Federal Outdoor Impact Laboratory—A New Facility for Evaluating Roadside Safety Hardware

MARTIN W. HARGRAVE AND ALLEN G. HANSEN

This paper describes the Federal Outdoor Impact Laboratory (FOIL), a new laboratory for evaluating roadside safety hardware. The FOIL has been designed and constructed to solve many of the roadside safety problems of the 1980's and beyond. As primarily a small-car crash test facility, it is used to research the higher probability of injury for small-car occupants. As a side impact test facility, it is used to develop side-impact technology and appropriate roadside solutions.

Highway safety research to enhance the technology of road building as well as improve the safety of highway users has long been a priority to the Federal Highway Administration (FHWA). This is in contrast to the function of the National Highway Traffic Safety Administration, which focuses on the safety performance of vehicles.

Much of the federally funded highway research is directed from FHWA's Turner-Fairbank Highway Research Center located in McLean, Virginia, just outside of Washington, D.C. A recent addition to this center is an outdoor test facility named the Federal Outdoor Impact Laboratory (FOIL). Here, roadside safety hardware such as sign supports, light poles, crash cushions, and roadside barriers can be tested and evaluated.

Traditionally, full-scale crash testing has been the standard for the development and evaluation of roadside safety appurtenances because of its reliable, close duplication of real world collision events. However, to reduce test costs and improve the repeatability of test results, alternative test methods have been developed over the years. The latest in this evolution is the FOIL, which can operate in frontal and side impact modes. Figure 1 shows the general layout of this modern facility.

FOIL FACILITY

Features

The FOIL consists of a 200 foot (61 m) paved acceleration runway followed by a 200 foot wide by 350 foot (61 m by 107 m) long, grassy runout area. The runway end of the site is slightly sloped (2 percent grade) with the highest point located at the head of the runway. The area is level for 25 feet (7.6 m) immediately before and after the impact area, with gradual transitions between the sloped runway and the sloped runout area. The runout area changes gradually from a 2 percent downgrade to a 2 percent upgrade approximately 200 feet (61 m) beyond the end of the runway.

A unique feature of this test laboratory is the reusable bogie test vehicle shown in Figures 2 and 3. This vehicle is designed for frontal testing of breakaway poles, luminaires, and large sign supports and is currently configured to represent a 1979 Volkswagen Rabbit. Frontal vehicle crush is replicated using replaceable cartridges of aluminum honeycomb material. Other vehicle properties are replicated as necessary to produce realistic impact and post-impact (runout) results.

Another significant feature of this test laboratory is the use of a large weight as the propulsion system. A falling weight, connected by a cable to the test vehicle, pulls the vehicle forward, accelerating it to test speed. This propulsion method provides a reliable and low-cost drive system that can accelerate small vehicles to test velocities in a very short distance.

Side impact testing using actual automobiles, as depicted in Figure 4, is another of the FOIL's unique features. This capability is important because approximately 25 percent of all single-vehicle fatalities result from side impacts into fixed roadside objects. Unlike frontal testing, side-impact test specifications, evaluation criteria, and vehicle definition are largely undefined. Consequently, a reusable side impact bogie is not currently being developed, though it may be feasible and may later be developed.

One additional feature of the FOIL is the pendulum testing device, shown in Figure 5, which is useful for evaluating the performance of roadside hardware at low speeds. This pendulum is equipped with the same crushable frontal structure that is installed on the bogie, and the speed of impact is controlled by the drawback distance of the pendulum. The pendulum can be used only where vehicle runout and hardware trajectory after impact do not need to be determined and where the impact has a short duration, so that the curvature of the pendulum swing does not bias the test results. In addition, the pendulum cannot be used to evaluate the performance of large, multi-legged sign supports where the pendulum cables could interact with the sign blank and distort the acceleration measurements.

M. W. Hargrave, Federal Highway Administration, Safety Design Division, HSR-20, 6300 Georgetown Pike, McLean, Va. 22101. A. G. Hansen, Analysis Group, Incorporated, Engineering Systems Division, 1750 New York Ave., N.W., Washington, D.C. 20006.

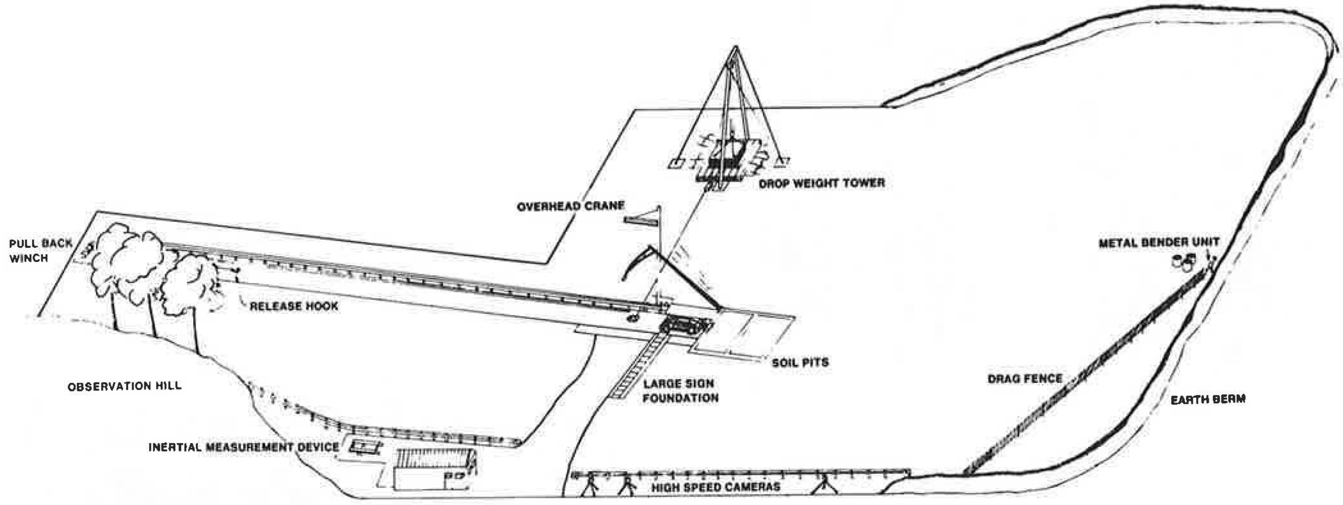

FIGURE 1 Schematic of FOIL facility.

Acceleration and Guidance System

The large weight that powers the FOIL's test vehicle is connected to the front of the vehicle by a cable that is released just prior to impact. Thus, at impact the test vehicle is free of all external restraints and is traveling at constant speed.

The speed of the vehicle, which can be varied between 0 and 60 mph (97 km/h) for front impacts and 0 to 45 mph (72 km/h) for side impacts, is determined by the distance of initial vehicle pullback and the size of the drop tower weight (up to 12,500 pounds or 5700 kilograms). This pullback is accomplished by a winch and second cable attached to the rear of

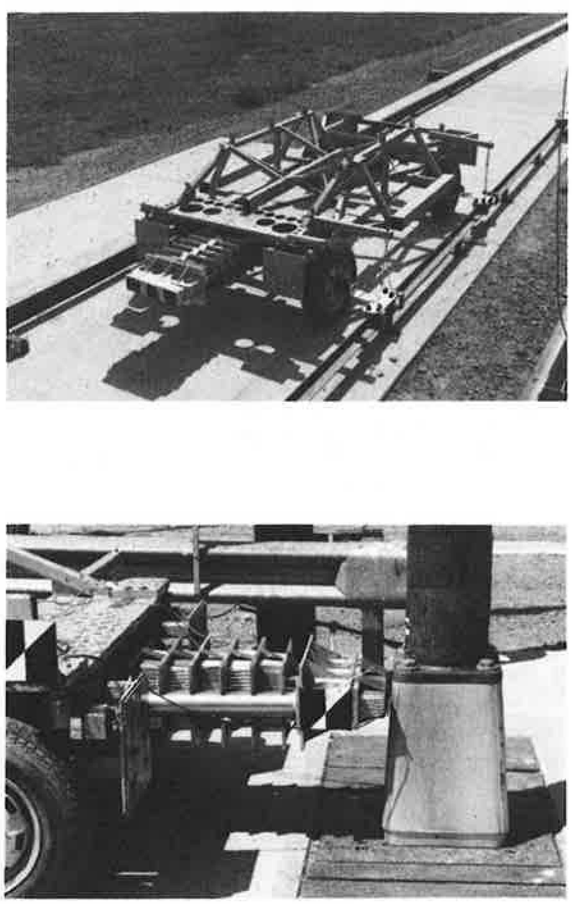

FIGURE 2 Frontal impact bogie test vehicle.

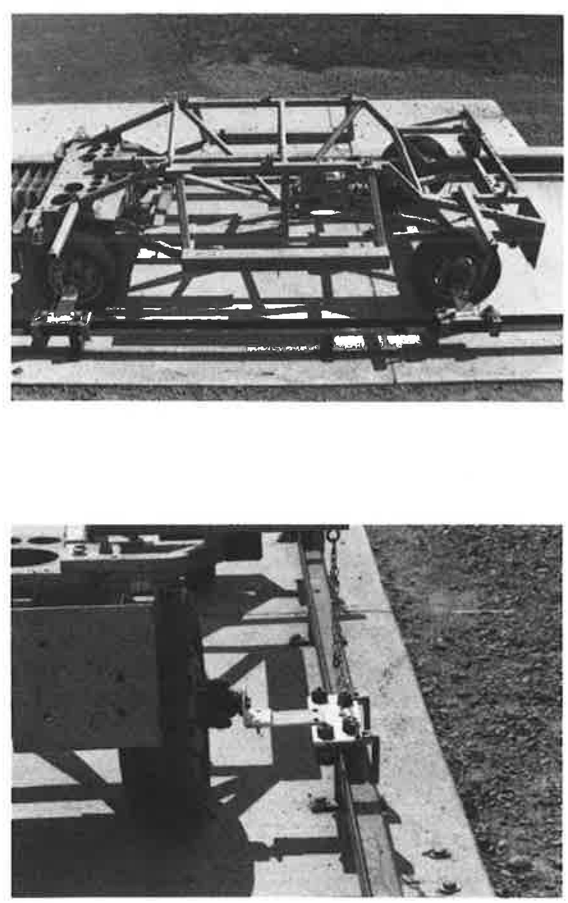

FIGURE 3 Frontal impact vehicle guidance system.

FIGURE 4 Side impact vehicle guidance system.

the test vehicle. When the second cable is automatically released, the test sequence is initiated. For front impacts, a single fixed rail and two attachment assemblies fastened to the vehicle's front and rear spindles guide the vehicle during acceleration, as shown in figure 3. For side impacts, a second rail is used to support the bulk of the vehicle's weight, with the other rail used to support an outrigger mounted at the back of the vehicle, as shown in figure 4.

Because the entire system operates under constant acceleration caused by gravity pulling on the large drop weight, the velocity of the test vehicle at impact can be calculated. The relationship between the velocity and pullback distance can be estimated from the following equation:

$$V^2 = \left[\frac{2gER * (1 + 6WS)}{(1 + R^2W)}\right] L \qquad (1)$$

where:

- V = Impact velocity of test vehicle
- L = Pullback distance
- E = System efficiency (0.75 to 0.80, including losses associated with the vehicle)
- W = Ratio of vehicle weight to drop weight
- g = Acceleration of gravity
- R = Reduction ratio of drop tower pulley system (6:1)
- S = Runway slope (2 percent).

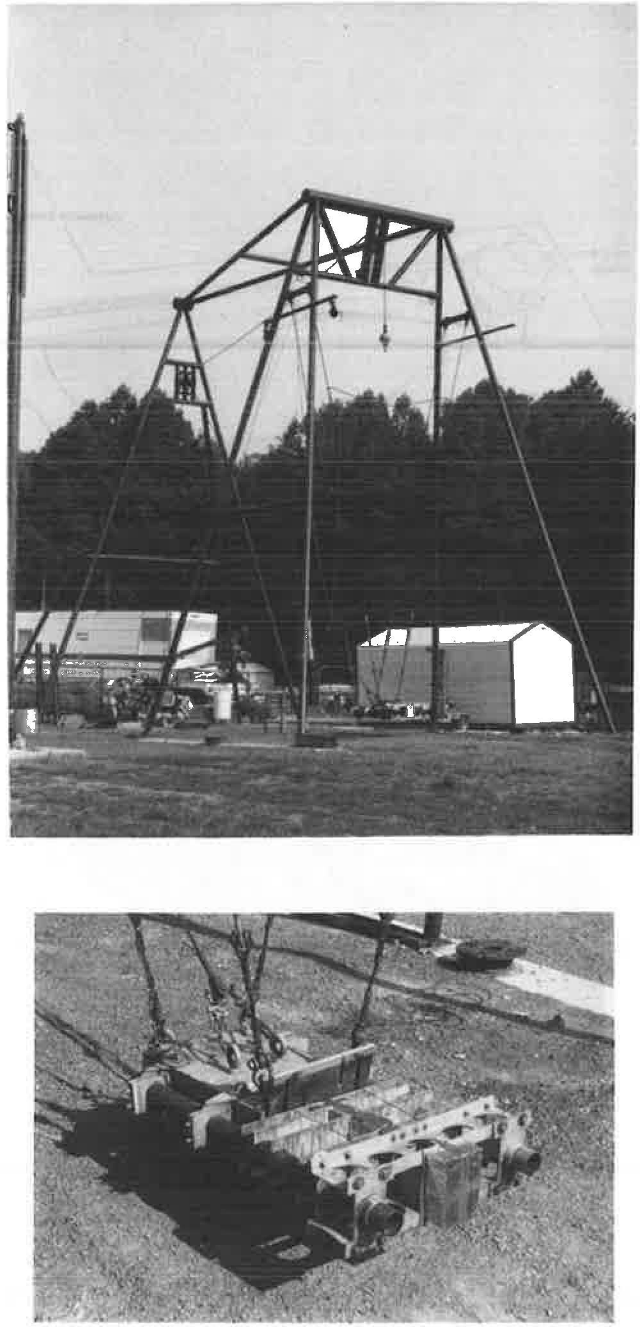

FIGURE 5 FOIL pendulum test system.

For each test, this equation is used to estimate the pullback distance for a desired impact velocity. Since the parameters E, W, g, R, and S are essentially constant for a given test, the velocity is directly proportional to the square root of the pullback distance. The system efficiency is adjusted based on environmental conditions such as ambient temperature and the presence of water on the runway.

Test Vehicle

The maximum vehicle weight for the full speed range is 2,250 pounds (1,020 kilograms) for front impacts and 2,500 pounds

(1,130 kilograms) for side impacts. The size of the falling weight and the corresponding strength requirements of the drop tower dictate this weight limit. Heavier vehicles can be tested but at lower maximum speeds. For example, the present system can test a 3,600 pound (1,630 kilogram) vehicle—typical of today's large size automobile—at speeds up to 50 mph (80 km/h).

The reusable bogie vehicle (Figure 2) is designed to emulate the actual impact and post-impact (the runout) performance of full-scale automobiles under real-world conditions. Any automobile weighing from 1,400 pounds (640 kilograms) to 2,250 pounds (1,020 kilograms) can be modeled by the bogie.

A principal feature of the FOIL, unlike earlier systems with reusable test devices, is the capability to observe and monitor the runout performance of the bogie after impact. Thus, in addition to analyzing injury severity criteria at impact, the tendency for a bogie to roll over after impact can also be observed and analyzed. This capability is important considering the greater likelihood of accident-related roll-overs with minisize vehicles and the higher probability of serious or fatal injury in roll-over accidents.

To emulate the crash performance of an actual automobile and to provide data for the bogie design, computer simulation runs using the Highway Vehicle Object Simulation Model were made. The results of these simulations were used to determine such properties as wheelbase, weight distribution, and suspension parameters required for a full-scale model. The computer simulations were validated by comparing the results with a full-scale crash test. After construction, the actual performance of the bogie was validated against additional full-scale tests.

Table 1 lists the vehicle properties which are modeled on the current bogie. Also shown in this table are properties of an actual automobile and of two earlier test devices, the pendulum and a low speed bogie. This table indicates that the bogie contains all of the significant properties of an actual automobile except for a suspension system and steerable front wheels. Computer simulation results indicate that the bogie duplicates actual vehicle impact and post-impact performance up to 22 feet (6.7 m) following impact and realistically simulates runout trajectory up to 150 feet (45.7 m) beyond impact. This result is expected because suspension system responses delay impulsive force inputs and the steering system tends to self-correct the vehicle with respect to trajectory. Therefore, the lack of steerable front wheels makes the bogie a worst-case test vehicle with regard to roll-over. The lack of both steering and suspension also makes the test device rugged and lowers its initial and operating costs.

Arrestor Systems

To stop the bogie after impact and runout, three arresting techniques are employed as shown in Figure 1: onboard four-wheel braking, an auxiliary energy absorbing arrestor system, and as a fail-safe, a large earthen berm. The onboard braking

TABLE 1 VEHICULAR DEVICES MODELED BY VARIOUS TEST DEVICES

General Category	Specific Property	Pendulum	Low Speed Bogie	FOIL Bogie	Automobile
Crush force deflection	Centered impacts	X	X	X	X
	Off-center impacts			X	X
Weight properties	Total weight	X	X	X	X
	Center of gravity			X	X
	Moments of inertia			X	X
Geometry	Wheelbase			X	X
	Track width			X	X
	Lower snag simulation	X	X	X	X
	Roof line penetration simulation		X	X	X
Suspension system	Tire stiffness		X	X	X
	Suspension stiffness damping				X
Steering system	Steerable front wheels				X
Speed capability	0 to 20 mph (32 km/h)	X	X	X	X
	0 to 60 mph (97 km/h)			X	X

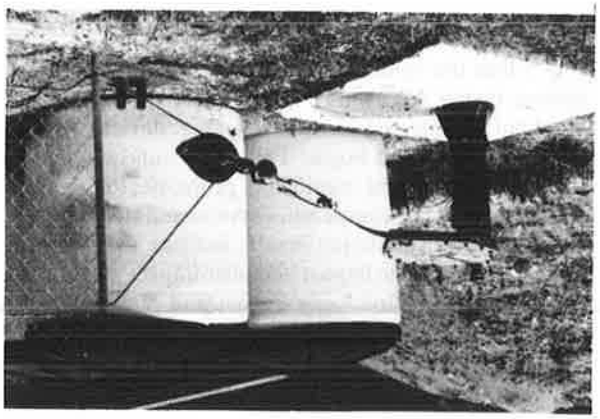

FIGURE 6 Energy absorbing arrestor system.

system is basically a pneumatic-over-hydraulic system. Under remote control, air, which is released from an onboard reservoir, acts through a piston at the interface to activate the hydraulic brakes. This braking technique is adequate for test speeds below approximately 55 mph (89 km/h) and without assistance can safely stop the test vehicle after runout.

At test speeds above approximately 55 mph (89 km/h), additional energy-absorbing devices are required. Secondary braking is achieved with two metal-bender units (see Figure 6) that absorb energy by forcing metal tape through a series of staggered rollers. The metal-bender units attach to each end of a drag fence that is stretched across the runout area. When the onrushing bogie is snagged by the fence, the kinetic energy of the vehicle is converted to strain energy as the vehicle pulls the metal tapes through and out of the metal-bender units.

Finally, as a backup to the primary and secondary braking systems, a large earthen berm surrounds the entire runout area. The berm, which is approximately 6 feet (1.8 m) high and has a sand face sloping upward at about 45 degrees, effectively contains out-of-control vehicles.

Data Collection Systems

The current FOIL data collection system is limited to 14 channels of data (13 for data signals plus a timing signal). These signals are transferred from the vehicle to the facility control enclosure using an umbilical cable. Each signal is recorded on an analog tape system and digitized after each test using a compact digitizer coupled to a microcomputer. Two new battery-powered 32 channel digital systems are currently being developed. One system can be mounted directly on the bogie vehicle, providing a significant increase in the recording capabilities at the FOIL while eliminating both the umbilical cable and the post-test digitization. The second system can be mounted together with the first system in a full-scale vehicle to provide up to 64 channels for data acquisition, or it can be used to gather data from transducers that are not mounted on the car, such as speed traps and force gages.

The test vehicle can be instrumented with up to three accelerometers to measure the longitudinal, lateral, and vertical acceleration, and a three-axis-rate gyroscope to measure the roll, pitch, and yaw angular velocities. (Currently, two accelerometers are used to provide redundancy in the measurement of the longitudinal acceleration in lieu of the vertical measurement.) These devices are located at the vehicle center of gravity and can be used to determine vehicle dynamics in addition to the following occupant injury measures:

- The velocity change (flail space velocity) of a theoretical occupant striking the interior of the vehicle just after a sudden impulsive impact (a measure of injury potential);
- The peak accelerations experienced by the vehicle averaged over 10 or 50 milliseconds (a second measure of injury potential).

A series of five contact switches both before and after impact is also used to determine the change in vehicle velocity due to impact (independent of the accelerometer data). The switches are a fixed distance apart on the runway, so that speed can be determined by measuring the time between successive pulses.

In addition to these two electronic data sources, independent film data are also recorded using a real-time documentary camera and several high speed cameras. Typically, two high-speed cameras are focused on the impact area while a third camera records the runout trajectory of the vehicle and the post-impact motion of the impacted object. The films are analyzed on a motion analysis system coupled with a microcomputer. The change in velocity of the vehicle due to impact and the motion of the impacted object are determined with this system.

The use of multiple accelerometers, speed traps, and cameras provides a high degree of redundancy in the determination of the change of velocity of the vehicle due to impact. A statistical weighted averaging technique is then used with the three independent velocity change calculations to provide a very accurate estimate of the actual velocity change of the vehicle (and the associated occupant) during a sudden impulsive impact with certain roadside safety devices such as breakaway poles or luminaire and sign supports. The lower the velocity change resulting from impact, the greater the safety effectiveness of the roadside device under test.

Other Equipment

Two additional major pieces of equipment available at the FOIL include a rigid instrumented pole (Figure 7) and an

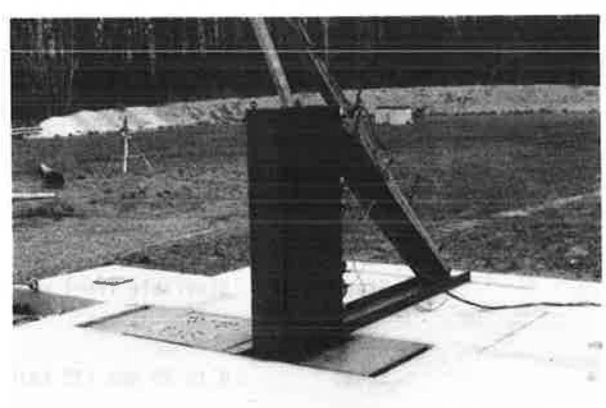

FIGURE 7 Rigid instrumented pole.

FIGURE 8 Inertia measuring device.

inertia measuring device (IMD, as shown in Figure 8). The crush force of a vehicle's front or side structure is measured by crash testing actual vehicles into the rigid pole. The resulting force data coupled with the corresponding crush distance are required for modeling bogie vehicles or for inputs to computer simulations and bogie vehicle models.

In the frontal mode, a single pole segment and two force measuring cells measure the overall crush force of the vehicle's front end. In the side impact mode, however, three pole segments (each with two load cells attached) are used because of the differing stiffness of the door, the roof line, and the lower sill. By using two load cells per segment, the rigid instrumented pole can measure the magnitude as well as the location of the crush force—necessary parameters for modeling.

The IMD is used to determine the rotary moments of inertia (weight distribution) and the center of gravity of an actual small vehicle or the bogie. The resulting data are used to confirm that the vehicle parameters have been replicated in the bogie, as well as to provide measurements from actual vehicles for inputs to computer simulations and bogie vehicle models.

The IMD is basically a simple pendulum or seesaw device on which a vehicle can be placed. The inertia about each axis can be calculated by accurately measuring the period of each oscillation. To measure the vertical center of gravity, the IMD is tilted through a known angle until it rests on a load cell. The center of gravity can then be determined by measuring the force at the load cell.

RECENT TEST PROGRAMS

Several series of tests have recently been completed at the FOIL. The bogie, which was originally developed using roadside luminaire supports mounted with slip bases, has now been validated for transformer bases and couplings.

Following this validation, the bogie was used to determine the breakaway performance of luminaire support systems currently accepted for federal-aid highways when impacted with a lightweight 1,800 pound (820 kilogram) vehicle. This testing was done in accordance with the new 1985 AASHTO specifications for sign and luminaire supports. The testing program included eighteen luminaire supports mounted on transformer bases, nine anchor base supports, four progressive shear supports, three coupling mounted supports, and one slip base support. In addition, three direct burial fiberglass supports were evaluated at an independent laboratory.

These 38 devices were previously accepted for use on Federal-aid highways under older criteria which specified an impact with a heavier 2,250 pound (1,020 kilogram) vehicle. Due to the nationwide trend to lighter, more fuel efficient cars, a new rule is being proposed by the Federal Highway Administration to adopt the lighter (1,800 pound or 820 kilogram) vehicle as a test standard.

Of the 38 devices evaluated, 10 devices pass the new AASHTO change in velocity criterion. When both the change in velocity and the stub height criteria are considered, only four devices pass. It must be noted, however, that this is based upon a measurement of the remains of the breakaway device at the foundation without regard to what is considered "substantial" stub height. The substantial part of a stub is that portion that would produce significant vehicle undercarriage snagging. A review of test data is currently under way within the Federal Highway Administration to better quantify the determination of what constitutes a substantial stub.

Other test programs that have been conducted at the FOIL include the determination of significant vehicle parameters for use in modeling impacts with small base bending sign supports. The results of these tests are being used as a basis for the design of a new bogie for evaluation of the performance of small sign supports. Base bending sign supports are commonly used with stop signs, speed limit signs, and similar small roadside signs. In addition, side impact tests are being conducted to advance the state of knowledge of this important research area. Because side-impact testing is in its infancy, not only must various kinds of breakaway hardware be tested to determine acceptability under dynamic side-impact tests but the test conditions, test evaluation criteria, and test vehicle must also be defined and evaluated.

FUTURE PLANS

Data Collection System

The installation of the new data acquisition system mentioned earlier will allow the following data to be collected and processed:

- Anthropometric dummy data from frontal or side impact dummies (8 to 16 channels frontal, 18 to 36 channels side impact)
- Crush force of a vehicle's front or side structure measured with a rigid instrumented pole (2 channels frontal, 6 channels side impact)
- Additional vehicle and test article instrumentation to determine specific parameters of interest during a test series.

Bogie Development

Currently, the bogie is designed for frontal impact testing into poles and pole-like objects. As mentioned above, a second bogie, for evaluating the performance of small sign supports, is currently being designed, and it will probably incorporate a suspension system, a windshield, and a new nose design to replicate the performance of a small car during a base bending small-sign impact.

The next step in bogie development will be to provide a full-width frontal crush capability. This will allow crash cushions and similar roadside objects to be evaluated using lower cost, reusable bogie vehicles. This could be followed by the development of a two-dimensional (longitudinal and lateral) crush bogie capable of testing roadside barriers. However, in addition to the complexity of a two-dimensional crush cartridge, a bogie capable of testing barriers would most likely require a complete suspension system and steerable front wheels for proper modeling. Although this is technically feasible, it may not be economically justifiable or prove rugged enough for repeated testing, making the practicality of such a vehicle uncertain.

Test Program

The FOIL facility is currently being upgraded to provide the capability to test large, multi-legged sign supports. When this upgrade is completed, currently accepted (for use on federal-aid roadways) large sign support systems will be evaluated using the current bogie to determine system performance with a lightweight, 1,800 pound (820 kilogram) vehicle. As with luminaire supports, these devices were previously accepted under older criteria, which specified impacts with a 2,250 pound (1,020 kilogram) vehicle.

When the new bogie for testing small sign supports is completed, it will be validated against several full-scale vehicle tests. Then a comprehensive capability program will also be conducted to evaluate the performance of small sign supports when impacted with the lighter, 1,800 pound (820 kilogram) vehicle.

ACKNOWLEDGMENT

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