SIMPLIFIED IMPACT TESTING OF TRAFFIC BARRIER SYSTEMS

(Phase 1)

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ABSTRACT

A simplified impact test configuration was developed to provide a preliminary, economical means of assessing prototype traffic barriers before proceeding to full-scale federal testing. Specifically, the test was configured to assess the federal criteria for structural adequacy of highway safety features. In general, the test configuration utilized a wheeled surrogate test vehicle of similar weight to a production vehicle, mounted by rail to a 110-foot long, steep hydraulic flume. The barrier system targeted for assessment was portable barriers consisting of hollow plastic shells that used dead weight fill of water or sand. Representing a relatively new concept for temporary barrier applications that has been developed largely by small proprietors, few of these systems have been tested according to federal standards, such that public safety would stand to benefit significantly from the availability of a more economical test.

Two impact tests were conducted on a plastic, water-filled portable longitudinal barrier system. While limitations of the test configuration prevented a detailed evaluation of the specimen according to federal standards, the tests were successful in providing an initial understanding of the system's performance. Lessons were drawn from the tests for application to future improvements of the test configuration.

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A variety of portable safety and security barriers for directing traffic and securing private and public locations against access have been developed by industry. Some higher capacity systems have been developed for use around high-speed automobile racing tracks. Portable barriers are hollow, plastic composite walls and use dead weight fill (sand, water) to resist impact without interconnection to the ground. Interest in portable barriers recently has heightened with concern about terrorist attacks creating nationwide security needs. Indeed, interest in potential use of portable barriers at the Salt Lake City Olympic Games site evolved belatedly. Lack of credible performance data was a deterrent to immediate acceptance. Thus, a step toward more rigorously verifying impact performance would help overcome that concern as well as encourage conduct of full federal crash tests, if needed.

Full-scale impact testing is the most effective method of evaluating the safety performance of median barriers, bridge railings, crash cushions, break away supports, work zone traffic control devices, etc. NCHRP Reports 230 and 350 present specific impact conditions for vehicle mass, speed, approach angle etc. for various vehicles. Alternative static tests and dynamic tests also are used during the development stage. Dynamic tests include use of a gravitational pendulum, drop mass, or bogie vehicle. Few of the portable systems have been crash tested to meet federal standards. Typically, manufacturers are small businesses without the resources to conduct federal tests similar to crash tests of bridge guard rails.

This project focused on developing a comparable, inexpensive test method to conduct dependable preliminary impact tests. In Phase 1, CSU researchers configured a simplified, economic test configuration which closely realized many of the recommendations of NCHRP Reports 230 and 350. Criteria for evaluating the outcome of a physical test were established. A preliminary test configuration was devised and constructed. Pilot tests were conducted to trouble-shoot the physical concept for achieving the needed speed and force of impact. A surrogate test vehicle was used in an inclined flume on a steep incline and produced the Impact Severity test levels required by NCHRP 350 for Level 1-3 type vehicle approval.

Confinement limitations at the base of the flume constrained the physical set-up of the barriers themselves. Specifically, the angle of attack was nearly head on, not angular, and the

vehicle could not approach on a horizontal plane. In addition, only three barriers or less could fit in the area at the base of the flume. However, significant advancement was achieved in understanding the physical test concepts and site conditions required to safely conduct an effective test. Trial tests on actual barriers led to observations about needed improvements in the test site to remove flaws inherent in those tests. A Phase 2 is recommended to improve the test by relocating outside the flume on a to be constructed inclined track, using real vehicles, and avoiding the physical constraints to allow setting up a much greater number of linked barriers, so true system performance can be examined. Performance testing can then be conducted on actual security barriers. The outcomes should be assessed using the established federal criteria for safely resisting the impact and for reusability of impacted barriers.

CHAPTER 1

INTRODUCTION

Background

Traffic barrier systems of various configurations are used to address a wide range of safety problems that occur in the roadway environment. Crash cushions, median barriers, end treatments, bridge guardrails, and work zone traffic control devices are among the more commonly employed features for reducing or preventing the hazards encountered by the occupants of errant highway vehicles. The importance of these systems' effective function is principally dictated by the life-threatening consequences of failure, created by the extreme forces associated with automobiles traveling at highway speeds. The potential for loss of life as a result of barrier failure is then compounded by the growing probability of a vehicle striking a barrier while traveling on the nation's increasingly crowded highways. National highway traffic statistics indicate a steady increase in traffic volume of approximately 3 percent annually for the last three decades (1). In conjunction with this growth, national highway fatality rates have exceeded 40,000 persons per year for the last 10 years, in spite of significant efforts to improve automobile safety during that time frame (2).

Recognizing the inherent danger of highway travel, federal standards for the testing of traffic barrier systems require a series of full-scale impact tests using production model vehicles for evaluating a new system's crashworthiness and suitability for various levels of highway service. These standards are presented in the Transportation Research Board's National Cooperative Highway Research Program (NCHRP) Report 350, titled "Recommended Procedures for the Safety Performance Evaluation of Highway Features" (3). Representing the results of a comprehensive review of testing methods and their sufficiency in terms of replicating actual highway accidents, the tests standardized under this document have been established as the only current means of acceptance for a barrier system by the Federal Highway Administration. Recent mandates from the U.S. Department of Transportation's Office of Engineering established an October 2002 deadline for the exclusive use of NCHRP Report 350-tested safety hardware for new construction and repair and replacement projects on the National Highway System (4).

Three primary appraisal factors are presented in NCHRP Report 350 for evaluating a new traffic barrier system's safety performance: structural adequacy, occupant risk, and post-impact vehicular trajectory. Specific criteria must be met in terms of all three of these factors for a barrier to pass any one test of the series of tests prescribed for a given level of service. Although no one factor of these three may be deemed more important than another in terms of overall safe performance, the occupant risk factor certainly is that which generates the most significant requirements for test set-up and instrumentation. Included are requirements for electronic measurement of occupant impact velocities and ride-down accelerations, and in some tests, the use of anthropomorphic dummies to evaluate physiological response to these parameters. Indeed, the use of production model vehicles for testing is necessitated in part by the requirement to investigate the complex interaction of vehicle occupants with the vehicle during and after barrier impact.

Unfortunately, the development process for a new traffic barrier system can be excessively arduous and costly as a result of the extensive, occupant-oriented instrumentation requirements of each NCHRP test series. During testing, the production model test vehicle or its instrumentation may be damaged, requiring costly repair or replacement. Importantly, failure of a trial barrier configuration in any one aspect of a test dictates repeating the entire, costly series of tests at a later date with a redesigned product to gain acceptance for a particular level of service. In its initial stages of development, a trial barrier system design might first seek to ensure that adequate structural capacity is achieved for withstanding a vehicle impact, as a structurally inadequate barrier is unlikely to prevent excessive occupant risk or to redirect a vehicle properly. Proper assessment of structural adequacy does require actual impact testing, as it is otherwise difficult to fully ascertain barrier response to the complex dynamic loading applied by an impacting vehicle. Nevertheless, proceeding directly to full-scale, fully instrumented impact testing with an early prototype barrier design usually is uneconomical. As such, an intermediate, simplified impact testing procedure that assesses a prototype barrier system's dynamic structural response at less expense would be of significant benefit to the product development process.

Objective

The objective of this study was to develop and implement a simplified, yet reliable impact test for assessing structural adequacy of prototype highway traffic barrier systems at minimal cost. Previous research at Colorado State University pursued similar objectives by investigating the load-displacement behavior of bridge guardrails under static point loading, and on impact of a pendulum-mounted concrete mass (5,6,7,8). The test developed under this study sought a closer approximation of the NCHRP test conditions by using a rolling test vehicle. By impacting a trial barrier system with a wheeled surrogate test vehicle of similar physical properties to those prescribed by NCHRP Report 350, the test described here endeavored to more adequately demonstrate structural response of barriers to impact without the expense of using a production model vehicle. To facilitate comparison of findings from other tests and to establish the reliability of the test, procedures included careful measurement of each of the specific performance parameters identified for evaluation of structural adequacy by the NCHRP standard. The simplified test was not developed to address barrier performance in terms of the occupant risk and vehicle trajectory after impact evaluation criteria. Instead, it was developed to aid in the barrier development process by revealing structural inadequacies prior to full-scale federal testing.

Targeted Specimens

A variety of portable barrier systems designed for use in directing traffic in road construction areas, public events, and other temporary applications recently have been developed. In general, these temporary barriers consist of lightweight plastic shells that use the dead weight of water or sand fill to resist impact without interconnection to the ground. A number of the portable systems have been designed to function as longitudinal barriers, and perform one of the most common roadway barrier applications. It is the marketing intention of many of these barrier systems' proprietors to create a viable substitute for so-called "Jersey" barriers and other similarly shaped concrete longitudinal barriers that are frequently used to isolate traffic in opposing directions and along roadsides to prevent vehicles from leaving the roadway. The physical characteristics of these concrete longitudinal barriers were originally developed to minimize penetration of out-of-control vehicles while reducing the need for costly and dangerous barrier maintenance in high-accident locations with narrow medians or shoulders (9). Although these concerns continue to dictate concrete barrier fabrication for many permanent applications, heavy concrete barriers are awkward when used in work zones and other temporary traffic control applications that require frequent transport and rearrangement. The lightweight, filled systems, including the system selected for testing in this study, are intended to provide a less cumbersome and cheaper approach for this temporary requirement. Unfortunately, very few of these systems have been crash-tested to date, as their manufacturers typically are small businesses with limited resources to conduct an extensive series of federal crash tests. Nevertheless, many of the untested systems presently are in use on non-federally funded roadways, such that public safety undoubtedly stands to benefit from the availability of a less expensive means of impact testing.

CHAPTER 2

EVALUATION CRITERIA

A key objective for this research was to establish the simplified test as a legitimate and reliable precursor to full-scale testing. This was not to be accomplished by attempting to fully replicate the full-scale tests described by NCHRP Report 350, but instead by drawing a careful comparison of the simplified test's physical parameters to those of the full-scale tests. Thus, the simplified test results would provide a legitimate indication of safe function, and could be used to make reasonable predictions of performance under the federal tests.

As previously mentioned, the simplified test was intended only to evaluate the structural adequacy of the test specimen, such that comparison to the federal standard was only to be drawn in terms of its structural adequacy criteria. This dictated characterization of test results in terms of the structural response parameters identified in NCHRP Report 350, as well as qualifying the severity of the impact imparted by the simplified test vehicle in terms of that report's specified "Impact Severity" levels. The following seeks to briefly illustrate these NCHRP criteria to provide the basis for later discussion of test procedures and results.

Test Levels

NCHRP Report 350 has established a hierarchy of test levels to permit testing and certification of safety features appropriate to the varying levels of service encountered on roadways. For a given type of test, the various test levels are differentiated by kinetic energy of the impact, termed in the federal standard as "Impact Severity":

$$IS = \tfrac{1}{2}\, m(v \sin q)^2 \qquad (2.1)$$

where m is the mass of the vehicle, v is the velocity of the vehicle at impact, and q is the angle between the longitudinal axis of the impacting vehicle and that of the barrier specimen.

For longitudinal barriers, six different test levels are prescribed in an effort to encompass the wide range of uses for this barrier type. Of these six levels, the lower three seek to model typical conditions on streets, collectors, and arterials by utilizing passenger vehicles and light trucks, which compose a majority of the traffic volume these low service level roadways encounter. Vehicle impact speeds generated for the lower three test levels range from 50 to 100 kilometers per hour (31 to 62 miles per hour), simulating maximum speeds typically encountered on lower level of service roadways. Test levels four through six are conceived for testing specimens intended for highway service, and therefore utilize not only the passenger vehicle and light truck, but also the heavy trucks that comprise a significant portion of highway traffic. Impact velocities for these tests range from 80 to 100 kilometers per hour (50 to 62 miles per hour), appropriate for highway levels of service. While the appropriate test level performance for a particular barrier application is left up to the using agency, test level three is cited by NCHRP Report 350 as usually qualifying barriers "for a wide range of high-speed arterial highways," and is identified as the highest test level typically assessed for temporary longitudinal barriers such as those evaluated in this report (3).

Evaluation Criteria

Regardless of the test level performed, the structural adequacy evaluation criteria set forth by NCHRP Report 350 are identical for a given safety feature type. Whether they are to be used on highways or on rural streets, longitudinal barriers are deemed structurally adequate for a given test level as long as they successfully "contain and redirect" the test vehicle traveling at the prescribed speed in such a way that the vehicle does not "penetrate, underride, or override the installation, although controlled lateral deflection of the test article is acceptable" (3). Having no corresponding quantitative limits, these criteria appear to be rather indefinite in light of the intention to explicitly approve or disapprove a barrier system for a particular level of service. The authors of NCHRP Report 350 indicate, however, that this apparent ambiguity is intended to place some of the burden of judgement on the using agency, which will have the best sense of acceptable performance limits for its particular application. Special note of this judgement sharing is made in NCHRP Report 350 with regard to portable longitudinal barriers such as those motivating the study described herein. With these barriers especially, a quantified lateral deflection may indicate acceptably safe performance in some applications and unsafe performance in others.

Evaluation Parameters

NCHRP Report 350 recommends measurement and documentation of a series of key test parameters for use in assessment of the three major performance criteria and for comparison of findings with those from other tests. In general, these parameters include vehicle mass, vehicle impact speed, impact angle, impact point on the vehicle and on the test article, dynamic deformation of the test article, permanent displacement of the test article, exit speed and angle of the test vehicle, vehicular accelerations, and three-dimensional response of the vehicle. For the simplified test conducted here, only the parameters pertaining to structural adequacy were measured. The parameters pertinent to assessing structural adequacy are those that are needed to determine severity of the impact, and those that measure how well the vehicle is contained in terms of penetration, underriding, or overriding on impact. Included are vehicle mass, impact speed, impact angle, impact point on the vehicle and test article, dynamic test article deformation, and permanent test article displacement. All other test parameters described in Report 350 pertain primarily to the occupant risk and post-impact vehicular trajectory criteria that were deemed beyond the scope of the simplified test.

In addition to parametric documentation of the barrier's structural response, a qualitative description of impact behavior also is identified in Report 350 as critical to assessment of performance. Indeed, comprehension of barrier function on the part of potential using agencies is not readily obtained by analysis of a few specific numbers; rather, a detailed description of vehicle-barrier interaction during impact is necessary for adequate prediction of safe performance. Such a description may reveal a manner of performance that is unacceptable for certain applications, or in the case of the simplified test developed here, it may indicate a deficient behavior that may be magnified during impact of an actual, production model vehicle. Thus, it is clearly important that the simplified test configuration include adequate means of recording the impact event for later analysis of structural behavior.

CHAPTER 3

TEST CONFIGURATION

Approaches Considered

In the initial stages of this research, three general test configurations were considered for generating an impact load on a barrier specimen. These approaches were conceived as a classroom exercise. The primary criteria for students developing test concepts were to minimize costs associated with initial fabrication and with execution of the test, while creating a reasonably realistic impact condition. To reduce initial costs, each option considered was to use a concrete block that had been cast for use in the pendulum impact testing previously accomplished at Colorado State University.

The first of these options was to develop a pendulum-type test similar to that used previously for guardrail testing. To limit encroachment on other laboratory activities, it was necessary to modify one of the load frames in the laboratory to accommodate the pendulum, rather than attaching the pendulum to the large load frame as done previously, or attaching the pendulum to the building's roof structure. The latter alternative would not only have usurped most of the laboratory space, but would have required safety analyses for approval. The conceptual design for the pendulum frame is shown in Figure 3.1a. Advantages of the pendulum approach included its independence of weather conditions, its easily controlled impact speed, and the ability to achieve a relatively horizontal alignment of the mass at the instant of impact, as typically is encountered with an impacting vehicle. Unfortunately, the mass would of course swing unrealistically into and out of the horizontal plane before and after impact, and the velocity of the mass was limited by the height of the structure to which it was to be mounted.

The second option considered was to mount the concrete block to a tall vertical rail that curved to the horizontal alignment at the bottom, again utilizing the acceleration of gravity to generate impact speed (Figure 3.1b). This option was dismissed because the funds needed for the material and fabrication costs associated with the tower structure were not available. Also unfavorable was the difficulty anticipated with safely controlling travel of the concrete block beyond the end of the rail.

a. b.

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Figure 3.1: a. Conceptual modification to load frame for pendulum testing. b. Conceptual design of tower and rail structure.

The test configuration chosen for the simplified test was to roll a wheeled cart carrying the concrete mass down a steeply inclined hydraulic flume at Colorado State University's Engineering Research Center. This option represented the most realistic test approach, as it involved use of a four-wheeled surrogate vehicle whose rolling motion into the barrier specimen and away from it on impact was expected to better simulate the movement and response of an actual vehicle. The surrogate vehicle also represented an opportunity for future improvement of the test, in that modifications to the originally developed vehicle frame could be later made to improve the extent to which it modeled an actual vehicle. The use of the flume as a track for the vehicle also was expected to permit generation of much higher impact speeds than were likely obtainable with the other test options. Just as important as the accurate simulation inherent with the surrogate vehicle was the minimal cost foreseen for initial construction and for operating the test once it was built. Very little modification to the existing flume structure was necessary to convert it to a track for the surrogate vehicle, even such that its originally intended function would not be hindered.

Description of the Flume

The hydraulic flume modified to serve as a track for the surrogate impact testing vehicle may be generally described as a 110-foot long, five-foot wide concrete channel inclined at 25 degrees from horizontal (roughly a 1:2 slope). The dimensions of the enclosed base at the foot of the inclined channel are roughly 10 feet by 19 feet. The north concrete wall at the base of the flume incorporates two three-feet wide by four-feet tall wide gates, whose presence effectively lengthens the available area for placement of longitudinal barrier specimens by approximately 10 feet. A plan view of the flume is shown in Figure 3.2.

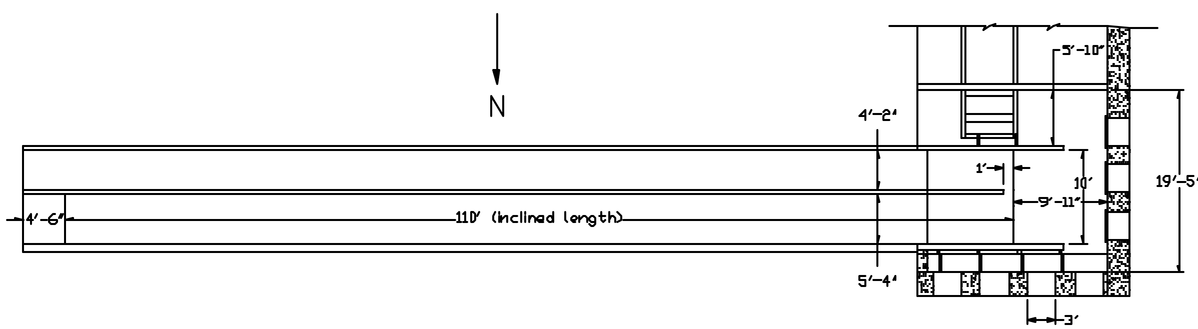
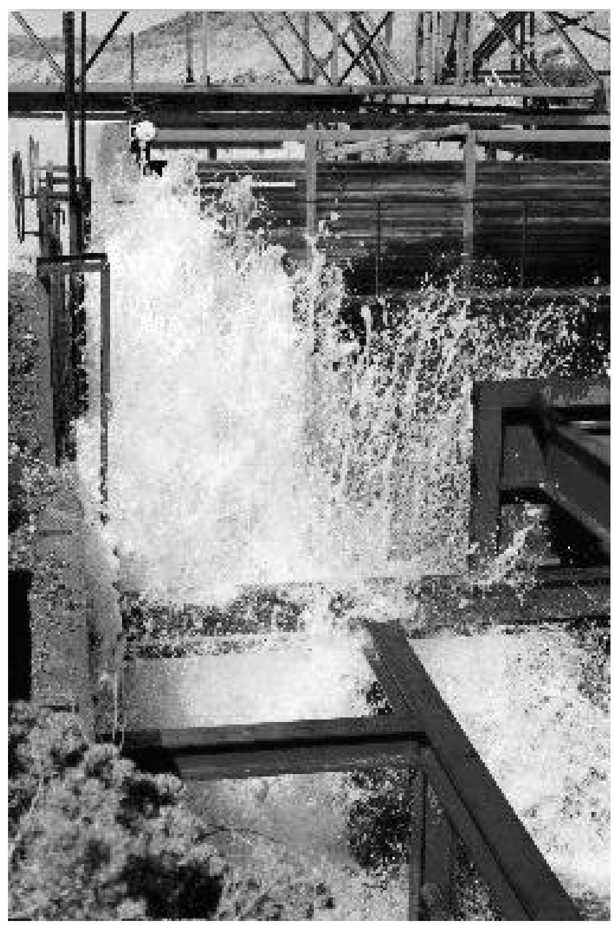


Figure 3.2: Hydraulic flume, plan view with general dimensions.

In its normal configuration, the flume structure actually consists of two separate channels: one on the south side, in which the hydraulic testing is actually performed, and another on the north side, which gives worker access to the flume while providing a foundation for lateral bracing that supports the adjacent flume wall during testing. The vehicle track for the simplified impact test was installed on the north side. Photographs of the flume during hydraulic testing are shown in Figure 3.3.

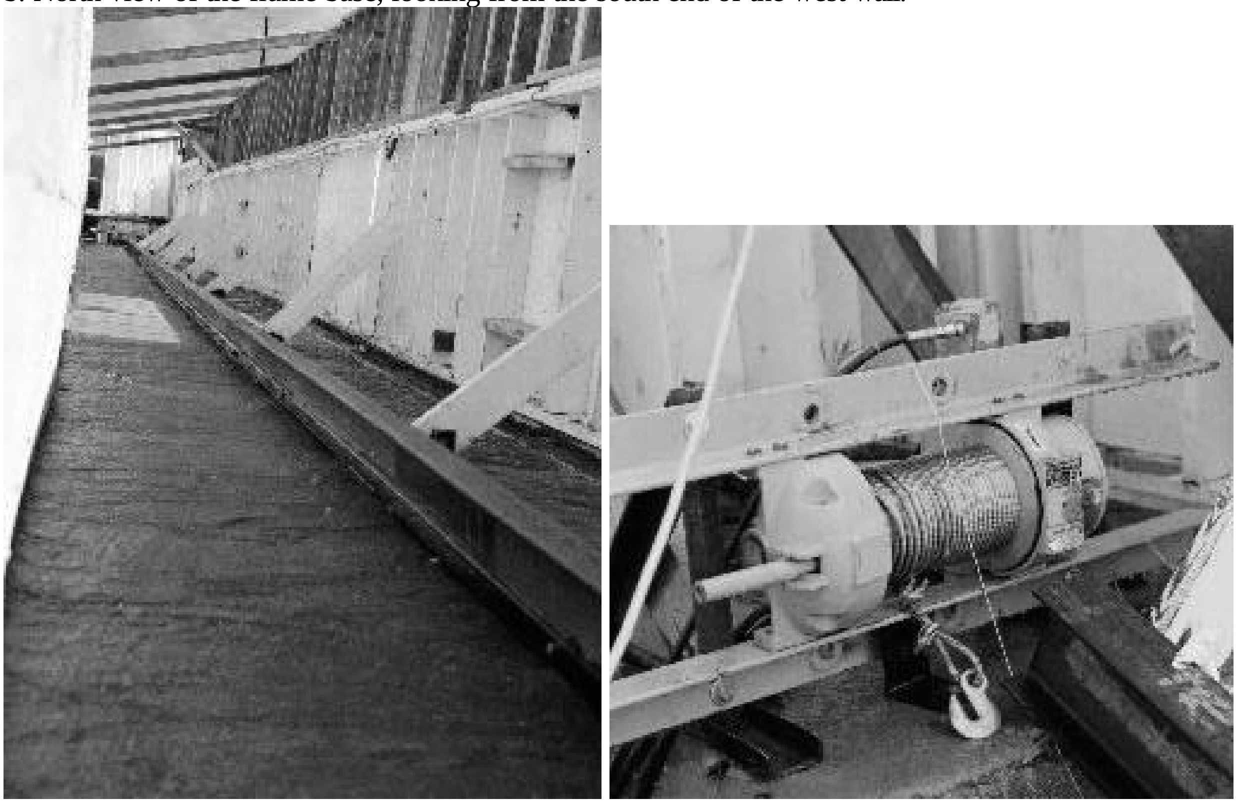
As previously mentioned, modifications to the flume structure were minimal and did not significantly impact performance of hydraulic testing during the overall timeframe of this research. Modifications accomplished include removal of a 10-foot segment from each of the two steel flume walls at the base of the flume to permit barrier placement closer to the end of the incline, temporary removal of the wooden lateral braces supporting the center flume wall, and installation of a W6 x 12 rail on which the test vehicle would ride. This rail was installed over the length of the concrete floor, stopping 10 feet from the bottom to permit free vehicle travel prior to impact. A winch also was installed at the top of the flume to hoist the test vehicle into position. The rail and winch installed in the flume are shown in Figure 3.4.

As it was critical to avoid damage to the flume during impact testing, minor modifications also were made to protect the base structure from the impacting vehicle. These included installation of a safety cable above the point of impact to prevent vehicle overturning, and stacking of several wooden timbers in front of the west wall to prevent damage to the outfall gates.



a. b.

Figure 3.3: Flume during typical hydraulic testing: a. East view of the flume, looking from the west wall. b. North view of the flume base, looking from the south end of the west wall.



a. b.

Figure 3.4: a. Rail installed for guidance of test vehicle. b. Winch installed at top of flume for hoisting test vehicle into place.

Use of the hydraulic flume with the dimensions and general configuration just described presented a number of limitations for the test that were accepted at the outset. The most significant limitation was the abrupt transition along the test vehicle path from a 25-degree incline to a horizontal surface at the base of the flume. This transition would result in the vehicle impacting the barrier at an angle, rather than horizontally, such that the force of impact would have a vertical component. This limitation could have been addressed by installation of a curved platform starting near the base of the flume, but was not feasible due to the second major limitation, which was the width of the flume available for placement of the barrier specimens. The longitudinal barriers selected for testing, which are described later in more detail, were designed to function as a unit when connected together in a series. As such, placement of at least three barriers was desired, which could only be accomplished if the first 3' x 4' gate in the north concrete wall was opened and used. Placement of a barrier through the gate prevented changing the elevation of impact with a curved platform, as it would have resulted in an inaccurate impact point of the vehicle on the barrier specimen. The need to place one of three test specimens through the gate also dictated an orthogonal orientation of the test specimens to the path of the test vehicle. While this represents a significant deviation from the NCHRP test procedures for longitudinal barriers, which involve impact angles of 20 to 25 degrees, it was seen as acceptable in light of the intention to assess structural adequacy only. The impact angle was anticipated to primarily affect the post-impact vehicle trajectory criteria, which was not to be assessed by the simplified test. The primary impact condition to be achieved for assessing structural adequacy is the impact severity prescribed for each test level, which could be obtained regardless of impact angle by varying the test vehicle impact velocity.

Dimensions of the flume also limited the design dimensions of the surrogate test vehicle. The available lateral width in the flume of 64 inches required that the overall width of the test vehicle be somewhat narrower than typical widths of passenger vehicles and light trucks, which generally vary between 64 and 80 inches (9). In addition, the presence of a permanent catwalk above the flume required the test vehicle to be less than 48 inches in height for adequate vertical clearance.

Surrogate Test Vehicle Design Objectives

The validity of the simplified test as a means of predicting structural response of barrier systems to vehicular impact was dictated in large part by the accuracy with which the surrogate test vehicle simulated a production model vehicle. Extensive efforts to model an actual vehicle were contrary to the overall objective of developing a more economical means of impact testing. Nevertheless, many design considerations for the test vehicle that would improve its realism were deemed essential and were attainable in the scope of the project.

While the test specifications in NCHRP Report 350 indicate that no widely accepted methodology has been obtained for the use of a surrogate test vehicle to test highway safety features, the report's authors recognize the potential value of such an approach and thus provide some general guidance for surrogate test vehicle development in the appended commentary. The most important guidance provided is that "the surrogate be configured to model a specific vehicle, as opposed to a generic vehicle, with the stipulation that the vehic le being modeled meet the specifications for production model test vehicles" (3). As previously described, passenger vehicles and light trucks are the test vehicles specified for impact testing at the levels specified for the temporary barriers to be tested herein (test levels 1, 2, and 3). Of these vehicles, NCHRP Report 350 defines a 2000-kilogram pickup truck as the "standard test vehicle," in place of the 4500-lb sedan identified as such in previous specifications, in recognition of the growing popula rity in the United States of sport utility vehicles, in general, and pickup trucks in particular (3). Since the 1993 publication of Report 350, the number of light trucks in use on U.S. highways has steadily increased, from less than 60 million to more than 80 million, according to market data produced by Automotive News (9). This represents approximately 37 percent of the total number of vehicles presently in use in the United States. In recognition of these data and the recommendations of NCHRP Report 350, the surrogate test vehicle for the simplified test was to be designed to model a light truck to the greatest extent possible.

The essential properties of the 2,000-kilogram pickup truck as specified in NCHRP Report 350 are presented in Table 3.1. In addition to these properties, the report also indicates the importance of replicating other properties that strongly influence impact behavior of the test vehicle, such as frontal crush stiffness, weight distribution, tire properties, and suspension properties. The limitations presented by the flume facility and by the intention to utilize the previously cast concrete block for vehicle ballast, as part of the overall pursuit of an economical test procedure, prevented a complete reproduction of these properties. Nevertheless, matching the properties that can be deemed most critical to the assessment of structural adequacy, namely test inertial mass and center of mass location, was not impossible in the constraints of the project.

MASS			DIMENSIONS			
Test Inertial Mass, kg	Center of Mass Location Above Ground, cm	Center of Mass Location Aft of Front Axle, cm	Wheelbase, cm	Front Overhang, cm	Overall length, cm	Track Width, cm
2000 +/- 45	70 +/- 5	140 +/- 15	335 +/- 25	80 +/- 10	535 +/- 25	165 +/- 15

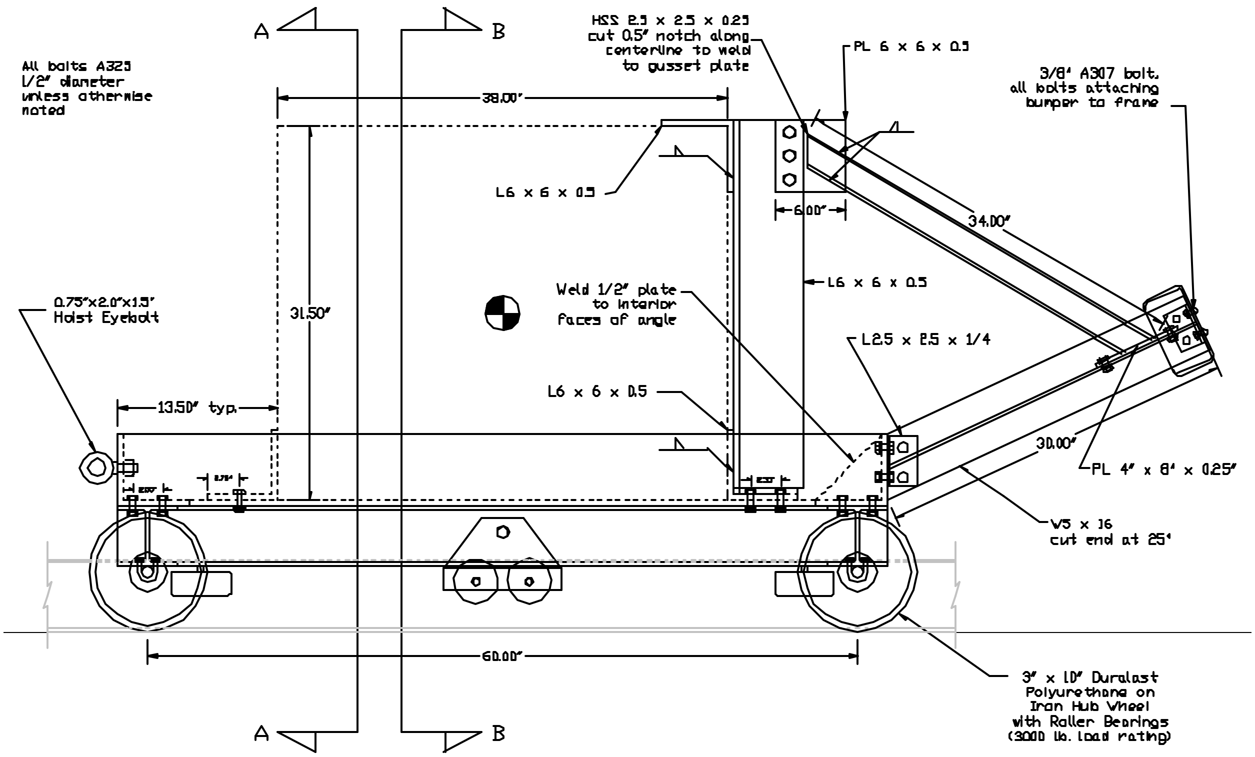
Table 3.1: NCHRP Report 350 recommended properties of the 2000 kg test vehicle.

Surrogate Test Vehicle Design

The surrogate test vehicle design represents a compromise of the intent to match the vehicle's essential properties to those of the 2,000-kilogram vehicle specification and the requirement for the vehicle to function adequately within the constraints of the flume at low cost. The prerequisite to use the previously cast concrete block dictated the general shape of the vehicle's frame. The dimensions of the concrete block were roughly 97 centimeters long by 80 centimeters wide by 80 centimeters tall, although it was considerably out of square on several faces. Assuming a density of 2,400 kilograms per cubic meter (150 pounds per cubic foot), the block was estimated to weigh roughly 1,500 kilograms (3,300 pounds). This would account for 75 percent of the 2,000-kilogram specification, leaving 500 kilograms for the weight of the steel vehicle frame, which was nearly achieved in the design—the vehicle frame, as constructed, weighs approximately 450 kilograms. Although these weights are only estimates, it is likely that the weight of the vehicle as designed fell within the specified 90-kilogram tolerance. Similarly, the center of mass computed for the loaded test vehicle was 65 centimeters, which falls at the lower tolerance specified for the 2,000-kilogram test vehicle.

In keeping with the need for minimal cost, the test vehicle frame was constructed entirely of readily available steel angles, channels, wide flange sections, and hollow tubes, as shown in Figures 3.5 and 3.6. Bolted connections were used for most of the frame to ensure that any parts damaged during a test could be quickly and inexpensively removed and replaced. The primary load-bearing portion of the frame consisted of half-inch plate angles, with six-inch legs to provide restraint to the concrete block.

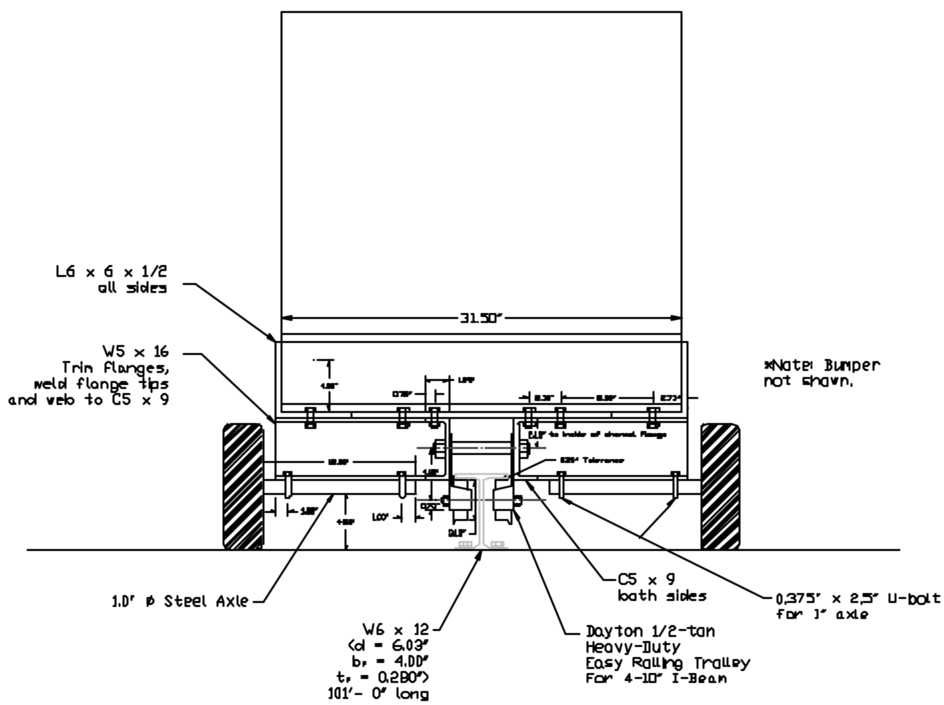
This frame was then mounted to wide-flange sections, to which one-inch axles and inexpensive, 10-inch iron-hub wheels with roller bearings were mounted. The use of 10-inch wheels then dictated dimensions of the guide rail and the wide-flange members that connected the main vehicle frame to the axles. Use of larger wheels, had they been available at reasonable cost, would have dictated using a taller, more expensive wide-flange section for the guide rail than the W6 x 12 that was used.



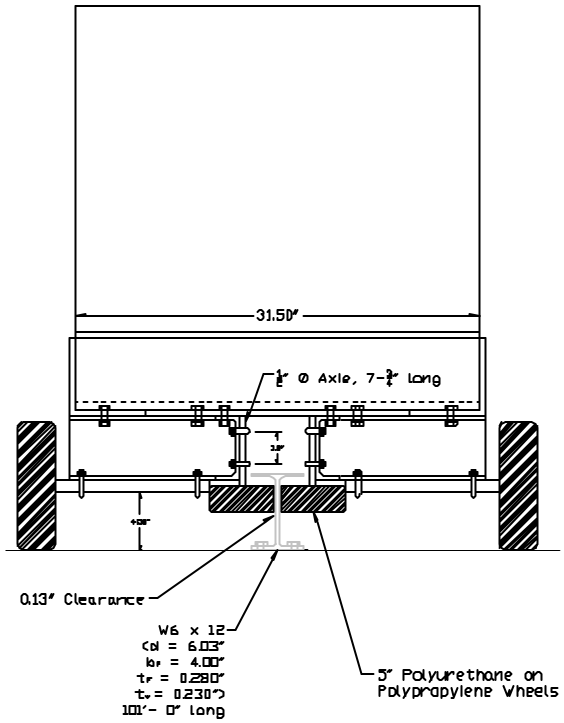
a.

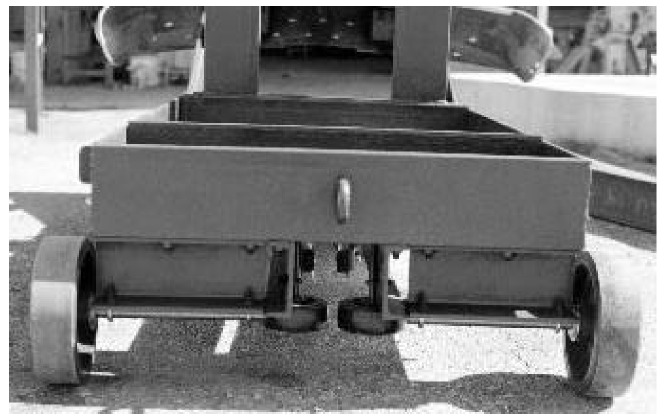
b.

Figure 3.5: a. Side elevation, test vehicle design. b. Cart, as built, with concrete block in upper left corner.



a.





b.

c.

Figure 3.6: a. Section A-A, showing the trolley. b. Section B-B, showing the lateral restraint wheels. c. Rear view of the test vehicle, as fabricated, showing the lateral restraint wheels and the trolley.

The guide rail had to be of a height that permitted alignment of the bottom of its top flange with the wheel treads of a manufactured trolley mounted to the vehicle frame, such that these wheels would ride on the rail's top flange for vehicle guidance. This height was obtained with a W6 x 12 section. Besides the trolley mounted at the vehicle's center, two additional guide wheels also were installed at both ends of the vehicle. These wheels turned on vertical axles and were designed to ride on the web of the rail to provide better lateral guidance, as the trolley provided primarily vertical restraint. Two section views of the test vehicle, which refer to section lines drawn in Figure 3.5, are provided in Figure 3.6 to illustrate the function of the trolley and lateral restraint wheels.

To give the test vehicle a realistic frontal impacting surface, a used, undamaged five-mile-per-hour bumper was purchased and bolted to the test vehicle frame in a manner similar to that used on the original vehicle. The bumper was taken from a 1991 Ford full-size van, which is mounted on a light-truck chassis. To make the bumper fit in the flume, a 20-inch segment was cut from its center, and the two remaining pieces were welded together. The installed bumper is shown in Figure 3.7. The steel frame members, which connected the bumper to the main vehicle frame, were dimensioned in such a way that the bumper would be vertically aligned, in spite of the 25-degree pitch of the flume, and at a realistic height above the ground upon impacting the barrier specimens placed at the flume's base.

A survey of light trucks revealed that the front bumpers on most factory-equipped models are between 18 and 20 inches above the ground at the center. Thus, the frame was designed to align the bumper's center at a height of 18.5 inches above the ground at impact. The frame also was designed to ensure the bumper fully contacted the barrier specimens before the test vehicle's front wheels reached the abrupt change in grade at the end of the flume. Otherwise, the test vehicle would absorb a significant portion of the impact energy before it could be transferred to the barrier specimen. The bumper alignment and wheel position at impact that was achieved with the frame member design is illustrated in Figure 3.8.

Figure 3.7: Ford light truck bumper installed on surrogate test vehicle.

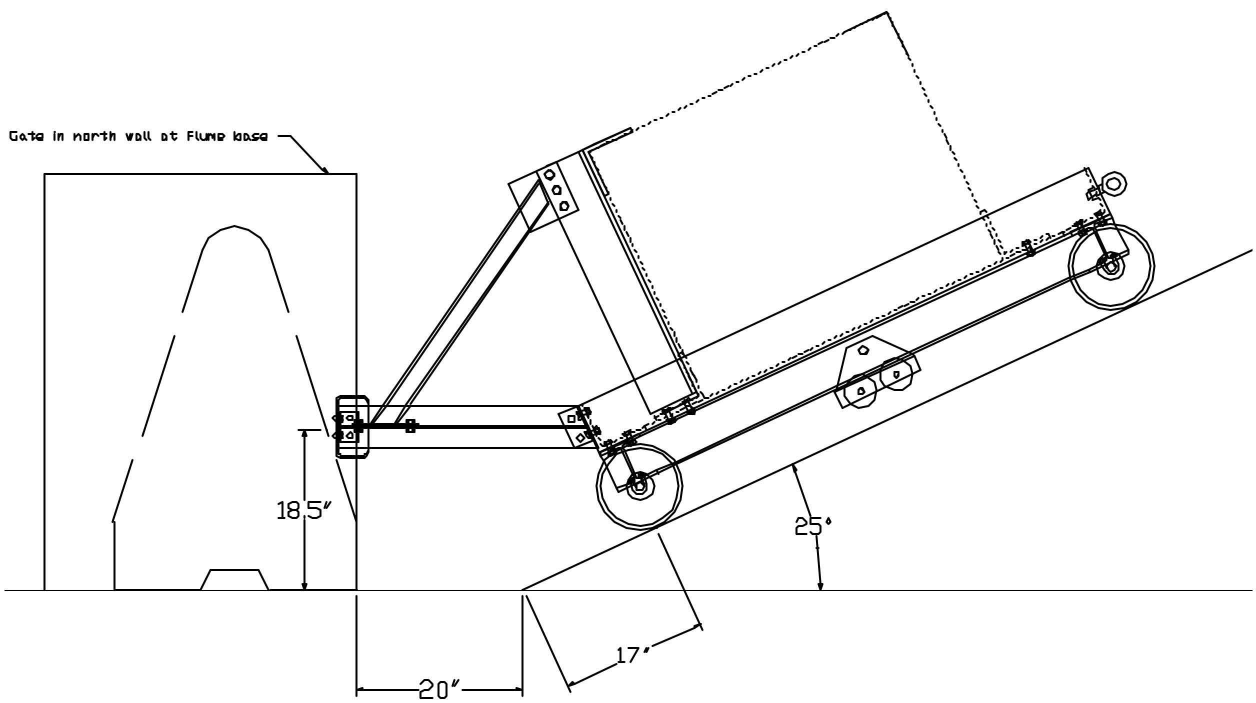


Figure 3.8: Orientation of the cart, barrier, and flume, optimized to provide proper bumper alignment at impact and to ensure impact of the bumper with the barrier prior to the front wheels reaching the bottom of the inclined flume.

The configuration of the bumper frame members was also selected to transfer the force of impact to the vehicle's primary frame members while bracing the concrete block in place, to prevent costly damage to the vehicle during each test. The square tube members, and the bolted and welded connections that comprise the bumper frame, were designed to resist an estimated force of 60,000 pounds. This estimate was obtained for impact conditions expected for test level 3, using the impulse-momentum equation:

$$F\,D\,t = m\,D\,v \qquad (3.1)$$

where F is the impact force, $D\,t$ is the impact duration, m is the test vehicle mass, and $D\,v$ is the change in velocity during the impact. While it is difficult to estimate the impact duration, a value of one-tenth of one second was conservatively selected based on published high-speed photography of federal barrier impact testing (3). Using the 1950-kilogram (4,300-pound) mass and an anticipated maximum test vehicle speed of 30 miles per hour generated the 60,000-pound design load. These calculations and the design of the frame members and connections are provided in Appendix A.

The final details of interest on the surrogate test vehicle frame include four tiedown points attached at the four corners of the frame and the eyebolt attached at its rear. Each tiedown point, which entailed a two-inch square plate with a 1.5-inch hole cut in its center, was positioned to permit strapping the concrete block in position on the test vehicle. The eyebolt was attached to the vehicle as a connection point for the winch cable, and was of adequate diameter to permit connection of a quick-release. The quick-release was to be operated by the pull of an attached rope, which permitted the operator to stand clear of the potential recoil of the winch cable. Figure 3.9 illustrates the connection of the quick release to the test vehicle and winch cable.

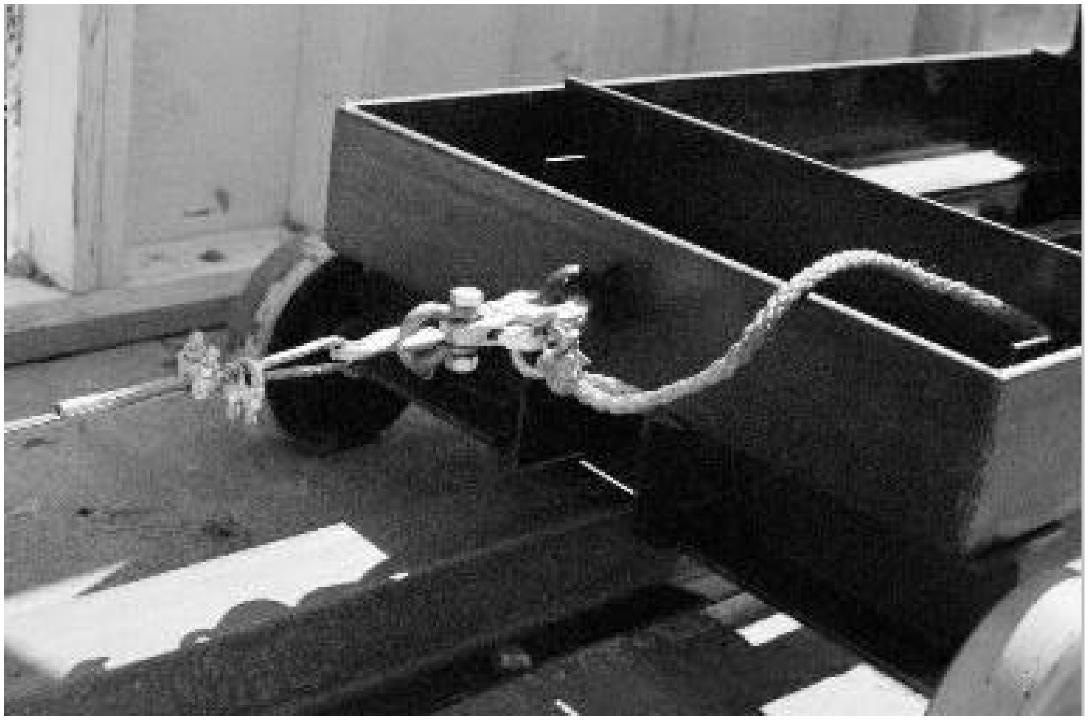


Figure 3.9: Quick-release connecting the winch cable to the surrogate test vehicle.

Test Specimen

Specimens selected for evaluation under the first applications of the simplified test were, as previously introduced, hollow, water-filled, portable longitudinal barriers intended for temporary applications. The physical characteristics of each barrier specimen are summarized in Figure 3.10. In addition to the specimen's general dimensions, certain design aspects that may be considered typical of many barriers of the same category were of significance in terms of the simplified test's configuration. As discussed earlier, the selected test specimens are not specifically designed to function independently, as with other more permanent longitudinal barriers that typically are affixed to the roadway. In the manufacturer's intended roadway application, shown in Figure 3.11, the portable barriers are not connected to the roadway surface, but instead are connected to one another to permit transfer of impact force applied to a single barrier to the entire line of barriers. This interconnection effectively presents to an impacting vehicle a flexible cable whose entire mass and resulting base frictional resistance is involved in the absorption of impact energy.

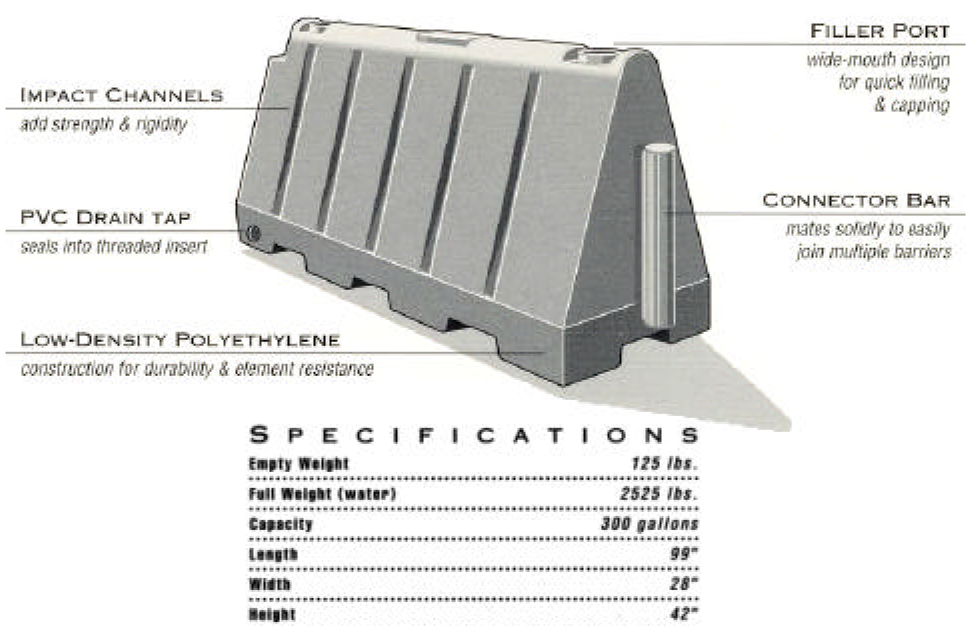


Figure 3.10: Physical characteristics of the barrier specimen.

Figure 3.11: Assembly of an interconnected line of barrier specimens in the field.

To provide a reasonably fair assessment of this barrier system, installation of at least three interconnected barriers at the base of the flume were deemed necessary. This required utilization of additional space created by opening the gate in the flume base's north wall, as previously described. Recognizing that a system of only three barriers still was not fully representative of a typical application, consideration was given to installing a steel cable through the three barriers and connecting its ends to the north and south flume walls. This initially was not seen as entirely unrealistic, as the barrier manufacturer previously had considered strengthening the connectivity of the barriers with a cable. Nevertheless, the decision ultimately was made not to install a steel cable, in light of safety concerns. In terms of the test environment, it was considered possible that the resultant tensile force in the cable, due to the normal impact force, might be in excess of a typical cable's tensile strength, depending on the initial tension in the cable and the angle formed by the normal force and the cable at impact. Without knowledge of the impulse time (Δt in equation 3.1) associated with impact, a dependable calculation of the impact force was not possible in advance of the test. Regardless of the test environment, installing a cable also might present safety concerns in terms of risk to vehicle occupants in the roadway environment.

Impact Severity Generation

Generation of the NCHRP Report 350 specified impact severity for a given test level was to be accomplished by varying impact velocity of the surrogate test vehicle, since the angle of impact and the mass of the vehicle were to be held constant. The specified nominal impact severity values for the six levels of tests on longitudinal barriers using the 2,000-kilogram test vehicle are shown in Table 3.2. The report's authors obtained these values by inputting into Equation 2.1 the 25-degree impact angle and 50, 70, and 100 kilometer-per-hour impact speeds specified for tests with the 2,000-kilogram vehicle. The suggested tolerances indicated were obtained by applying a four kilometer-per-hour impact speed tolerance, and do not account for any vehicle mass or impact angle tolerances (3).

TEST LEVEL	VELOCITY for $\theta=25^o$,	NOMINAL IMPACT SEVERITY, kJ	SUGGESTED TOLERANCE, kJ	
1	50	34.5	-5.3	+5.7
2	70	67.6	-7.5	+7.9
3	100	138.1	-10.8	+11.3
4	100	138.1	-10.8	+11.3
5	100	138.1	-10.8	+11.3
6	100	138.1	-10.8	+11.3

Table 3.2: NCHRP Report 350 Impact Severities for the 2000-kg test vehicle.

The simplified test was configured for an impact angle of 90 degrees, as opposed to the 25-degree impact angle specified in the federal standard. However, since the impact severity as given by equation 2.1 is computed using the normal component of the velocity vector, the impact severity specified for a given test level can still be achieved with the simplified test's 90-degree impact angle by using the normal component of the specified velocity, as shown in Figure 3.12.

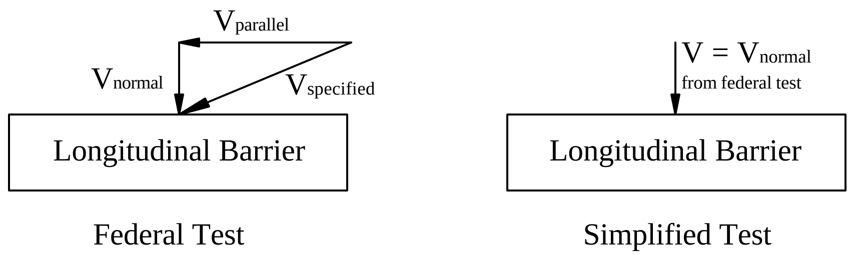


Figure 3.12: Use of the normal component of the federal test's specified velocity.

To account for the reduced mass of the surrogate test vehicle as well, the velocity required to generate a given impact severity for the simplified test configuration is obtained by equating the specified impact severity with the kinetic energy resulting from the 1,950-kilogram surrogate test vehicle impacting at a 90-degree angle to the test specimen, as follows:

$$IS_{specified} = \frac{(1950kg)(v \cdot \sin(90^\circ))^2}{2} \tag{3.2}$$

The required velocity is then given as:

$$v_{required} = \sqrt{\frac{IS_{specified}}{975kg}} \tag{3.3}$$

This velocity was to be achieved by varying the height at which the test vehicle is released in the flume. The height at which the vehicle needed to be released to achieve the required velocity was determined by equating potential energy of the test vehicle at the release point with kinetic energy at the impact point. A portion of the energy is lost to friction, as the test vehicle rolls down the hill, but is considered to be negligible. Equating potential and kinetic energies and neglecting friction gives

$$m\,g\,h = ½\,m\,v^2 \tag{3.4}$$

where g is the acceleration of gravity and h is the vertical drop from the release point to the point of impact. Rearranging yields the following expression for the required vehicle release height in the flume:

$$h_{required} = \frac{v^2}{2g} \tag{3.5}$$

Equations 3.3 and 3.5 were used to generate the release heights required to generate the impact severities associated with NCHRP Report 350 test levels 1, 2, and 3. These are presented in Table 3.3, along with corresponding lengths of travel along the 25-degree incline of the flume ($L_{required}$), which were easier to measure during testing.

NCHRP Test Level	Impact Severity, kJ	$v_{required}$ for m = 1950 kg, km/h (mph)	$h_{required}$, m	$L_{required}$ (distance along incline), m
1	34.5	21.41 (13.30)	1.8	4.27
2	67.6	29.98 (18.63)	3.53	8.36
3	138.1	42.84 (26.62)	7.22	17.08

Table 3.3: Calculated test vehicle release locations in the flume for test levels 1, 2, and 3.

Test Documentation

For the simplified test to serve adequately in the assessment of prototype traffic barrier systems, careful documentation of test procedures was essential. This included adequate means of recording key evaluation parameters previously described as pertinent to structural adequacy evaluation, such as impact speed, dynamic test article deformation, and permanent test article deflection. In addition, sufficient means of recording the impact event were necessary to permit later analysis of the barrier specimen's structural behavior and the manner in which the test vehicle was contained by the specimen. NCHRP Report 350 provides acceptable measurement techniques for each of the key test parameters used throughout the tests in specifimens. These are summarized for structural adequacy parameters measured by the simplified impact test in Table 3.4.

Three methods were established for measurement of test vehicle speed at impact in the simplified test. First, a programmable, battery-operated, bicycle-type speedometer was installed on the right rear wheel of the surrogate test vehicle. This instrument functions by counting wheel revolutions per unit of time with a magnet mounted on the wheel, and retains a maximum speed traveled in memory. Radar speed guns also were used, and were situated in a safe position at the top of the flume, looking down along the incline at the back of the test vehicle. Finally, a high-speed camera capable of filming at a rate of 1,000 frames per second was installed above the point of impact, and could be used to determine the travel time of the vehicle between two points separated by a known distance.

Parameter	Acceptable Measurement Technique	Remarks
Impact Speed	Speed Trap High-speed Camera Radar Fifth Wheel	 Minimum film speed of 400 frames/sec
Impact Point on Test Article	Conventional Scales	
Impact Point on Vehicle	Conventional Scales	
Test Article Dynamic Deformation	High-speed Camera Displacement Potentiometers	Minimum film speed of 200 frames/sec
Test Article Permanent Deformation	Conventional Scales Transit	
Test Article Permanent Displacement	Conventional Scales Transit	
General Damage	Visual Inspection	Identify and report significant damage.

Table 3.4: Acceptable measurement techniques identified by NCHRP Report 350.

To provide a frame of reference for documenting parameters related to deflection of the test article, a line was painted on the ground across the full width of the flume base to mark the leading edge of the barriers. The line was given a width of two inches, such that it would be visible when filmed and to give scale to the dynamic deformation experienced by the test specimen.

Besides the high-speed camera filming from overhead, a series of conventional video cameras were situated at various angles to the impact point for documenting the vehicle-specimen impact event. Three conventional video cameras were used. One camera positioned on the flume base west wall was used to film the event from above and behind the barriers, while another positioned on the flume framework directly south of the impact point was used to film profile of the impact. A third camera was positioned at a higher point on the north wall of the flume base and was used to document the travel of the test vehicle in case any unexpected vehicle behavior was encountered prior to impact.

To standardize reporting of key parameters following each run of the simplified test, a data sheet was composed according to NCHRP guidelines. This was expected to provide a better means of data comparison between multiple tests, and to provide a clear means of relating results obtained in the simplified test to the federal test criteria. The data sheet is attached in Appendix B. The test procedure in general also was standardized through a safety alert briefed to all personnel prior to testing, as well as with a standard operating procedure that detailed assigned personnel tasks. These documents also are attached in Appendix B.

CHAPTER 4

TEST PROCEDURES

Trial Run

Objective

The primary objective for the trial run was to verify performance of the surrogate test vehicle in the flume track. This run was accomplished without the concrete block loaded on the test vehicle, as it was anticipated that any difficulties encountered would involve the function of the trolley and lateral restraint wheels mounted to the guide rail, or with the bumper or some other part of the test vehicle frame catching on some part of the flume. The trial run also would permit verification of the speedometer's function.

Procedures

Since only one-quarter of the design surrogate test vehicle weight was to be involved in the impact for the trial run, a single barrier filled to capacity with water (2,525 pounds total weight) was expected to provide adequate resistance. This barrier was placed in the position that was to be used in the first actual test, which was perpendicular to the test vehicle path with the leading edge 20 inches from the end of the inclined track, as shown in Figure 3.8. The barrier's center of mass was aligned with the centerline of the test vehicle path to produce a direct impact. Positioning of the barrier is shown in Figure 4.1.

A moderate test vehicle release height for the trial run was chosen to minimize danger to personnel and the test facility associated with the unknown behavior of the test vehicle, while still confirming the function of the trolley and the lateral restraint wheels. A release height of 3.5 meters was selected, which corresponds to the release height for the loaded vehicle to generate the impact severity of test level 2 in a direct impact (θ = 90 degrees). This release height was obtained by measuring a vehicle travel length of 8.3 meters, or roughly 27 feet, along the inclined flume.

Figure 4.1: Placement of a single test specimen at the base of the flume prior to the trial run.

Results

No significant problems were experienced with the function of the surrogate test vehicle during the trial run. Upon release of the vehicle, the winch cable did not recoil noticeably, and no personnel were endangered. The vehicle's travel was adequately controlled by the trolley and lateral restraint wheels, without any binding or catching on the segment of the track traveled. Due to a one-inch discontinuity in elevation of the track near the bottom where the guide rail was terminated and the concrete flume transitions to a steel plate, the rear lateral restraint wheels came into momentary contact with the top flange and were pried off of their axles. This problem was easily remedied by replacing the plastic washers and thin cotter pins holding the wheels on the axles with steel washers and thicker cotter pins.

A second minor problem encountered was the function of the bicycle speedometer mounted to the test vehicle's right rear wheel. The anticipated speed for the release height was 18.6 miles per hour, but the speedometer only registered a maximum speed of 5.6 miles per hour. It subsequently was determined that the speedometer only registers maximum speeds achieved and maintained for a few seconds. Thus, the speedometer did not serve as a reliable indicator of test vehicle velocity for the actual tests. The remaining two-speed measurement methods, including the radar gun and the high-speed camera, were deemed to be more reliable and were expected to provide a verified impact speed.

The test vehicle impacted the test specimen in the manner intended by the vehicle design, with the bumper striking the barrier at a realistic height of approximately 18 inches above the ground. Perhaps the most important observation drawn from the trial run was the tremendous magnification of force resulting from the test vehicle's motion. Since the test vehicle was not loaded to its design weight, the impact condition was not anticipated to be especially remarkable. The effect of the impact force on the single test specimen, however, was quite impressive. Several gallons of water were spouted through the specimen's top fill hole 10 to 15 feet into the air upon impact, and the 2,500-pound mass was instantly pushed the entire available width across the base of the flume (4.5 feet), as shown in Figure 4.2. These conditions were not fully anticipated, and lead to more careful consideration of the progression of test levels to be pursued in actual testing with the fully loaded test vehicle.

Figure 4.2: Position of the unloaded surrogate test vehicle and single test specimen following the trial run.

First Actual Test

Objective

The objective of the first actual test was to implement simplified test procedures as designed, to assess its acceptability for use in examining structural adequacy of a barrier specimen. Therefore, the most important assessment to be derived from the test was its ability to evaluate structural adequacy parameters relating to vehicle penetration and lateral deflection of the barrier specimen. With this objective in mind, the impact condition achieved and the response of the barrier system were to be observed and evaluated in terms of the degree to which an actual vehicular impact was imitated, with the intent to better understand limitations of the test and the extent to which it could be improved.

Procedures

In light of the impact condition witnessed during the trial run, the impact severity to be generated during the first test was chosen with caution. Unfortunately, weather conditions and the number of barrier specimens available for testing were expected to limit the number of tests that could be accomplished. Two tests using the six barriers provided by the manufacturer were considered feasible before the onset of winter weather conditions. Considering these limitations and the objective of the first test to assess reliability of the test itself, an intermediate impact severity was chosen, as opposed to starting from the lowest impact severity with the intent to test barriers at every test level. Thus, the first test was run to imitate NCHRP test level 2.

To ensure safety for the individuals who were to position test specimens at the base of the flume, the loaded surrogate test vehicle was hoisted partway onto the flume incline and chained in place, as shown in Figure 4.3. Three interconnected barriers were then positioned according to the design test configuration, as shown in Figure 4.4. The right barrier was positioned with approximately 3.5 feet of its width protruding through the gate in the north flume base wall, to permit a direct impact of the test vehicle on the center barrier. In an attempt to provide similar translational restraint to the left barrier as imparted by the concrete gate to the right barrier, a fourth barrier was placed six inches behind the left barrier. Once positioned properly, the barriers were filled to capacity with water, and were photographed in their initial position. After all personnel were clear of the flume base, the test vehicle was hoisted onto the guide rail and then to the 3.53-meter height necessary for development of the 67.6-kilojoule impact severity for test level 2. The test vehicle is shown in Figure 4.5 in its initial position.

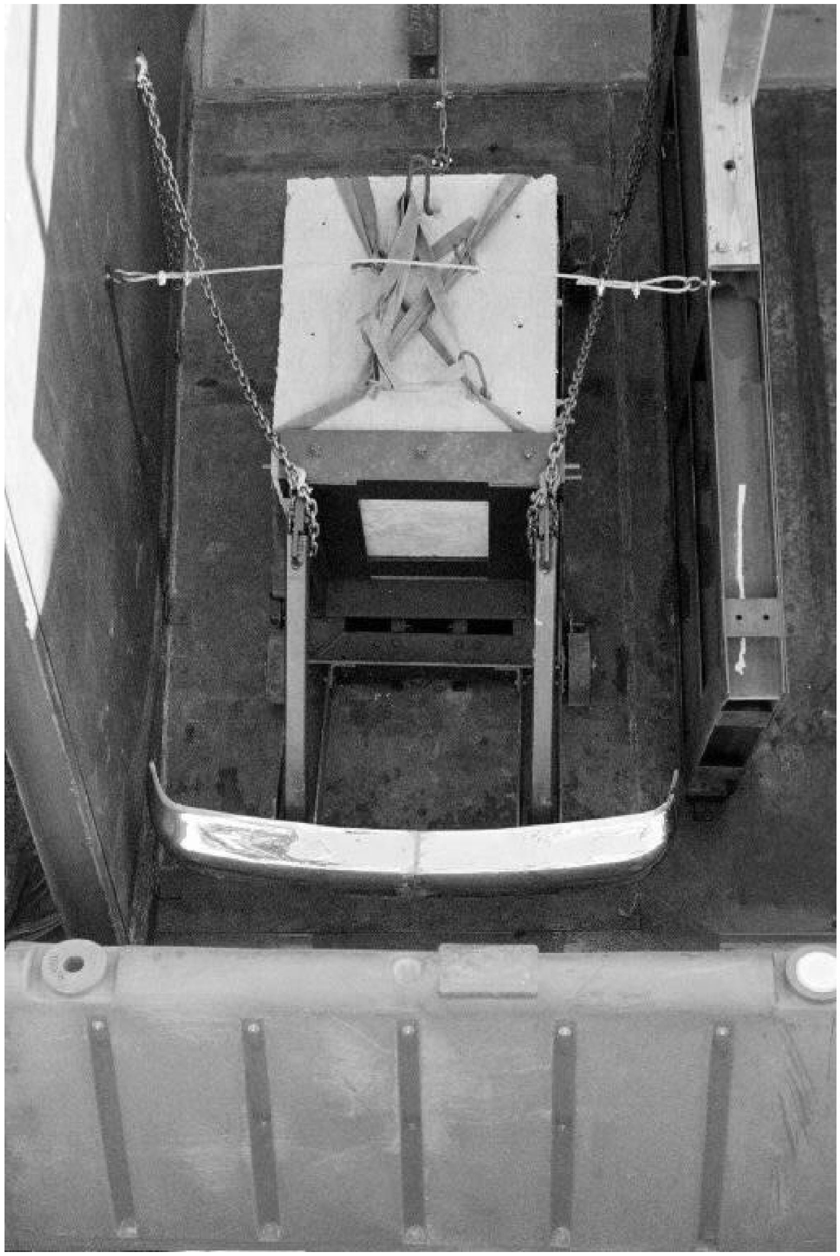
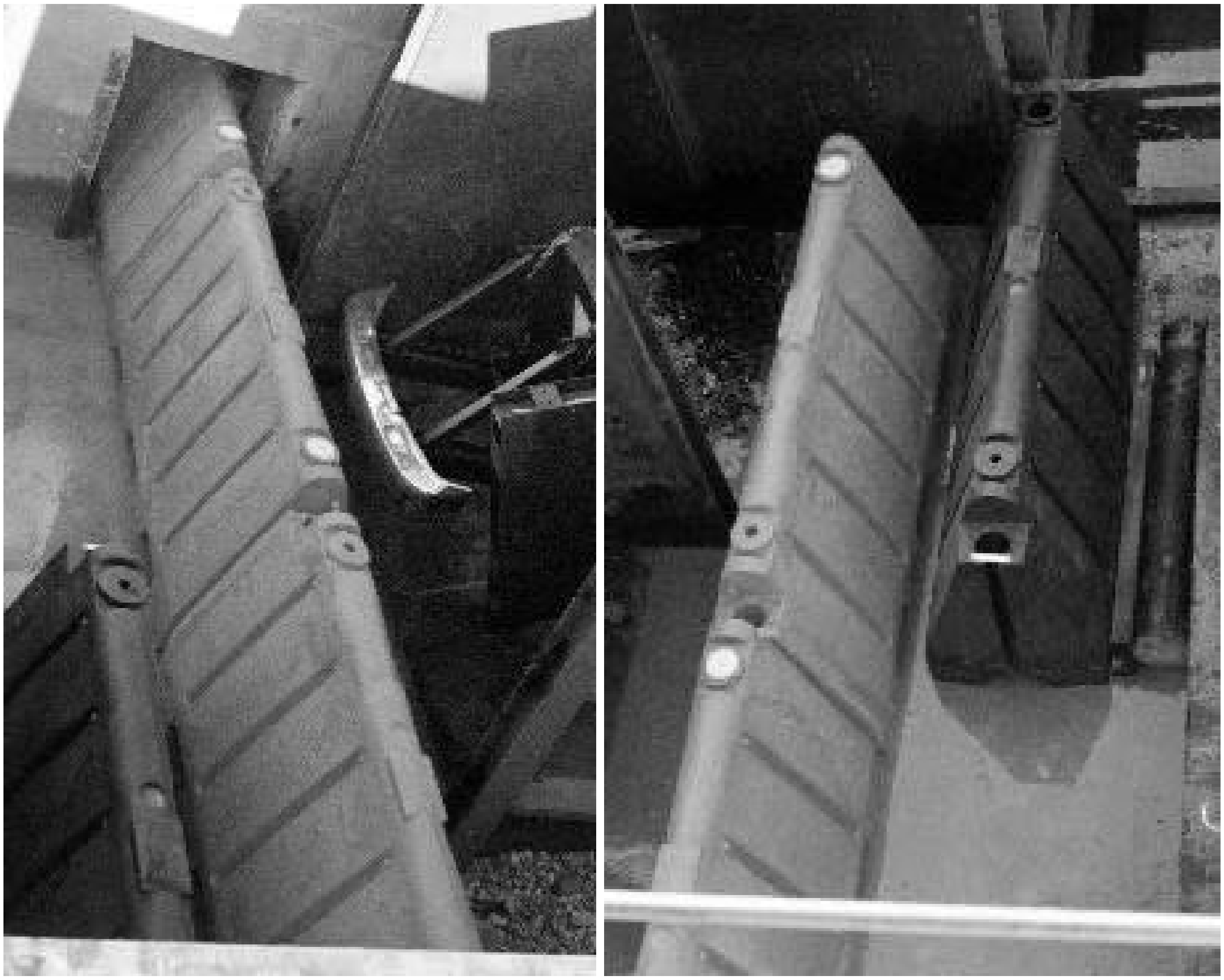


Figure 4.3: Surrogate test vehicle loaded with the concrete block and chained to the flume to permit safe barrier placement. Also visible are the safety cable, tiedown straps, and the end of the guide rail.



a. b.

Figure 4.4: Initial position of test specimens for the first test. a. North view, showing the gate in the north wall. b. South view, showing the position of the fourth barrier.

Figure 4.5: Surrogate test vehicle hoisted to the release height for test level 2.

Results

Once again, the surrogate test vehicle traveled smoothly down the flume and impacted the barrier specimen at the intended location. The radar gun registered an impact speed of 15 miles per hour, while the speed computed from the high-speed camera footage was approximately 18 miles per hour. This difference in results is attributed to calibration error on the radar gun. Using the speed calculated from the high-speed footage results in a computed impact severity of 63.6 kilojoules, which is well within the NCHRP suggested tolerance for test level 2, as given in Table 3.2.

The first test was successful in many respects, as it effectively illustrated the mode of the barrier specimen's structural response and features of the test configuration that were in need of improvement. In accordance with NCHRP reporting procedures, several frames from the contact phase of the impact were extracted from high-speed photography, and are presented in Figure 4.6a and b. Photographs of the barrier specimens and the surrogate test vehicle in their final positions after impact are shown in Figure 4.7.

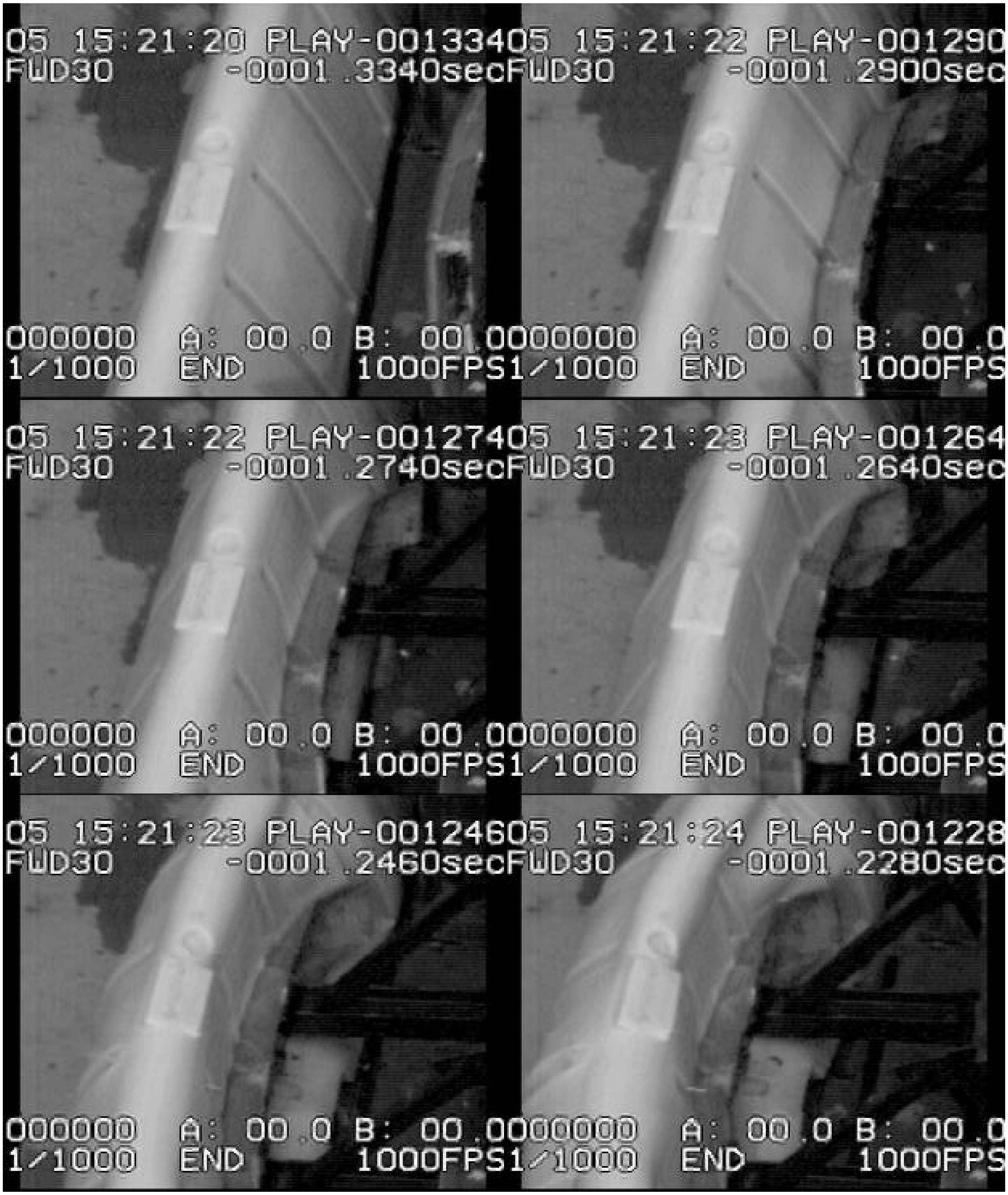


Figure 4.6a: Selected frames from high-speed photography of the impact event in the first test.

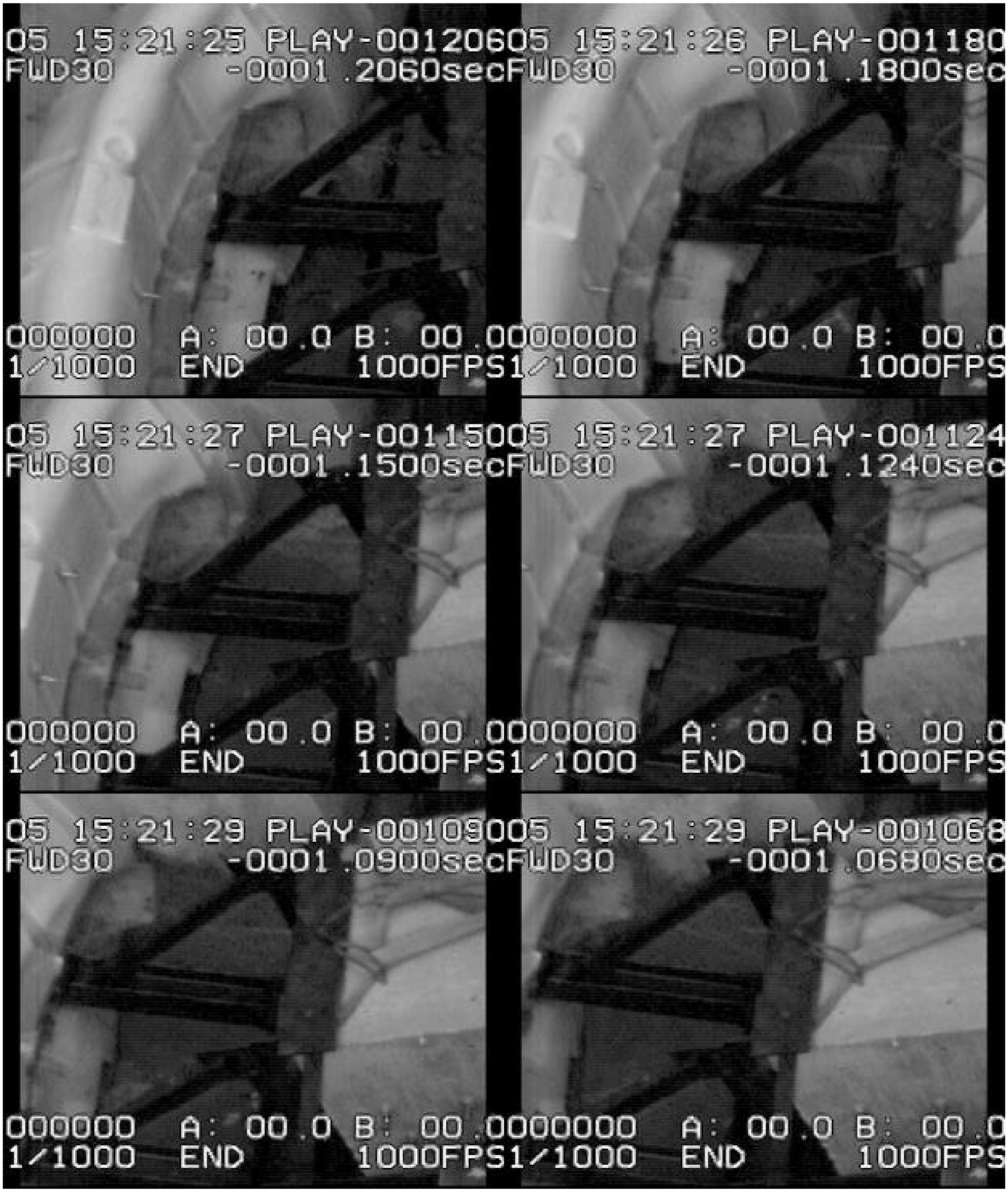


Figure 4.6b: Selected frames from high-speed photography of the impact event in the first test.

a.

b.

Figure 4.7: Deflected position of test specimens and final position of the test vehicle following the first test. a. Overhead view. b. North view, showing tearing of the right barrier's connector bar.

Test Deficiencies Observed

While the simplified test succeeded in providing a preliminary indication of the barrier specimen's structural performance, anticipated limitations of the test configuration were highlighted by the first run. The most important inaccurate test condition witnessed was restraint applied by the gate structure to the right barrier. As shown in Figure 4.7b, the right barrier only was permitted to translate six to eight inches, after which its connector bar was torn from the barrier's main body, due to the shear caused by the continued, unrestrained travel of the center barrier. Restraint applied to the right barrier, and restraint created by placing the fourth barrier behind the left barrier, prevented full mobilization of friction between the end barriers and modeled roadway surface. As a result, these barriers only absorbed a small fraction of the impact energy that they would have absorbed had they been unrestrained.

The ease with which the barriers slid across the flume floor, both in the trial run and the first test, exposed a second inaccuracy in the test configuration, which was the roughness of the modeled roadway surface. While the surfaces of typical asphalt and tined concrete roadways are purposefully rough to provide vehicle skid resistance, the flume base floor is incomparably smooth in finish. This undoubtedly magnified permanent lateral displacement of the barrier specimens on impact, although the extent of this effect is difficult to quantify. The effect of the modeled roadway's smoothness certainly also was magnified by the standing water on its surface at the time of the test, although this condition was deemed to be realistic of potential roadway conditions. It also may be stated that the extensive lateral deflection observed can be attributed in part to smoothness of the bottom surface of test specimens, which provided limited frictional resistance as designed.

The limited distance available for deflection of the barriers also was underscored as a limitation of the test configuration during the first test. The center barrier still was moving at a considerable velocity after traveling the available four feet before contacting the back (west) wall of the flume base, such that the measurable displacement certainly was not representative of what would have occurred had the wall not been present. Although the other limitations just described significantly complicated assessment of permanent displacement in this particular test, it is expected that the limited width of the flume would have prevented accurate measurement of this parameter regardless of the other complications.

Restraint applied to the test specimen also may have been partly responsible for unanticipated damage to the test vehicle experienced during the first test. The webs of the wide-flange sections connecting the main frame to the front and rear wheels were buckled to some extent following the test. It is believed that the front-wheel frame members buckled upon impacting the horizontal surface at the base of the flume. The buckling experienced by the rear wheel members is more difficult to explain, but is suspected to have resulted from the test vehicle rebounding off the restrained barriers and striking the inclined flume. This rebounding was evident only from the high-speed film of the impact event. The buckled rear sub-frame members are shown in Figure 4.8.

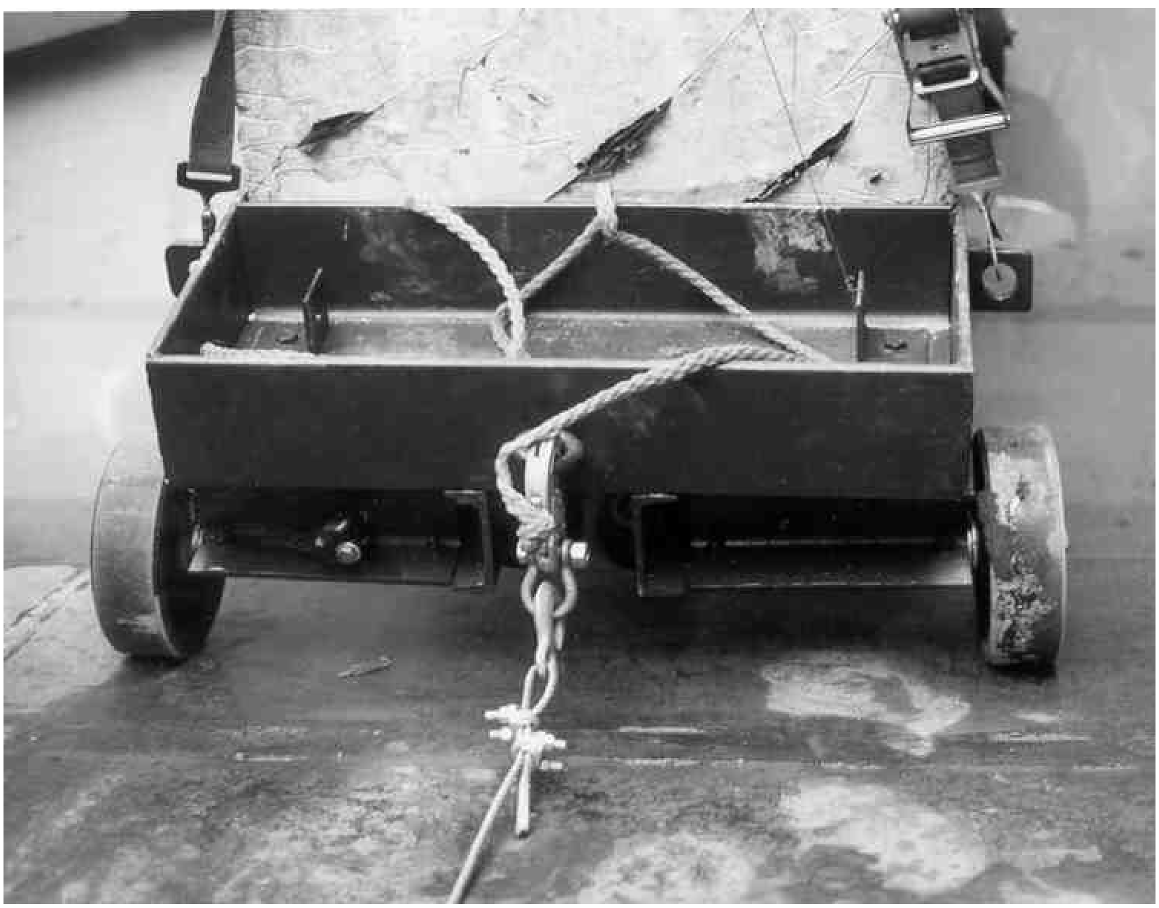


Figure 4.8: Web buckling of the wide-flange sections connecting the test vehicle frame to the axles.

Discussion of Barrier Response

As anticipated, limitations of the test configuration prevented a decisive evaluation of the barrier specimen's structural adequacy in terms of the NCHRP Report 350 criteria. Nevertheless, the test was not without value, as much was learned about how the barrier would respond to a vehicular impact.

The high-speed photography images presented in Figure 4.5 revealed positive performance aspects in terms of the manner in which an actual test vehicle would be contained by the barrier system. When struck by the test vehicle bumper at a realistic height, the test specimen showed no tendency to overturn, indicating that the barrier's height, profile, and resulting mass distribution were appropriately designed. Rather than overturning, the specimen exhibited a large dynamic deformation, perhaps as much as 12 inches at the point of impact. As it deformed, the barrier effectively enveloped the bumper of the test specimen, preventing any overriding or underriding of the test vehicle as might be exhibited with a more rigid barrier system. Importantly, the deformation exhibited was primarily elastic, in that no fracturing of the test specimen occurred until it struck the back wall of the flume base, and no dangerous fragmentation occurred. The permanent deformation measured at the middle of the center barrier was approximately five inches. Some portion of this deformation likely was the result of the secondary impact of the barrier with the west wall of the flume base.

By deforming on impact to the extent that it did, the barrier specimen essentially provided what could be described as a more cushioned impact to the test vehicle. A great deal of the impact energy was absorbed through this dynamic deformation process, such that the vehicle was more slowly decelerated than it would have been had the barrier been more rigid. While this decreased rate of deceleration is associated with the excessive lateral displacements witnessed, it might nevertheless prove to be a positive design feature in terms of vehicle occupant safety.

The total permanent displacement experienced by the center barrier specimen was 50 inches, measured from the line painted at the barrier's leading edge in its initial position. Unfortunately, this value probably is not representative of what would have occurred had the barrier been mounted on a more realistic, rougher roadway surface, and had it not been restrained against movement by the flume gate, the fourth barrier, and ultimately the west wall of the flume base. It is difficult to predict total displacement the barrier would have experienced, or the degree to which the barrier system would have exhibited a "controlled lateral deflection" under actual roadway conditions. On the one hand, the high speed at which the center barrier impacted the west wall, as observed in the film from the conventional cameras, would indicate that considerably more displacement would have occurred had the barrier's motion not been limited by the wall. However, the limited length of the barrier installation provided much less weight and frictional resistance than would have been present in a more typical application. Moreover, the frictional resistance of the two end barriers was not permitted to fully develop in this test's configuration, as just discussed. It is therefore possible that the impacted barrier would exhibit a more acceptable, controlled lateral deflection when installed in its intended configuration with a longer series of unrestrained barriers attached.

Second Actual Test

Objective

The second test performed involved a significant modification to the first test in terms of test specimen configuration. Since the first test was somewhat inconclusive in terms of performance for longitudinal barrier applications, it was the desire of the barrier system manufacturer to evaluate the barrier system for a second intended use, which is that of roadblock or asset protection applications. Following the terrorist events in Oklahoma City in 1995 and those in New York in 2001, a major requirement developed in the United States for easily transportable security barriers to be placed in proximity to important government facilities for protection against vehicle-mounted terrorist attacks. Both the roadblock application and this security application can be considered to have significantly different requirements from those of roadway longitudinal barriers in terms of barrier performance. The most important structural performance parameter for these applications is prevention of vehicle penetration, while there is less concern for the safety of the vehicle and its occupants upon impact.

Procedures

The simplified impact test developed here accommodated a barrier specimen configuration appropriate for modeling a typical roadblock or facility protection type of application. For this test, a roadblock specimen configuration was modeled with two rows of two barriers placed at the bottom of the flume. The barrier manufacturer indicated that this configuration had been used at the end of racetrack straight-aways and in facility protection applications. To explore the effect of an angled impact to the extent possible in the flume test configuration, barriers were angled at approximately eight degrees to the perpendicular position used in the first test. Thus, the impact angle was approximately 82 degrees. A smaller angle of impact was not possible in the constrained space of the test site. Orientation of the barriers for the second test is illustrated in Figure 4.9 and Figure 4.10.

Figure 4.9: Barrier specimen configuration for the second test.

Figure 4.10: Test specimen configuration for the second test. Note that no barrier is positioned within the concrete gate as in the first test.

For the sake of comparing response of the barrier specimen, the same released height utilized in the first test was used in the second test. No adjustment was made for the slight difference in impact severity resulting from the 10-degree difference in impact angle.

It is important to note that weather conditions on the day of the second test were significantly different from those experienced on the day of the first test. Although the ambient temperature at the time of the test was approximately the same during both tests (about 45 degrees Fahrenheit), the overnight temperature experienced by the prepositioned barriers was considerably colder. During the second test, barriers had been exposed to temperatures below 30 degrees Fahrenheit for approximately eight hours prior to the test (overnight) and had not been exposed to direct sunshine prior to execution of the test.

Results

Unfortunately, the high-speed camera used to document the dynamic deformation of the impacted specimen in the first test was not available for use during the second test. Nevertheless, the final condition of the specimen struck by the test vehicle, as shown in Figure 4.11, is somewhat indicative of the difference in response during the second test. During the impact, this barrier was observed to experience sudden fracture when struck by the test vehicle. Several large fragments of the barrier's front sidewall were thrown into the air at onset of the impact event as the test vehicle bumper punched through the surface. Therefore, it is believed that the extent of dynamic lateral displacement observed during the first test was prohibited during the second test. This can be explained primarily by the prevention of lateral movement imparted initially by the rear line of barriers, and also by the rear wall of the flume after only one to two feet of lateral displacement of the entire system. The degree of fracturing witnessed also draws into question the effect of cold temperature on low-density polyethylene material of which the barriers were constructed. It is possible that the material was considerably more brittle during the second test as a result of the colder temperatures.

Variance from the design test configuration in terms of location of the test specimens relative to the end of the inclined flume resulted in much more significant damage to the test vehicle than was experienced in the first test. Since the barriers were angled away from the impacting bumper, considerably less energy was transferred to the barriers before the test vehicle's front wheels reached the abrupt change in grade at the bottom of the flume. As a result, the axle of the front left wheel was fractured in shear at its connection to the wheel, and the web of the wide-flange section connecting this axle to the frame was buckled approximately 60 degrees out of its original plane, as is visible in the lower right corner of Figure 4.11b. Importantly, some of this damage had been initiated in the first test, which had not been repaired prior to the second test. The altered test configuration was nevertheless responsible for considerably more damage to the test vehicle.

a.

b.

Figure 4.11: Final condition of the barrier specimen and test vehicle after the second test.

In spite of the damage experienced by the test specimen and the test vehicle, the second test was successful in terms of illustrating ability of the test specimens as configured to stop an impacting vehicle. It is anticipated that the test vehicle would have been prevented from penetrating the barrier installation even if the rear wall had not been in place to limit the installation's lateral deflection. Had the rear wall of the flume been an important structure that the barriers were intended to protect from an impacting vehicle, the barriers would most likely have proven successful in that respect.

CHAPTER 5

CONCLUSION

A simplified test configuration was developed and pilot tests were implemented to enable a preliminary assessment of the structural adequacy of prototype traffic barrier systems. The objective of creating a more economical, logistically convenient impact test for the benefit of testing barrier systems that might otherwise never be tested was met. In an attempt to make the test an intermediate step toward more rigorous testing according to federal standards, the test was configured to model similar conditions to those used in the more costly federal test procedures. However, site limitations identified at the outset led to some shortcomings in the outcome of the test. Despite these shortcomings, significant progress was made toward realizing a test configuration that is realistic and low-cost.

As a result of the priority to minimize fabrication costs, the test as developed entailed a number of limitations that decreased the accuracy with which a vehicular impact was modeled. Most limitations were inherent in the use of the steep hydraulic flume as the test facility. Limited space at the base of the flume limited the length of installation for the longitudinal barriers to be tested, and the abrupt transition in slope of the flume at the base prevented modeling of a perfectly horizontal vehicle path prior to impact. Also limited was the extent to which an actual production model vehicle was modeled. The surrogate test vehicle was designed to model only the most essential physical properties of a production model light truck, to at least develop the correct impact severity during the test. This was accomplished by correctly modeling the weight of the vehicle and by generating appropriate vehicle impact velocities.

When the test was executed, the effects of its accepted limitations were illustrated. Due to the limited space at the base of the flume, a realistic measurement of the federal structural adequacy parameters was not feasible. Nevertheless, the test did provide some valuable insight into the barrier specimen's mode of structural response, and exposed certain strengths and weaknesses of its design. This insight was gained without significant investment on the part of the barrier's manufacturer, and thereby offered an opportunity for improvement of safety that may otherwise have never been experienced.

RECOMMENDATIONS

Experience gained in development and execution of this test should prove valuable in future efforts to develop an improved test that pursues the same general objectives. The use of a simple surrogate test vehicle to generate specific impact energy was shown to be feasible and economical. It is considered possible that another test developed to use a similar surrogate test vehicle but another, less limited test facility could more closely model the impact conditions specified by the federal standard, while still achieving economical objectives.

To progress toward an improved test configuration, the following recommendations are made:

1. Introduce a curved segment in the test vehicle track just prior to the position of the test specimens such that the test vehicle impacts specimens in the horizontal plane.
2. Utilize an alternate site that does not restrict the installed length of longitudinal barrier test specimens. To more realistically model lateral deflection response of specimens similar to those used in the pilot tests, adequate space for at least 10 interconnected specimens should be available in the alternate site.
3. Incorporate adequate space behind test specimens to permit uninhibited lateral displacement.
4. Configure the site to permit impacting test specimens at the 25-degree angle specified in NCHRP Report 350.
5. Pave the surface to which the test specimens are to be mounted in a manner similar to that encountered on actual roadways.
6. Establish a means of measuring the impulse duration of the impact to quantify force imparted to the test specimen.
7. Instrument the test vehicle with accelerometers, to provide a secondary means of quantifying the impact force.
8. Improve realism of the impact condition and durability of the test vehicle by installing rubber tires and a suspension system on the test vehicle.

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APPENDIX A

Design Calculations for the Surrogate Test Vehicle Frame

Design of Surrogate Test Vehicle Frame Members and Connections

- Estimate Impact Force:

  m = 4300 lb

  Δv = 44 ft/sec (or 30 miles per hour)

  Δt = 0.10 sec (conservative estimate)

$$F = \frac{m(\Delta v)}{?t}$$

F = 58805 lbf

$\boxed{\text{Use F = 60,000 lb}}$

Determine compressive force applied to four frame members:
-Lower frame members are inclined at –25 degrees to the line of force.
-Upper frame members are inclined at 38 degrees to the line of force.

$$\sum F_x = (60000lb)/2 - F_1 * \cos(38) - F_2 * \cos(25) = 0$$
$$\sum F_y = F_1 * \sin(38) - F_2 * \sin(25) = 0$$

$$-0.788F_1 - 0.906F_2 = -30000$$
$$0.616F_1 - 0.423F_2 = 0$$
$$F_1 = 14300lb$$
$$F_2 = 20800lb$$

Apply live load factor = 1.6:

$\boxed{F_1 = 22900 \text{ lb}}$ -Factored compressive force applied to upper square-tube members.

$\boxed{F_2 = 33300 \text{ lb}}$ -Factored compressive force applied to lower W-shape members.

- Check compressive strength of JSS 2.5 x 0.25 tube members

-Choose effective length factor K = 1.0 (conservative- closer to fixed-fixed conditions).

-K*L = 3 feet

AISC LRFD Manual: ϕP_n = 69,300 lb > P_u = 22,900 lb

-Members sized adequately.

- Check compressive strength of W5 x 16 members

-Choose effective length factor K = 1.0

-K*L = 3 feet

AISC LRFD Manual: : ϕP_n = 137,000 lb > P_u = 33,300 lb

-Members sized adequately.

- Check strength of bolted connection

-AISC LRFD Manual: For a single ½" A325 bolt, threads included, ϕr_n = 7000 lb.

-For e_x = 3.0 inches, 3 bolts spaced at 3 inches,

$\phi R_n = C \bullet \phi r_n$
= 1.89 * 7000 lb/bolt * 3 bolts
ϕR_n = 39,700 lb > R_u = 22.900 lb

-Bolt group adequate.

- Check strength of welded connection

-Length of weld, total = 4 * 3.9 inches = 15.6 inches

-Minimum weld thickness for ½" plate: 3/16"

t_e = 0.707 * 0.18875 in t_e = 0.133 in

-Required strength per inch of weld = 22.900 lb/15.6 in
= 1468 lb/in

Actual shear resistance of weld = 0.30 * t_e * $F_{u, rod}$
$F_{u, rod}$ = 70,000 psi

= 2780 lb/in > 1470 lb/in

-Welded connection adequate.

APPENDIX B

1. **Test Data Sheet**
2. **Safety Alert**
3. **Standard Operating Procedure**

BARRIER IMPACT TESTING DATA SHEET

TEST NO:__________

DATE:____________

TIME:___________

TEMPERATURE, °F:___________

WEATHER:_____________________________

FLUME CONDITION:_____________________

VEHICLE MASS- TEST INERTIAL, lb:__________

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:____________________________

BARRIER EMPTY MASS, lb:___________

BARRIER INSTALLATION LENGTH, ft:______________

BARRIER WATER CONTENT, lb:____________

MOUNTING SURFACE AND CONDITION:____

IMPACT SPEED, SPEEDOMETER, mph:____________

IMPACT SPEED, RADAR, mph:_____________

COMPUTED SPEED FROM HIGH-SPEED CAMERA, mph:___________

VEHICLE IMPACT POINT:____

BARRIER IMPACT POINT, inches above ground:___________

MAX. DYNAMIC TEST ARTICLE DEFLECTION, inches:___________

LOCATION OF MAX. DYNAMIC DEFLECTION:_____________________________________

MAX. PERMANENT TEST ARTICLE DEFLECTION, inches:___________

LOCATION OF MAX. PERMANENT DEFLECTION:__________________________________

DECRIBE POST-IMPACT VEHICULAR BEHAVIOR:_________________________________

____

____

DECRIBE VEHICLE DAMAGE:____

____

DESCRIBE TEST ARTICLE DYNAMIC PERFORMANCE:______________________________

____

____

____

____

____

DESCRIBE TEST ARTICLE DAMAGE:____

____

____

FLUME IMPACT TESTING

SAFETY ALERT

1. BE ALERT AT ALL TIMES TO THE POSITION OF THE CART IN THE FLUME. WHEN THE RED FLAG IS FLYING AT THE TOP OF THE FLUME, STAND CLEAR OF THE FLUME. WHEN THE GREEN FLAG IS FLYING, YOU MAY PROCEED CAUTIOUSLY IN THE FLUME AS NECESSARY.

2. ALL PERSONNEL INVOLVED WITH SET-UP OF THE BARRIERS AND CART SHALL WEAR HARDHATS, STEEL-TOED BOOTS, AND GLOVES.

3. ALL PERSONNEL SHALL VACATE THE FLUME AS SOON AS THE CART IS MOUNTED ON THE RAIL AND WINCHING UP THE FLUME COMMENCES.

4. THE CART SHALL BE CHAINED IN PLACE ON THE FLUME WHEN PERSONNEL ARE WORKING AT THE FLUME BASE. DO NOT STEP IN FRONT OF THE CART ONCE THE CHAINS ARE RELEASED AND THE CART STARTS UP THE RAIL.

5. WHEN THE TEST SET-UP IS COMPLETE, DR. GUTKOWSKI WILL CHECK THAT THE FLUME IS CLEAR AT THE BASE. WHEN DEREK GIVES THE “ALL-CLEAR” COMMAND FROM THE TOP OF THE FLUME (OVER RADIO), DR. GUTKOWSKI WILL ENSURE ALL PERSONNEL ARE CLEAR OF THE FLUME BASE, AND RETURN THE “ALL CLEAR” TO DEREK (OVER RADIO).

6. THE PERSON RELEASING THE CART (DEREK) SHALL GIVE ONE FINAL VISUAL CHECK OF THE FLUME, AND SHALL RELEASE THE CART ONLY AFTER THE FLUME IS IDENTIFIED AS CLEAR. A FIVE-COUNT COUNTDOWN SHALL BE GIVEN.

7. SPECTATORS SHALL STAND ONLY IN THE DESIGNATED AREA ON THE EMBANKMENT WEST OF THE FLUME BASE OR ON THE STAIRS ADJACENT TO THE FLUME, AT LEAST 1/3 OF THE WAY UP FROM THE BASE.

8. ONLY JUNIOR AND DEREK SHALL BE PERMITTED IN THE FLUME INITIALLY AFTER THE IMPACT. ONCE MEASUREMENTS HAVE BEEN TAKEN AND THE FLUME IS DEEMED SECURE, PERSONNEL DESIGNATED TO ASSIST WITH BARRIER SET-UP MAY ENTER.

9. REPORT ANY UNSAFE ACTIVITY IMMEDIATELY TO DEREK OR JUNIOR.

PEOPLE AND TASKS FOR BARRIER IMPACT TEST DAY:

BEFORE TEST:	**TASK:**	**NOTES:**
DEREK	ANNOTATE TEST CONDITIONS ON DATA SHEET	
DEREK	CONFIGURE HIGH-SPEED CAMERA AND LIGHT	Need to ensure video transfer works.
RYAN, JENO, COLE, 367 STUDEN	POSITION VIDEO CAMERAS (4)	
DEREK	RESET SPEEDOMETER	
DEREK,RYAN, COLE	WINCH CART UP TO START OF RAIL, THEN CHAIN I PLACE	
DEREK, RYAN, COLE	POSITION BARRIERS ON LINE	
JUNIOR	FILL BARRIERS WITH WATER	
JENO/DR. GUTKOWSKI	PHOTOGRAPH BARRIERS BEFORE TEST	
JENO/DR. GUTKOWSKI	PHOTOGRAPH LOADED TEST VEHICLE BEFORE TES	
DEREK	CHECK RAIL CONDITION, FLUME FREE OF DEBRIS	
DEREK	CHECK ALL PERSONNEL CLEAR OF FLUME, THEN R RED FLAG	
COLE	RUN WINCH UNTIL TEST VEHICLE TO PROPER HEIG FLUME	
JENO/DR. GUTKOWSKI	PHOTOGRAPH TEST VEHICLE IN READY POSITION	
DURING TEST:		
DEREK	GIVE THE "ALL CLEAR" OVER RADIO	
DR. GUTKOWSKI	CHECK THE FLUME BASE IS CLEAR, RETURN "ALL (TO DEREK	
DEREK	COUNTDOWN FOR VEHICLE RELEASE (FIVE-COUNT	
DEREK	RELEASE VEHICLE (PULL ROPE ON QUICK-RELEASE	
COLE	TRIGGER HIGH-SPEED CAMERA *ONE SECOND AFTER IMPACT*	
JENO	VIDEOTAPE: looking up flume from top of west wall (Jeno camera)	
COLE	VIDEOTAPE: looking at barrier from side, base of flume (la camera)	
RYAN	VIDEOTAPE: looking down at barrier from cat-walk (Dr. C camera)	
367 STUDENT	VIDEOTAPE: looking down flume from above cart.	
DR. GUTKOWSKI/JENO	PHOTOGRAPH CART IN MOTION/AT IMPACT	
AFTER TEST:		
DEREK	ANNOTATE TEST RESULTS ON DATA SHEET	
JUNIOR/DEREK	ARIGHT TEST VEHICLE, WINCH ONTO FLUME, CHAI PLACE. ALL OTHERS STAY CLEAR OF FLUME UNTII CLEARED.	
DEREK/RYAN/COLE/JUNIOR	DRAIN, REMOVE DAMAGED BARRIER	
ALL	VACATE FLUME BASE IMMEDIATELY ONCE CART S UP FLUME	