The nature and frequency of inadvertent encroachments by a motorist are functions of numerous factors, including the motorist himself. Data are needed to determine this interrelationship. With regard to roadway variables, encroachments are believed to be a function of roadway type (interstate, divided, two-way undivided, urban arterial, etc.), roadway and roadside geometry (vertical and horizontal alignment, shoulder and curb, enbankment, etc.), traffic control devices (delineation, signing, lighting), traffic conditions (vehicle mix, volume, operating speed, environmental conditions, etc.) and vehicle size. An encroachment data base should be gathered sufficiently to develop a statistically reliable accident prediction algorithm with capability to predict the following:

1. Number of times an object will be struck in a given time period,
2. type of vehicles expected to strike object in a given time period,
3. speeds at which vehicles will strike object,
4. angle at which vehicles will strick object, and
5. attitude at which vehicles will strike object.

Once the number and type of vehicle involvements with a given roadside object have been estimated, one must ascertain the probability and level of injuries associated with each involvement. Impact severity can be estimated from physical test data (crash tests, skid tests, laboratory tests, dummy tests, etc.), accident data, computer simulation (vehicle and/or occupant dynamic simulation models), accident reconstruction combining accident data with test data and/or computer simulation, or engineering judgment.

Data from which the severity of a predicted accident can be quantified are also quite sparse. Variables that influence the severity of a given impact include the type of object hit (fixed objects, continuous objects, temporary objects used in work zones, etc.), type of vehicle (automobile, truck, special vehicle, etc.) and impact conditions (speed, angle, attitude, etc.). Impact severity data should be gathered to eventually develop a data base sufficient to evaluate the severity of the accidents predicted by the accident prediction algorithm.

CRASH TEST AND OPERATION EXPERIENCE

Eric F. Nordlin, California Department of Transportation

The procedures for testing and evaluating highway appurtenance performance have become increasingly more complex since 1962 when the original single-page guideline for crash testing guardrail with a 4000-lb. passenger car was first published in Highway Research Board Circular 482. Updated by NCHRP Report 153 in 1974 and Transportation Research Circular 191 in 1978, these guidelines have necessarily and progressively expanded into the present 42-page NCHRP Report 230, Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances. The new guidelines cover not only guardrail but also median barriers, bridge rails, crash cushions and breakaway or yielding supports for signs, luminaries and other selected highway appurtenances.

The vehicles of interest now include 1800-lb., 2250-lb. and 4500-lb. passenger cars, a 20,000-lb. utility bus, 32,000-lb. and 40,000-lb. intercity buses and an 80,000-lb. articulated tractor-trailer truck. It also appears that the range of vehicles will be even greater in the foreseeable future as the number of still smaller, lighter passenger cars and still large, heavier and longer tractor-multiple trailer trucks increase as the current trends continue.

Actually, the number of test vehicle variables alone become almost infinite when one considers all of the sizes, weights and shapes of vehicles; their different manufacturers, models and ages; their different mass distributions, location of center of gravity and suspension systems; the location of the engine and type of transmission; the numbers of axles and wheels, wheel and tire sizes and track widths; their general maintained condition and the many other characteristics that affect the structural integrity, stability and dynamic response of an impacting vehicle.

However, the number of potential test variables expands still further when consideration is given to the number of passengers, their physical conditions and ages, how they are restrained and the other occupant protective measures that have been designed into the vehicles; the types of other cargo (gas, liquid or solid), how it is located or stacked and how securely it is restrained; the vehicle velocity, angle, lateral offset and orientation at the time of impact; and the ability of the driver to react to, through and recover from the vehicle/appurtenance interaction situation.

In addition, there also are the many potential variables associated with the location of the appurtenance on the highway; the riding surface leading to and immediately adjacent to the appurtenance; the type and condition of the soil; the horizontal and vertical alignment and other highway geometric design conditions; the point of impact on the appurtenance; the design of the appurtenance and the quality of materials used to construct it; the environmental conditions that affect durability and weatherability; and the general maintenance upkeep efforts expended.

Full-scale vehicle crash tests performed, instrumented and photo documented in accordance with NCHRP Report 230 are very costly; ranging from $10,000 to $20,000 per test at Caltrans. Therefore, an agency must be somewhat restrictive in the number of tests and selective in the variables to be considered.

Structural laboratory tests, analytical procedures, computer simulations and pendulum or bogie vehicle tests are very useful techniques employed to reduce the number of full-scale vehicle impact tests. These less costly complementary procedures frequently serve to screen out the less critical variables and interpolate between the data points generated from a limited number of crash tests.

However, even with these complementary techniques, it is impractical and virtually impossible to duplicate and accurately determine, in a limited number of standardized crash tests, the effect that all of the aforementioned variables will have on vehicles impacting a highway appurtenance. Recognizing this, NCHRP Report 230 establishes normalized test conditions; straight longitudinal barriers are tested although curved installations exist; flat grade is recommended even though installations are sometimes situated on sloped shoulders or behind curbs; idealized soils are specified although appurtenances are often located in poor, frozen or saturated ground, etc. These normalized factors have significant effect on the performance of an appurtenance and may obscure serious safety deficiencies that exist under more typical but less ideal actual 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 tests on two or more systems. The normalized test conditions are more easily duplicated and thus promote better correlation of results by different testing agencies. For these reasons, the highway engineer is warned that when the performance of an appurtenance is required for a specific site situation or the performance of an appurtenance is suspected of being unacceptable under some likely conditions, it is important that these specific conditions should be used instead of, or in addition to, the normalized test factors.

For example, several years ago Caltrans was involved in a blanket safety program to install crash cushions in off-ramp gore areas with raised curbs where it was not feasible to remove rigid overhead sign supports. Based on the results of a series of vehicle jump and crash tests into a raised curb test installation, with and without a crash cushion installed, it was reasonably proven that it was not necessary to remove the raised curbed gore area provided the crash cushion was located sufficiently close to the curb to minimize the effect of vehicle vaulting or dipping. This test series also provided Caltrans engineers with valuable test data that could be applied to make engineering judgment at other situations and locations where the same height of curb existed.

However, even when performing a minimum matrix of normalized tests such as those recommended in NCHRP Report 230, seemingly inconsequential differences between test vehicles of the same mass can drastically change the outcome of the crash tests. For example, several years ago Caltrans conducted a series of four almost identical crash tests on the same concrete median barrier. In all four tests the passenger car weights were 4800-4900 lb., the impact speeds were close to 65 mph and the angle of impact was approximately 25 degrees. In the first two tests, one make of car was used and in both tests the car rolled over three times after impact with the barrier. In the last two tests, another make of car was used and did not roll over in either test. The difference in vehicle behavior could only be contributed to differences in the two comparable makes of cars; perhaps in the suspension systems, the crushability of the front ends, the dynamic strength of the front wheels and steering assemblies, etc.

For all of these reasons, standardized or normalized crash testing procedures actually can only constitute another screening phase in the development and evaluation of a highway appurtenance. In fact, it is questionable whether a crash testing program could ever be designed, regardless of cost, to predict and give complete assurance in regard to how an appurtenance would perform under all highway situations and conditions. This is why NCHRP Report 230 includes in-service evaluation as the final phase in the development of a new or extensively modified highway safety appurtenance. Appurtenances that have been judged to perform acceptably through controlled crash testing and the other complementary techniques are introduced into actual service on a limited trial basis and the installations are extensively monitored, preferably for a 2-year period where possible. The in-service evaluation is intended to expose the appurtenance to all of the variables of the "real world" to proof test or "debug" the design, learn the application limitations and/or modify the design before approving for broad operational use.

As an example, a number of years ago one of the first median barriers developed by Caltrans through crash testing consisted of a single steel cable 9 in. and a pair of cables 30 in. above ground, and chain-link mesh fencing all mounted on yielding lightweight steel posts. However, contrary to the controlled test results, the in-service experience on a limited number of trial installations showed the tendancy for vehicles to ramp up over this original cable chain-link mesh median barrier. A subsequent series of controlled crash tests resulted in the elimination of the single lower cable. In-service experience with subsequent trial installations of the modified design resulted in statewide approval and a number of years of successful experience with this low-cost median barrier in California.

However, the in-service monitoring and evaluation of all highway safety appurtenances should not cease with the initial trial period but should always be ongoing. This need is also best illustrated by the Caltrans experience with the cable median barrier. After a number of years of successful experience, impacting vehicles started penetrating under the pair of cables resulting not only in cross median accidents but even decapitation of the driver. Analysis of the accident data showed that the penetrating vehicles were all the low-nosed small sport cars that were just starting to appear in significant quantities on California highways. A third series of crash tests involving standard size and the small passenger cars and various terrain conditions resulted in lowering the pair of cables to a height of 27 in. above the ground and new warrants that limited the terrain conditions where the further modified cable median barrier could be used. With these changes, the modified cable median barrier continued to be effectively used in California until medians started to get much narrower and the range of vehicle sizes continued to spread to the point where this flexible cable design was no longer effective. However, by the time the concrete median barrier started replacing the cable median barrier, this low-cost system had paid for itself many times over. Furthurmore, through continued in-service monitoring and accident statistic review, the modifications and ultimate termination of this design were always made as unsatisfactory performance started to develop.

Highway engineers should realize that safety appurtenances are not perfect and subject traffic to a degree of risk. They, themselves, are fixed objects regardless of the amount of testing and evaluation they have undergone and never should be installed if there is doubt about its need. For example, in California in 1980 on the state freeway system there were 267 fatal accidents involving fixed objects. Of these accidents, 19 percent involved guardrail and 15 percent involved median barrier. Undoubtedly, in many of these accidents a fatality would have occurred whether or not a barrier was involved in the chain of events. However, it is also obvious that contact between an out-of-control vehicle and a barrier does not always eliminate fatalities and serious injuries. In fact, it is possible that in a few of these accidents, the collision was more severe due to the presence of the barrier than would have been the case without it.

Highway agencies must generally rely on cost-benefit evaluations in establishing priority for appurtenance placement. There never are enough funds available to correct all of the safety problems. Appurtenances will generally have to be installed or modified where the resulting expenditures will save the most lives. However, the first cost for installing a safety appurtenance may not be the sole cost factor to be considered in selecting one of several candidate designs or systems. For example, a well-designed cable-type median barrier may be less costly to install than a concrete barrier. However, if installed in the median of a relatively heavily traveled urban freeway, it will be frequently hit unless the median is quite wide. Each hit would result in costly repair to 25-100 ft. of barrier whereas the concrete barrier would be relatively maintenance free. Thus, repair costs become a significant part of the total cost of a cable barrier over its service life. In addition, maintenance and repair effort in the median of an urban freeway is a hazard to maintenance personnel as well as to the traveling public, which can result in additional loss of life.

In establishing priority for roadside safety improvement, including appurtenance installation or modification, the highway engineer must be able to put spectacular individual accidents, such as the relatively infrequent accidents involving school buses, in proper perspective and consider them in overall highway safety strategy. Where funds are limited as they usually are, emotional issues must be tempered with thorough safety and economic analysis.

HARDWARE PERFORMANCE AS AFFECTED BY SITE CONDITIONS

Maurice E. Bronstad, Southwest Research Institute

In appraising dynamic performance of a safety appurtenance in a real-world accident, it is important that the device was subjected to conditions within its performance range. That is, the device should have been installed and maintained properly and that the vehicle impact conditions (i.e., mass, speed and angle) were within the device capability.

Examples abound in which the device was improperly installed or that some highway feature severely restricted the potential performance range, for instance, longitudinal barriers mounted behind mountable curbs that cause errant vehicles to vault over the system; flexible longitudinal barriers mounted too close to rigid fixed objects (during collisions, the barrier deflects to the fixed object subjecting the vehicle to pocketing and snagging possibilities); improper transitions between approach and bridge railing causing pocketing or snagging of the vehicle; post-and-beam bridge rail systems that are not compatible with the bridge deck; and improper or inadequate terminals that fail to develop the barrier strength or present undue hazard to the motorists.

In addition to improper installations, there is concern that many existing installations are not being maintained. Longitudinal barriers have been permitted to settle or the surrounding grade or pavement surface has been allowed to build up; this has essentially reduced the effective height of the barrier and has increased the number of vehicles that vault over the system.

Thus, in performing field evaluation of appurtenances, it is most important to document the condition of the system prior to the impact so that improperly installed or maintained devices will not reflect adversely on a system's general capability.

DESIGN REQUIREMENTS--DATA NEEDS

Robert J. Reilly, Cooperative Research Programs, Transportation Research Board

During this workshop, three questions concerning data on safety-appurtenance accidents will be addressed: What is needed? What is available? and How can the gaps be filled?

This presentation concentrates on the first question in the context of the evaluation of safety appurtenances, for which the design requirement is that the system demonstrate acceptable performance during specified crash tests.

The primary reason for installing a safety appurtenance should be to make a particular site safer than it would be without it. However, some appurtenances are needed primarily for other reasons, for example, breakaway supports for signs and luminaries, which are designed by conventional structural methods to resist wind, gravity and other loads. The basis for the structural design of such appurtenances is well accepted and is not directly dependent on field performance data. Although safety is not the primary reason for installation of such hardware, its presence should add the least possible extra hazard to the site, therefore, its safety performance must be determined by crash tests and field evaluation. An exception to the requirement for crash-test evaluation of safety appurtenances presently exists in the case of bridge railing systems. The AASHTO Standard Specification for Highway Bridges requires an allowable stress design except for railing systems that have been successfully crash tested.

NCHRP Report 230, Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances, published in 1981, introduced some significant changes to appurtenance evaluation as previously specified in NCHRP Report 153, Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances.

- o Test conditions were modified to consider mini-compacts (1800 lb.), trucks and buses, and a multiple-service-level approach was introduced to require various levels of structural adequacy as appropriate for particular site conditions.
- o Evaluation criteria had not previously been consistent among various types of appurtenances, in that some were based on average accelerations and others on change in momentum. The flail space concept, used in Report 230, sets limits on both the velocity with which the occupant may strike the interior of the vehicle and the subsequent ride-down acceleration.
- o An entirely new chapter is devoted to in-service evaluation, in which an appurtenance is installed on a trial basis, monitored for some period of time (e.g., 2 years), and a conclusion is reached, whereby the period of evaluation is extended or the appurtenance is either accepted, rejected or modified.
- o Report 230 also contains a new section on analytical simulation and experimental techniques other than full-scale testing (e.g., static tests and component testing).

We should now consider various types of accident data and how they might be used.

- o Detailed, case-by-case accident information, such as envisioned in the system of in-service evaluation recommended in Report 230, is most useful for gaining insight into the behavior of a particular item. A few well-documented cases of unsatisfactory performance might be all that is needed to call attention to a problem in a particular system.