  |  |
|  | A. Gravitational  Pendulum | Compliance test for luminaire and single-leg sign breakaway supportsEvaluation of breakaway mechanismsForce/deformation properties of guardrail post/soil interactionsDynamic strength of anchor systemsDynamic properties of barrier subsystems | Impact speed 25 mph (40 km/h) or less For dual-leg supports, upper-hinge mechanisms are not examinedDoes not simulate off-center impactsTrajectory of article not reproducedNot applicable for base-bending supportCrushable nose must be tuned for type and width of specimen and recalibrated periodicallyCannot properly evaluate criterion D, Table 5-1B |
| B. Drop Mass | Quality control test of breakaway componentTest can be performed in a confined, indoor space | Same limitations as for pendulumFor 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 safety feature components |
| D. Bogie  Vehicle Test | Compliance test for single or multi-leg breakaway supportRepeatable test vehicle suspension, nose crash, and other dynamic propertiesLow-cost, high-speed 0–60 mph (0–96.6 km/h) experiments | Must be carefully designed and calibrated to represent vehicle characteristics of interest, which is often a long and expensive processDesigns have been appropriate for testing only limited variations in featureMust be updated and recalibrated periodically |
| E. Vehicle  Crash  Test | Compliance test for all featuresInvestigation of unusual conditionsMost direct tie to actual highway collisionsFinal proof test | Relatively expensive to performRequires extensive capital facilitiesDeliberate and slow to performTest results pertain to the specific vehicle model tested and may not be applicable to other vehicles |