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Validation of a Surrogate Vehicle for Certification Testing of Coupling-Mounted Luminaire Supports

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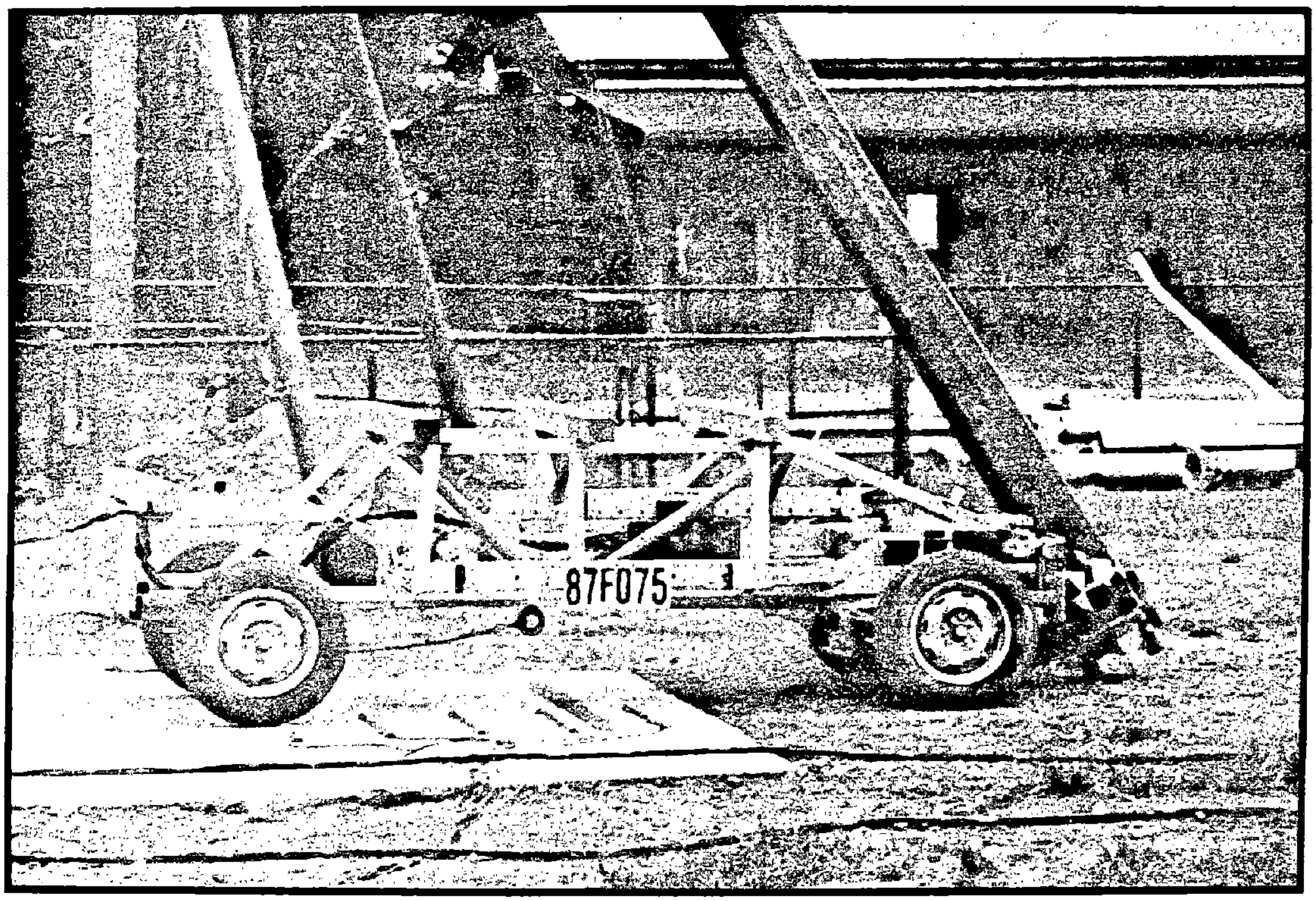
May 1989



U.S. Department of Transportation

Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report documents a study of the reusable "breakaway" bogie vehicle as a substitute for an 1850-pound (839 kg) vehicle. The vehicle used for comparison was a 1979 Volkswagen Rabbit adjusted to the required 1850-pound (839 kg) weight. This study was performed at the Federal Outdoor Impact Laboratory (FOIL) located on the grounds of the Federal Highway Administration's Turner-Fairbank Highway Research Center located in McLean, Virginia.

The objective of this study was to validate the reusable bogie as a surrogate for coupling-mounted sign and luminaire support testing at speeds of 20 mi/h (8.94 m/s) and 60 mi/h (26.8 m/s). This research compared test results from a Volkswagen Rabbit with those of the reusable "breakaway" bogie to determine the level of validation obtained.

R. J. Betsold
Director, Office of Safety
and Traffic Operations
Research and Development

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16. Abstract

This report contains the results of tests performed to validate the FHWA FOIL bogie vehicle as a surrogate for testing coupling-mounted sign and luminaire supports. The tests were performed at the FOIL located in McLean, Virginia. Vehicle tests using 1979 Volkswagen Rabbits were compared with tests using the FHWA FOIL bogie. The comparisons included in this report are used to show that the FOIL bogie is validated as a surrogate vehicle for testing coupling-mounted luminaire supports.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

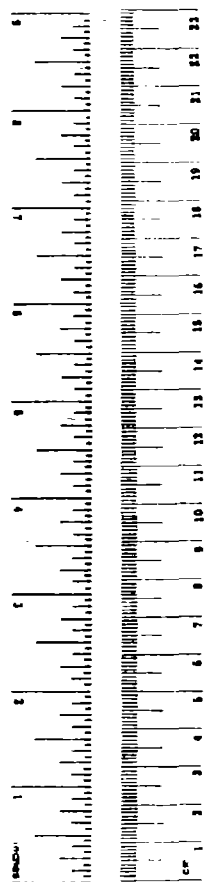
Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

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

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

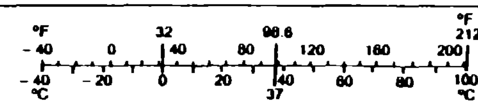
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190 1A.

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1. OBJECTIVE

The objective of this test program was to validate the FOIL bogie as a surrogate vehicle for coupling-mounted luminaire support testing. The bogie vehicle's performance was compared with that of full-scale automobiles at impact speeds of 20 mi/h (8.94 m/s) and 60 mi/h (26.8 m/s). The testing was conducted between December of 1985 and July of 1986. The automobiles used were 1979 Volkswagen Rabbits.

Test data were collected with onboard accelerometers, high-speed film, and speed traps placed in the path of the moving vehicles. The data were analyzed, and the results are presented in this report.

2. TEST VEHICLES

a. Automobiles: All test automobiles were 1979 Volkswagen Rabbit 2-door sedans with gasoline engines and manual transmissions. Each was ballasted to a test weight of 1850 lbs (839.9 kg) and equipped with a data acquisition package consisting of accelerometers and rate gyroscopes. An impact switch recorded the exact time of contact with the test article, while a similar switch triggered a flash unit which was used to synchronize the high-speed film data. A remote braking system was installed in each vehicle. It consisted of an air tank and a cylinder with a remotely triggered electronic valve. The cylinder was attached to the brake pedal. Each vehicle was marked with a test number and distance markers for use in post-test film analysis.

Pre-test preparation for the vehicles included draining all fluids and placing each on the Inertial Measuring Device (IMD) for roll, pitch and yaw moment of inertia measurements. The inertial properties of three vehicles were measured in the as-received condition with the gas tank and batteries in place and all fluids drained. The results are presented in table 1. The gas tanks and batteries were then removed from all vehicles. Each was weighed and ballasted to a uniform weight of 1850 lbs (839.9 kg). Inertial measurements were then repeated. The results of the second set of measurements are presented in table 2.

Table 1. Inertial measurements of 1979 Volkswagen Rabbits, as received.

VEHICLE NO.	WEIGHT (lb)	MOMENTS OF INERTIA ($slug\text{-}ft^2$)			CENTER OF GRAVITY (C.G.) HEIGHT (in)
		ROLL	PITCH	YAW	
6	1864	208	812	904	20.9
7	1750	173	777	867	21.5
8	1835	188	790	880	21.0

Table 2. Inertial measurements of 1979 Volkswagen Rabbits, as ballasted.

VEHICLE NO.	WEIGHT (lb)	MOMENTS OF INERTIA ($slug\text{-}ft^2$)			C.G. HEIGHT (in)
		ROLL	PITCH	YAW	
6	1850	211	814	904	20.9
7	1850	209	768	873	20.2
8	1850	200	836	905	20.4

b. FOIL Bogie: The FOIL bogie was configured to represent an 1850-lb (839.9 kg) 1979 Volkswagen Rabbit 2-door sedan with manual transmission. It was only configured for centered impacts. Its inertial properties were set as closely as possible to the values obtained for the full-scale vehicles. These are presented in table 3.

Table 3. Inertial properties of the FOIL bogie vehicle.

CONFIGURATION	WEIGHT (lb)	MOMENTS OF INERTIA ($slug\text{-}ft^2$)			C.G. HEIGHT (in)
		ROLL	PITCH	YAW	
Centered	1850	190	770	890	20.4

The honeycomb configuration used in the bogie vehicle's nose to model the crush of a 1979 Volkswagen Rabbit is presented in table 4.

Table 4. FOIL bogie honeycomb configuration.

CARTRIDGE	20 mi/h SIZE* (in)	PRESSURE** (psi)	PUNCH*** (in^2)	60 mi/h SIZE* (in)	PRESSURE** (psi)	PUNCH*** (in^2)
1	2-3/4x16x3	130	-	4x16x3	130	-
2	Nose	-	-	4x16x3	230	-
3	Nose	-	-	4x16x3	230	-
4	4x5x2	25	-	Nose	-	-
5	8x8x3	130	21	Nose	-	-
6	8x8x3	230	15	4x5x2	25	-
7	8x8x3	230	6	4x5x3	25	-
8	8x8x3	230	-	8x8x3	230	-
9	8x8x3	400	21	8x8x3	400	21
10	8x8x3	400	12	8x8x3	400	12
11	8x8x3	400	-	8x8x3	400	-
12	8x10x3	400	-	8x10x3	400	-

(*) Width x height x length
(**) Manufacturer's static crush rating
(***) Punch indicates the amount of material effectively removed

1 psi = 2.8 kpa   1 in^2 = 645 mm^2 1 in = 25.4 mm

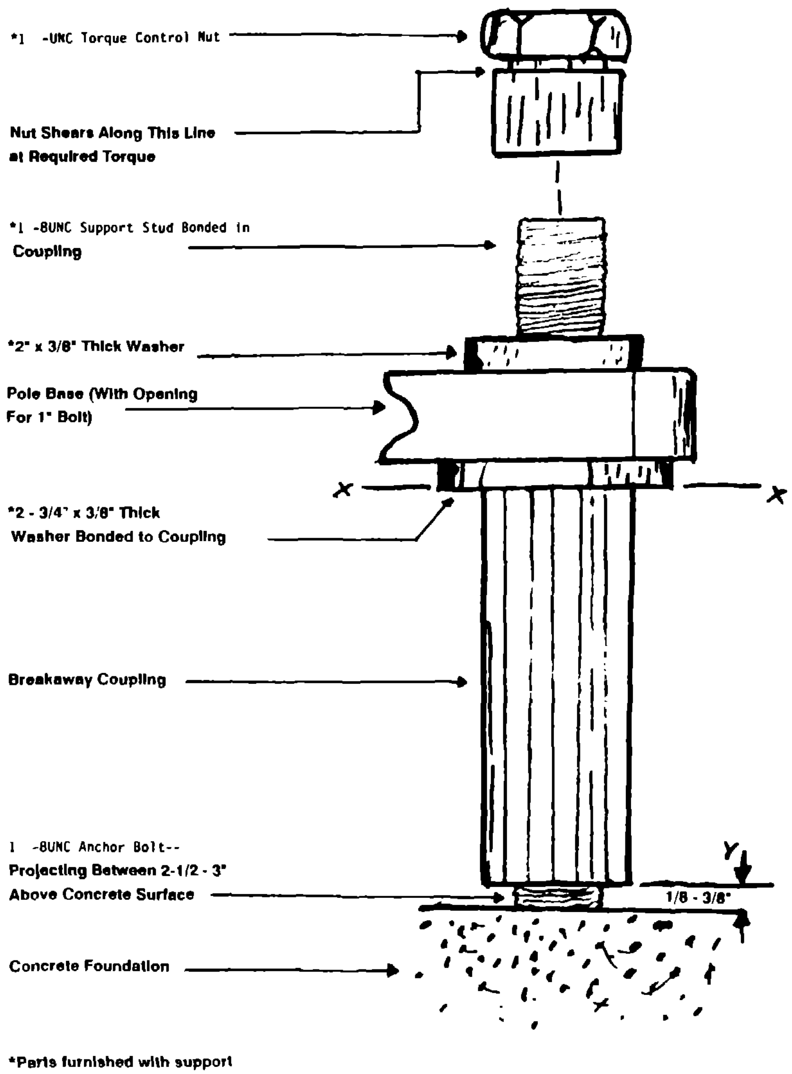
3. TEST HARDWARE

All tests utilized Alcoa couplings with a 40-ft (12.2 m) aluminum pole. Each pole weighed approximately 250 lb (113.5 kg) and was made of two sections. The poles were assembled by sliding one section into the other and inserting a bolt through the sections prior to testing. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. Figure 1 presents a sketch of a coupling and the procedure used to install each coupling.

4. DATA SYSTEMS

a. Speed Traps: Speed traps consisting of two contact ribbon switches placed a known distance apart were used to measure test vehicle speeds just

ALCOA BREAKAWAY SUPPORT #100-1



INSTALLATION INSTRUCTIONS

- MUST BE OBSERVED TO INSURE PROPER PERFORMANCE -

<u>REQUIRED TOOLS</u>

1 - 1-1/2" Socket or box wrench
1 - 1-13/16" Open end wrench

<u>PROCEDURE</u>:

<u>Caution</u>: The support must not be colder than 10°F when installed to insure free flow of grease seal in bottom threads of coupling.

1. Remove plastic plug in bottom of coupling and turn coupling onto anchor bolt. If the bolt threads are damaged or oversize, repair by filing or rethreading. Do not use torque above 40 ft. -lbs. or hammer coupling. The anchor bolt may be lubricated. <u>Do not</u> lubricate top stud of support.

2. Level top of washers on all four couplings in plane xx. Distance Y must be between 1/8 and 3/8 inches. <u>Do not</u> bottom couplings on concrete foundation.

3. Remove nut, paper spacer, and small 2" washer from supports and set pole in place--the support studs should fit freely in base opening without binding and be vertical. With the pole plumbed vertically, the base should sit squarely on all four support washers and not rock. Anchor bolts may be straightened only if coupling is removed -- Do not hammer on stud or coupling. Installation should not proceed unless square fitup of base and washers is obtained.

4. Install 2" O.D. washers and torque control nuts. <u>Do not</u> lubricate stud or nut threads. Holding the couplings to prevent rotation, tighten all four nuts hand tight.

5. When pole is plumb, hold couplings and tighten nuts until separation of hex top occurs. Caution should be used as separation occurs suddenly. This completes the installation of supports.

NOTE: Use only parts packaged with the Alcoa 100-1 support.

Figure 1. Coupling sketch and installation procedure.
(Manufacturer's documentation reproduced)

prior to and approximately 6 ft (1.83 m) after impact. Signals received were recorded on analog tape.

NOTE: To improve the accuracy of measurement in later test programs, multiple contact ribbon switches (5) were used, before and after impact, in lieu of the two switches described above. This improvement was incorporated in September 1986.

b. Electronic Data: For each test, the test vehicles were equipped with the following data acquisition package:

- Vehicle X accelerometer (A_x).
- Vehicle Y accelerometer (A_y).
- Roll rate gyro (Roll).
- Yaw rate gyro (Yaw).
- Impact switch (Impact).

In addition to the above package, the nose of the bogie vehicle was equipped with an accelerometer (N_x). A displacement transducer (D_t) was mounted between the nose and the frame of the bogie vehicle to measure the relative movement between them during test runs.

Table 5 summarizes the data channel assignments and the maximum range of each transducer.

Table 5. Data channel assignments.

TAPE CHANNEL NO.	DATA	MAX. RANGE
1	A_x	50 g's
2	A_y	25 g's
3	N_x	5000 g's
4	D_t	20 in
5	Roll	500 deg/s
6	Yaw	500 deg/s
7	Impact	N/A
8	Pre-Impact speed trap	N/A
9	Post-Impact speed trap	N/A
10	A_x	25 g's

c. Film Coverage: Each test was photographed using three high-speed movie cameras and one real-time movie camera. The high-speed cameras used KODAK 7251, 16 mm, color movie film. Both black and white 35 mm prints and color slides were also taken. The camera configuration and placements are summarized in table 6.

Camera 1 provided a close-up view of the impact zone and was used to determine impact and exit speeds, bogie nose performance, and coupling failure patterns. Camera 2 provided an overall view of the entire event and was also used to obtain pole translation and rotation rates. Camera 3 provided an angled view of the impact zone.

Table 6. Camera setup and placement.

CAMERA NO.	TYPE	SPEED (fps)	LENS	LOCATION
1	locam	500	50 mm	right side close
2	locam	500	12.5 mm	right side overall
3	locam	500	25 mm	right side angled
4	Bolex	24	zoom	documentary

5. TEST PROCEDURES

Each test was conducted in strict accordance with the checklists, safety procedures, and other requirements of the FOIL Operation and Safety Plan.[1]

a. Test Matrix: Six tests were performed in this study. The first three tests used automobiles, one at 20 mi/h (8.94 m/s) and two at 60 mi/h (26.8 m/s), followed by three bogie vehicle tests, one at 20 mi/h (8.94 m/s) and two at 60 mi/h (26.8 m/s). The test matrix is presented in table 7.

b. Impact location: During the developmental stage of the "breakaway" bogie vehicle (in the early 1980's), the prevailing document for testing luminaire supports was NCHRP Report Number 230.[2] This document mandated a 2250-lb (1021.5 kg) vehicle, but strongly recommended the use of an 1800-lb (817.2 kg) vehicle. At this point in time, this was the only document which specified testing using an 1800-lb (817.2 kg) vehicle. It should be noted

Table 7. Test matrix for coupling tests.

TEST NUMBER	VEHICLE	SPEED (mi/h)	IMPACT POINT
86F062	Bogie	20	Centerline
86F056	79 Rabbit	20	Left quarter point
86F061	Bogie	60	Centerline
86F063	Bogie	60	Centerline
86F058	79 Rabbit	60	Left quarter point
86F060	79 Rabbit	60	Left quarter point

that the 1975 American Association of State Highway and Transportation Officials (AASHTO) specification for testing luminaire supports was also in effect at that time, but stipulated that a 2250-lb (1021.5 kg) vehicle was to be used instead of the smaller 1800-lb (817.2 kg) vehicle.[3] Thus, because NCHRP 230 was the only document specifying luminaire support testing procedures using an 1800-lb (817.2 kg) vehicle, the research study which included the development of the "breakaway" bogie focused largely on this document for guidance.

NCHRP 230 mandated that centered, low-speed tests and off-centered, high-speed tests be conducted on luminaire supports. The off-center, high-speed test was mandated to evaluate vehicle yaw and the resultant potential for high-speed rollover (rollover is a failing result due to the high potential for fatality or serious injury). However, in 1985, AASHTO revised the sign and luminaire specifications and mandated an 1800-lb (817.2 kg) vehicle for safety evaluation testing.[4] In addition, the revised specifications did not require high-speed, off-centered tests, only centered. This change was due to the fact that vehicle rollover is a function of run-out surface conditions and these conditions, which have not been rigorously quantified, vary widely between test facilities.

Concurrent with the bogie development, tests were conducted at several frontal impact locations on a 1979 Volkswagen Rabbit.[5] Tests were also conducted on other vehicles in the 1800-lb (817.2 kg) class.[6] The results of this research indicated that, for the then current selection of vehicles available, the 1979 Volkswagen Rabbit impacted at 14 in (0.35 m) to the left of the vehicle's centerline (the left quarter point) provided the best choice of force-deflection characteristics and was the "reasonable worst case" for predicting change in velocity. The crushable honeycomb aluminum model developed represents these force-deflection characteristics. In addition, this model is used for the bogie for all test configurations (centered and off-centered).

Because the off-center location was modeled in the Rabbit, this impact location was used for all automobile tests in this series. For tests with the bogie, the impact location was at the vehicle's centerline. Results of previous testing had shown that no substantial yaw was induced by off-center impacts with either the automobile or the bogie. Because of these results, and the fact that the revised 1985 AASHTO specifications for sign and luminaire supports specify only centered impacts, the tests using the bogie were all conducted on-center.

6. DATA ANALYSIS

Analyses were performed on data gathered in each test using three independent systems: (1) speed traps, (2) high-speed movies, and (3) accelerometers mounted at the vehicle's center of gravity (c.g.).

a. Speed Traps: Velocities before and after impact (i.e., impact and exit) were determined through speed traps, which consisted of two contact switches attached to the runway before and after the impact area. The passage of the vehicle over the contact switches generated an electronic signal, which was recorded on analog tape and input to a computer program that measured the time elapsed between signal pairs. To obtain the respective velocity (impact and exit), this time was subsequently divided into the known distance between the contact switches. The exit velocity was then subtracted from the impact velocity to obtain the change in velocity.

> **NOTE:** To improve data accuracy in later test programs, five contact switches were used, before and after impact, in lieu of the two switches described above. To determine the respective velocity

(impact and exit), a computer generated linear regression curve was subsequently fitted to the five displacement versus time data points, usually with a correlation coefficient of 0.9900. The slope of this linear curve, the respective velocity, was then automatically determined. This improvement was incorporated in September 1986.

b. High-Speed Film: The high-speed films were analyzed to obtain the vehicle's displacement trace and, subsequently, the impact and exit velocities. The displacement trace data were gathered by the following method:

A nonmoving reference point relative to the ground was selected. The distance between this reference point and the moving vehicle was then determined for each film frame (0.002 second per frame). A reference point relative to the ground was used, because the film can shift slightly (jitter) from frame to frame (both in the camera and in the film analysis machine), but the relative position of the vehicle to the reference point is not affected by this shifting. Using this method, a series of time-displacement data points was gathered for the entire impact event or for segments of interest.

To determine impact and exit velocities, a selected series of time-distance points (usually 10) was plotted for vehicle displacement before and after impact. Linear regression analysis was performed using the least squares method to determine the slope of each time-distance trace. This slope is the velocity. The exit velocity was then subtracted from the impact velocity to obtain the change in velocity.

c. Accelerometer Data: Vehicle X accelerometers were analyzed to obtain the change in velocity. During the test event, acceleration data were recorded on analog tape, "wide band" filtered with a filter cut-off frequency of 1,000 Hz. Following testing, the analog acceleration data were converted to digital data. Prior to digitizing the data with a frequency of 1.25 kHz, the data were passed through an 8-pole Butterworth filter with a cut-off frequency of 350 Hz. The data were then filtered using a digital filter with a cut-off frequency of 100 Hz and transferred to a spreadsheet. Subsequently, the data were single integrated to obtain the vehicle's change in velocity (a number) and the change in velocity trace, and then again integrated to obtain the displacement trace.

Data were then plotted from the spreadsheet program to develop the following graphs: (1) acceleration vs time, (2) occupant velocity (relative to the vehicle) vs time, and (3) relative occupant displacement vs time.

d. Graphs: The graphs of the acceleration versus time plot were developed from the longitudinal accelerometer located at the vehicle's c.g. (graphs plotted from film data were used when longitudinal accelerometer data were unavailable). The acceleration vs time graphs are labeled with an "A" where breakaway starts and with a "B" where breakaway is completed. The high-speed films were analyzed to determine the instant in time the base began breaking away and the instant the base was completely broken away from its mounting after impact with the test vehicle.

The velocity vs time graphs depict the change in velocity of the vehicle's longitudinal c.g. (change from impact velocity) during the event. These graphs are also the velocity of a theoretical occupant relative to the moving vehicle. These graphs were constructed by integrating the accelerometer trace with respect to time.

The displacement vs time graphs (when shown) depict the displacement of a theoretical occupant relative to the moving vehicle. The graphs were constructed by double integrating the longitudinal c.g. accelerometer trace with respect to time.

7. CHANGE IN VELOCITY

For most of the test results given in section 8, two velocity change values are given, "Reported Change in Velocity" and "Flail Space Change in Velocity." Both are measures of occupant injury. Under appropriate conditions (see section 9f), the two velocity change values are reasonably the same with the reported change in velocity considered the more accurate. This is because the reported change in velocity is based upon three independent measurement techniques coupled with a weighted average statistical analysis procedure, rather than upon a simple integration of acceleration data as is used to obtain flail space change in velocity (see below). For the high-speed tests conducted during this study, the speed traps were located too close to the impact point (a violation of one of the necessary conditions) and, as a result, the less accurate flail space results had to be used as a predictor of occupant injury. However, for the low-speed tests, the speed traps were adequately located and the more accurate reported velocity change results could be used.

a. Reported Change in Velocity: To obtain the "reported change in velocity" the velocity change values from speed traps, high-speed film, and electronic data (X-accelerometer) were averaged. This averaging technique used a weighted value for each measurement. This weighted method of averaging was chosen because the number of measurements (three) was small and a simple average does not necessarily yield the correct result, especially if one of the measurements tends to be grossly different from the others for no explainable reason (outlier). The reported change in velocity for each test was determined using the following relationship:

$$\text{Reported change in velocity} = w_1V_1 + w_2V_2 + w_3V_3$$

where:

V_1 = Velocity from the speed traps

V_2 = Velocity from the high-speed film

V_3 = Velocity from the accelerometer data

w_1, w_2, w_3 = weighting factors corresponding to each respective velocity measurement

The weighting factors were calculated for each test using statistical distribution relationships as defined in the "Luminaire Support Capability Test Plan."[7]

Note: The expressions for calculation of the weighting factors are such that, if for any given test the three velocity measurements are essentially identical, the resulting weighting factors will also be identical (i.e., a simple average result). However, if one velocity measurement tends to deviate from the other two for any reason, the corresponding weighting factor is automatically reduced relative to the other two (i.e., the deviant velocity is given less weight).

b. Flail Space Velocity: To obtain the "flail space change in velocity" both a single integration of longitudinal accelerometer data (to obtain occupant velocity relative to the vehicle) and a double integration (to obtain occupant displacement relative to the vehicle) are required. This method is based upon an occupant movement or "flail space" concept defined in NCHRP Report 230.[2] Given an impact with a fixed roadside object (in this case a coupling-mounted luminaire support), a theoretical occupant is assumed to move forward relative to the car until an interior surface is struck. This interior surface/occupant collision is assumed to occur at a relative distance (movement) of 2.0 ft (0.61 m). Thus, to determine the time at which a movement of 2.0 ft (0.61 m) has occurred, a double integration of the longitudinal accelerometer is performed followed by an inspection of the single integration to determine the corresponding flail space velocity change value occurring at that time.

8. TEST RESULTS

a. TEST 86F056

Test Purpose: This was the first full-scale automobile test used for validation of the FOIL bogie vehicle at 20 mi/h (8.94 m/s). The test vehicle was a 1979 Volkswagen Rabbit 2-door sedan with a gasoline engine and manual transmission, weighing 1850 lb (839.9 kg). The planned impact point was 14 in (0.35 m) to the left of the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The test vehicle was accelerated to a velocity of 20.0 mi/h (8.94 m/s) before impacting the test article. The actual impact point was 14 in (0.35 m) left of the vehicle's centerline. Upon impact, the vehicle broke away the couplings and proceeded in a straight trajectory into the run-out area. The pole then fell on top of the vehicle and rolled off just after the vehicle came to a stop.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f) the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **17.2 ft/s (5.25 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.166 s after impact and was determined to be **16.7 ft/s (5.03 m/s)**. In this test, the reported change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury (see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

The data analysis summary sheet is given in table 8. Pre-test and post-test photographs are presented in figures 2 and 3. Graphs of the data are presented in figures 4 and 5.

Table 8. Data analysis summary sheet, test 86F056.

TEST NUMBER	86F056	TEST VEHICLE	79 VW Rabbit
TEST DATE	06/06/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		

IMPACT SPEED (ft/s)	FILM 30.4
	SPEED TRAP 29.4 (20.0 mi/h)
EXIT SPEED (ft/s)	FILM 12.9
	SPEED TRAP 12.4
CHANGE IN VELOCITY (From INTEGRAL A_X)	X-ACC 1 17.2
	X-ACC 2 16.9
IMPACT-EXIT SPEED (ft/s)	FILM 17.5
	SPEED TRAP 17.0
	AVG. INTEGRAL A_X 17.0
REPORTED CHANGE IN VELOCITY (ft/s)	**DELTA V 17.2***
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	X-ACC 1 16.9* X-ACC 2 16.5*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	**AVG. FLAIL DELTA V 16.7***
MOMENTUM CHANGE (lb-s)	988
MAX FORCE (kips)	24.6
MAX ACCELERATION (g's)	13.3
VEHICLE CRUSH LENGTH (in)	MEASURED 13.5
IMPACT TIME (s)	
BREAKAWAY START	0.066
BREAKAWAY COMPLETE	0.074

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.

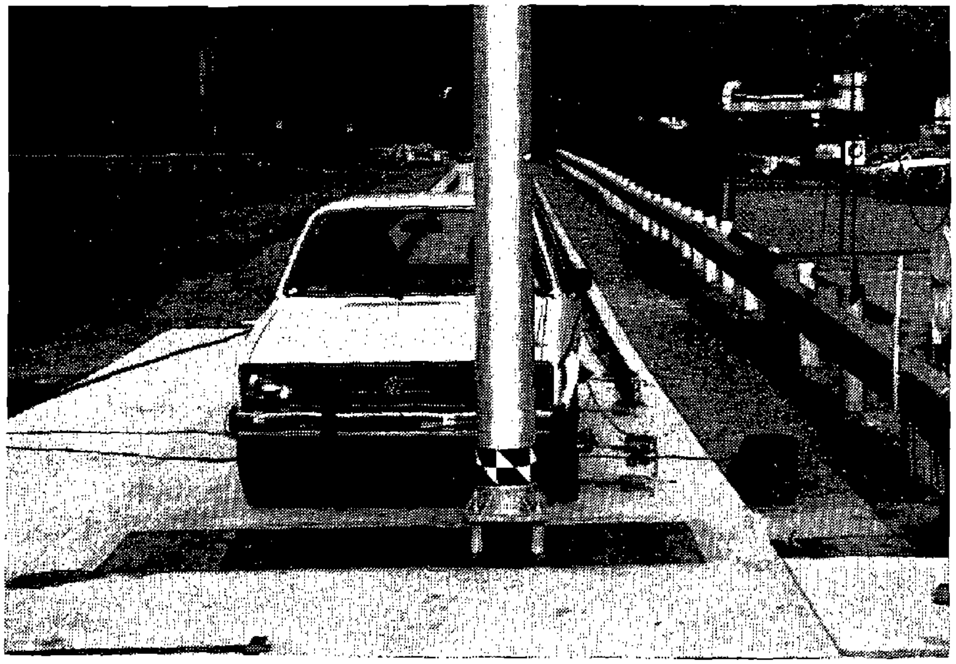
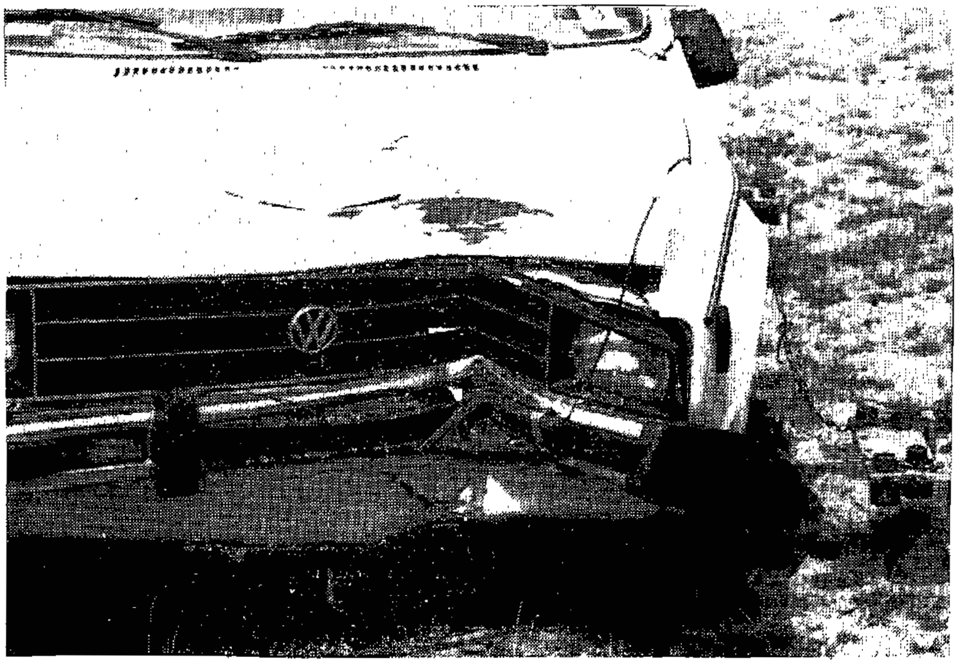


Figure 2. Pre-test photographs, test 86F056.



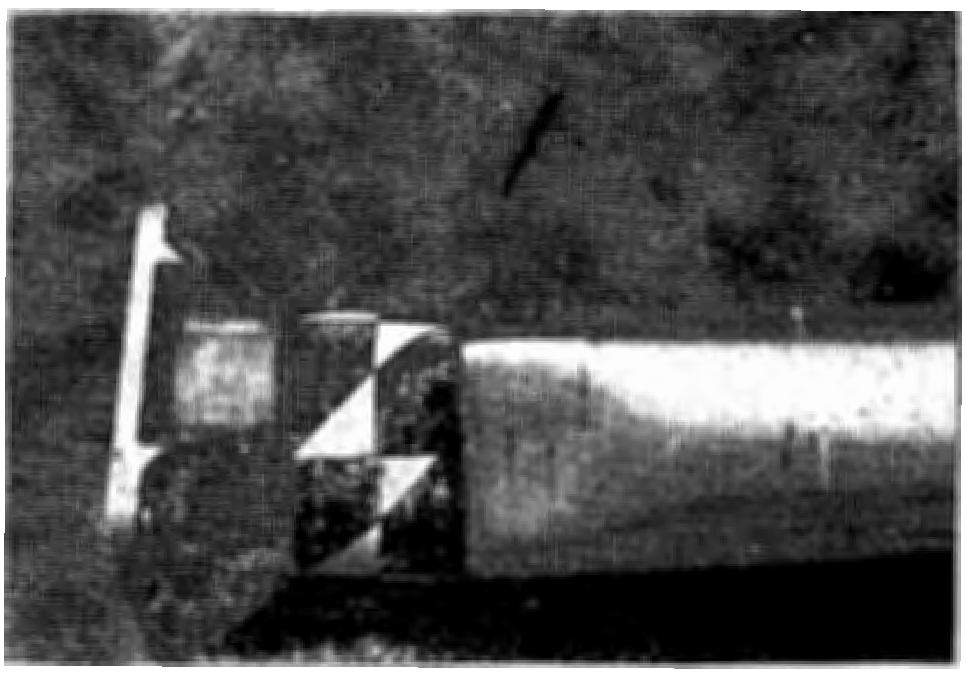
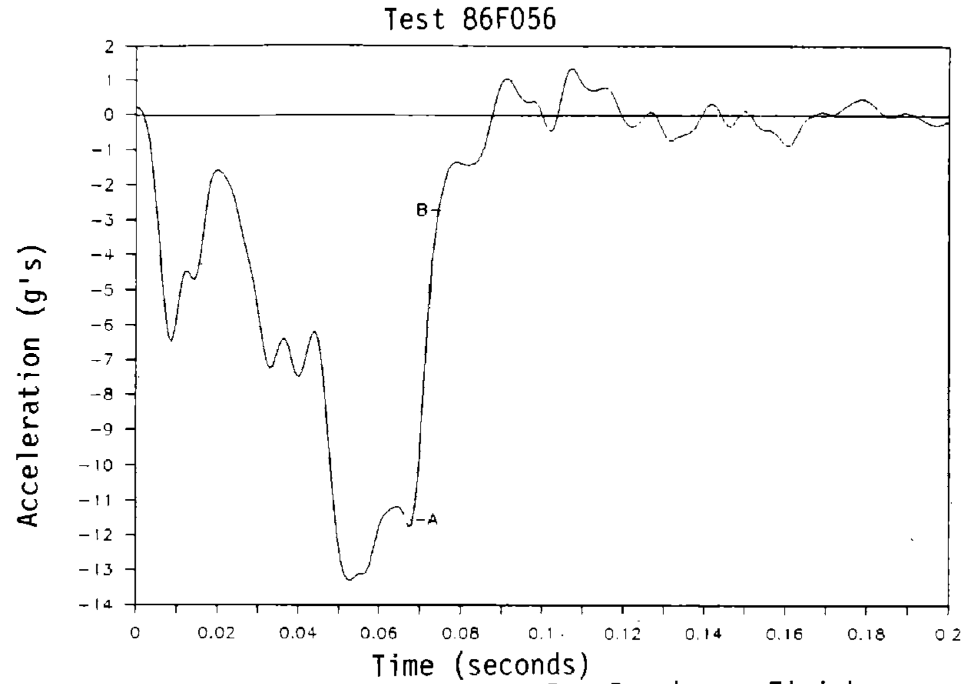


Figure 3. Post-test photographs, test 86F056.



A - Breakaway Start B - Breakaway Finish

Figure 4. Acceleration vs time, cut-off frequency 100 Hz, test 86F056.

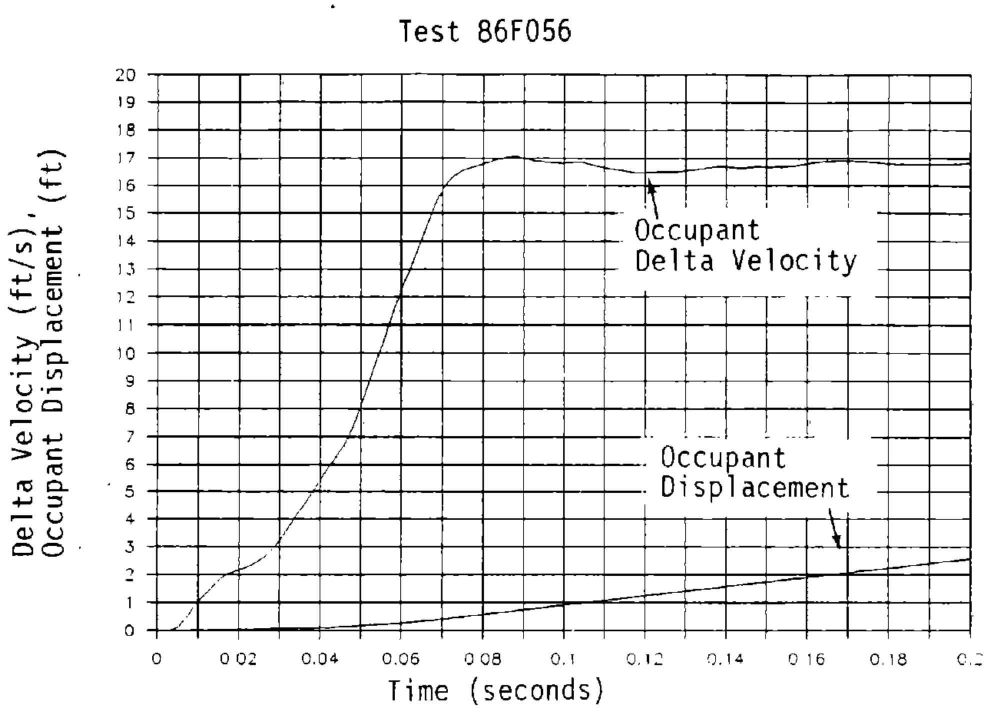


Figure 5. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F056.

b. TEST 86F058

Test Purpose: This was the first full-scale automobile test used for validation of the FOIL bogie vehicle at 60 mi/h (26.8 m/s). The test vehicle was a 1979 Volkswagen Rabbit 2-door sedan with a gasoline engine and manual transmission, ballasted to 1850 lb (839.9 kg). The planned impact point was 14 in (0.35 m) to the left of the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The bogie was accelerated to a velocity of 61.6 mi/h (27.5 m/s) before impacting the test article. The actual impact point was 14 in (0.35 m) to the left of the vehicle's centerline. Upon impact, the pole sheared away from its couplings and rotated, allowing the vehicle to pass beneath. The pole struck the ground, top end first, while the vehicle continued in a straight trajectory into the run-out zone where it was stopped by the catch net.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f) the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **7.7 ft/s (2.35 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.267 s after impact and was determined to be **8.2 ft/s (2.50 m/s)**. In this test, the flail space change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury. This less accurate result (from a computational standpoint) is used because all of the appropriate conditions for use of the more accurate reported change in velocity were not met due to the location of the speed trap (it was too close to the impact point - see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

The data analysis summary sheet is given in table 9. Pre-test and post-test photographs are presented in figures 6 and 7. Graphs of the data are presented in figures 8 and 9.

Table 9. Data analysis summary sheet, test 86F058.

TEST NUMBER	86F058	TEST VEHICLE	79 VW Rabbit
TEST DATE	06/11/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		

IMPACT SPEED (ft/s)	FILM 88.4
	SPEED TRAP 90.4 (61.6 mi/h)
EXIT SPEED (ft/s)	FILM 80.7
	SPEED TRAP 83.3
CHANGE IN VELOCITY (From INTEGRAL A_x)	X-ACC 1 8.4
	X-ACC 2 8.1
IMPACT-EXIT SPEED (ft/s)	FILM 7.7
	SPEED TRAP 7.1
	AVG. INTEGRAL A_x 8.2
REPORTED CHANGE IN VELOCITY (ft/s)	**DELTA V 7.7***
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	X-ACC 1 8.4* X-ACC 2 8.1*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	**AVG. FLAIL DELTA V 8.2***
MOMENTUM CHANGE (lb-s)	442
MAX FORCE (kips)	23.6
MAX ACCELERATION (g's)	12.8
VEHICLE CRUSH LENGTH (in)	MEASURED 16.5
IMPACT TIME (s)	
BREAKAWAY START	0.010
BREAKAWAY COMPLETE	0.018

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.

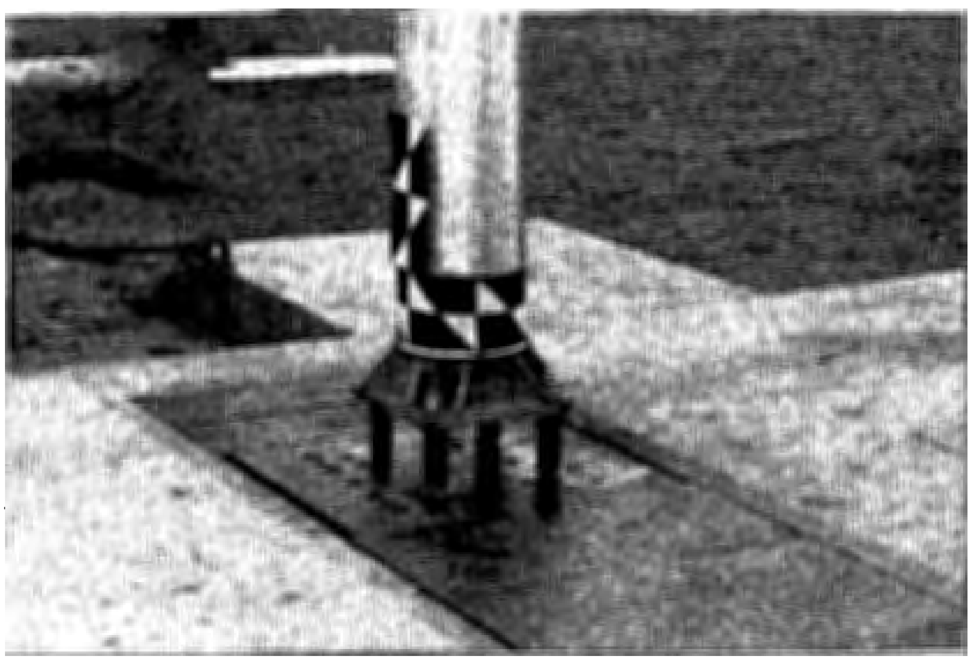
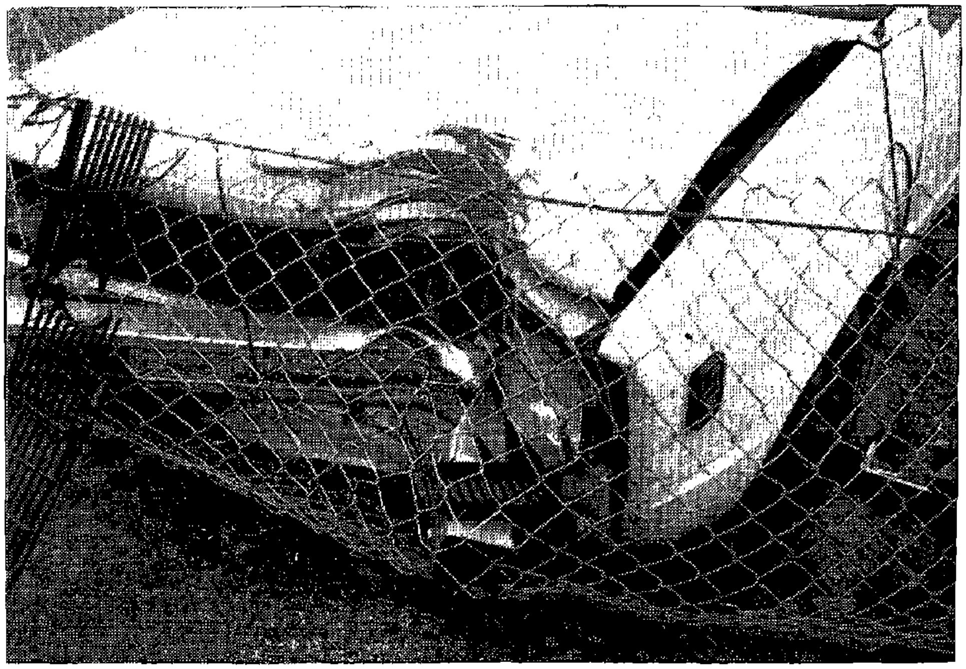


Figure 6. Pre-test photographs, test 86F058.



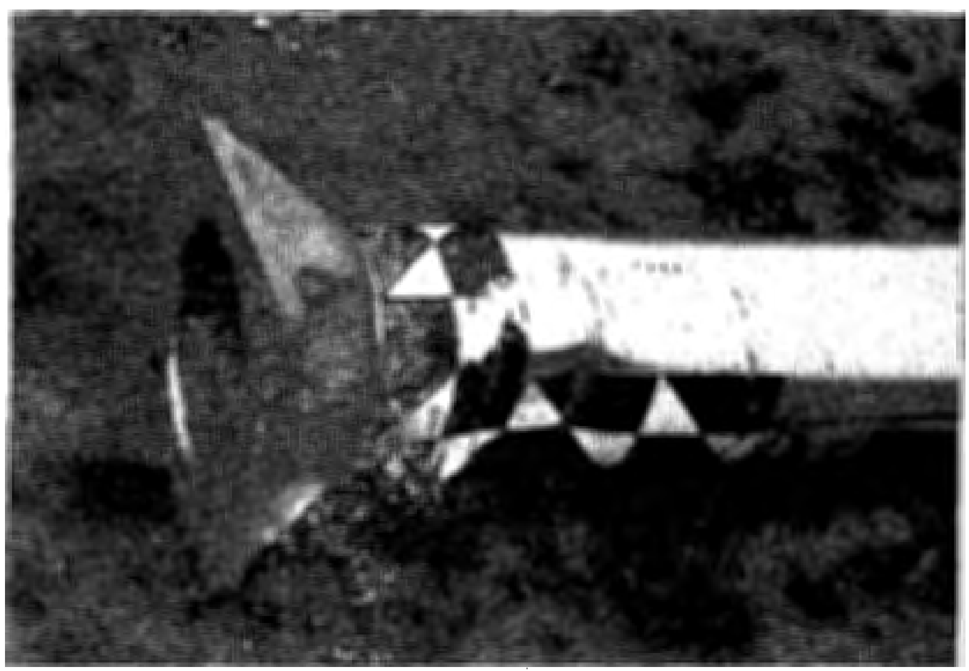


Figure 7. Post-test photographs, test 86F058.

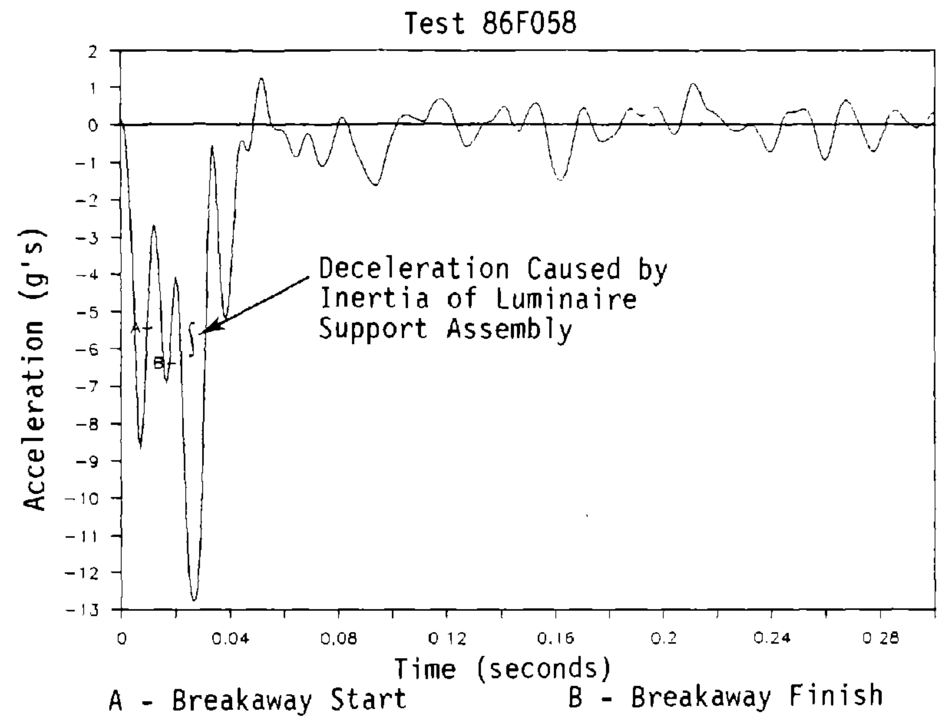


Figure 8. Acceleration vs time, cut-off frequency 100 Hz, test 86F058.

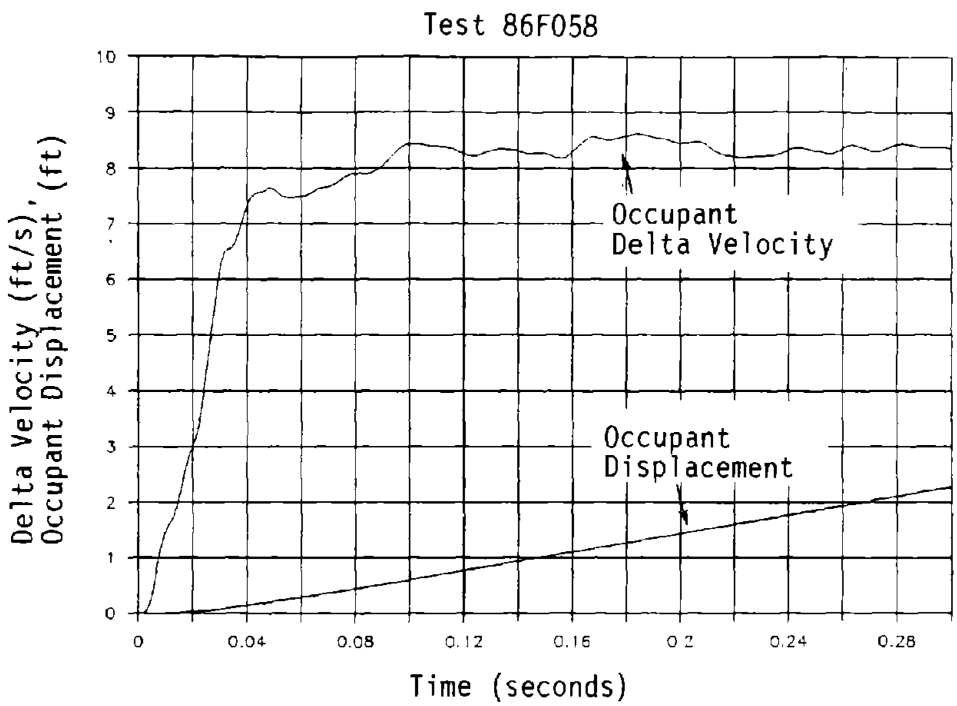


Figure 9. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F058.

c. **TEST 86F060**

Test Purpose: This was the second full-scale automobile test used for validation of the FOIL bogie vehicle at 60 mi/h (26.8 m/s). The test vehicle was a 1979 Volkswagen Rabbit 2-door sedan with a gasoline engine and manual transmission, weighing 1850 lb (839.9 kg). The planned impact point was 14 in (0.35 m) to the left of the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The vehicle was accelerated to a velocity of 59.5 mi/h (26.6 m/s) before impacting the test article. The actual impact point was 14 in (0.35 m) left of the vehicle's centerline. Upon impact, the couplings sheared away and the pole rotated rapidly, allowing the vehicle to pass beneath. The vehicle continued in a straight trajectory into the run-out zone where it was stopped by the catch net.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f) the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **8.2 ft/s (2.50 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.270 s after impact and was determined to be **8.3 ft/s (2.53 m/s)**. In this test, the flail space change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury. This less accurate result (from a computational standpoint) is used because all of the appropriate conditions for use of the more accurate reported change in velocity were not met due to the location of the speed trap (it was too close to the impact point - see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

The data analysis summary sheet is given in table 10. Pre-test and post-test photographs are presented in figures 10 and 11. Graphs of the data are presented in figures 12 and 13.

Table 10. Data analysis summary sheet, test 86F060.

TEST NUMBER	86F060	TEST VEHICLE	79 VW Rabbit
TEST DATE	06/19/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		

IMPACT SPEED (ft/s)	FILM 86.8
	SPEED TRAP 87.2 (59.5 mi/h)
EXIT SPEED (ft/s)	FILM 79.1
	SPEED TRAP 79.0
CHANGE IN VELOCITY (From INTEGRAL A_x)	X-ACC 1 8.6
	X-ACC 2 8.4
IMPACT-EXIT SPEED (ft/s)	FILM 7.7
	SPEED TRAP 8.2
	AVG. INTEGRAL A_x 8.5
REPORTED CHANGE IN VELOCITY (ft/s)	**DELTA V 8.2***
FLAIL SPACE CHANGE IN VELOCITY(ft/s)	X-ACC 1 8.4* X-ACC 2 8.2*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	**AVG. FLAIL DELTA V 8.3***
MOMENTUM CHANGE (lb-s)	471
MAX FORCE (kips)	32.0
MAX ACCELERATION (g's)	17.3
VEHICLE CRUSH LENGTH (in)	MEASURED 16.0
IMPACT TIME (s)	
BREAKAWAY START	0.014
BREAKAWAY COMPLETE	0.020

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.

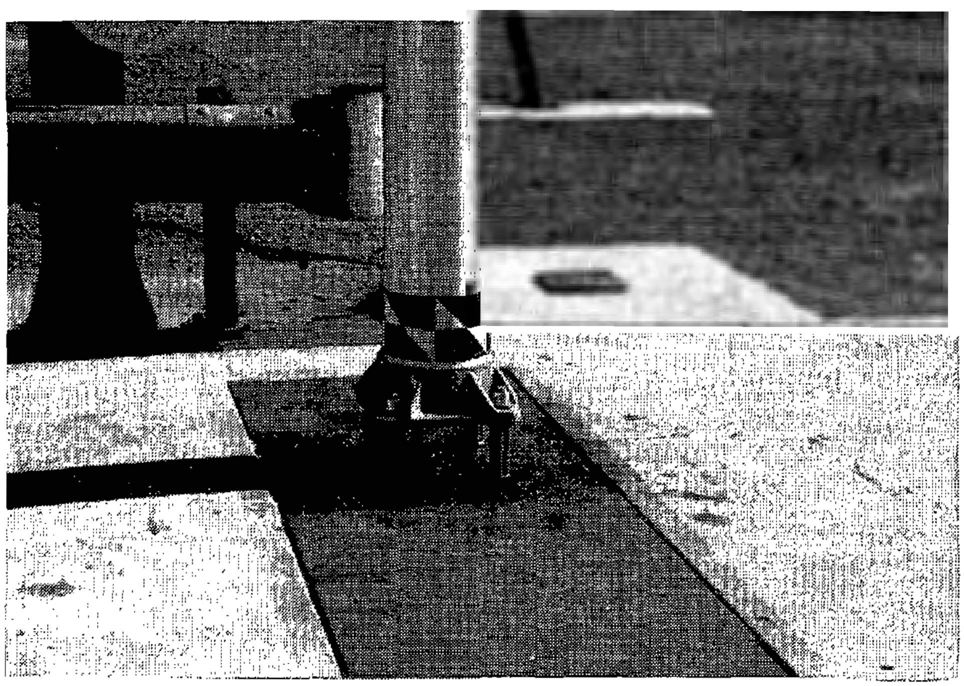


Figure 10. Pre-test photographs, test 86F060.

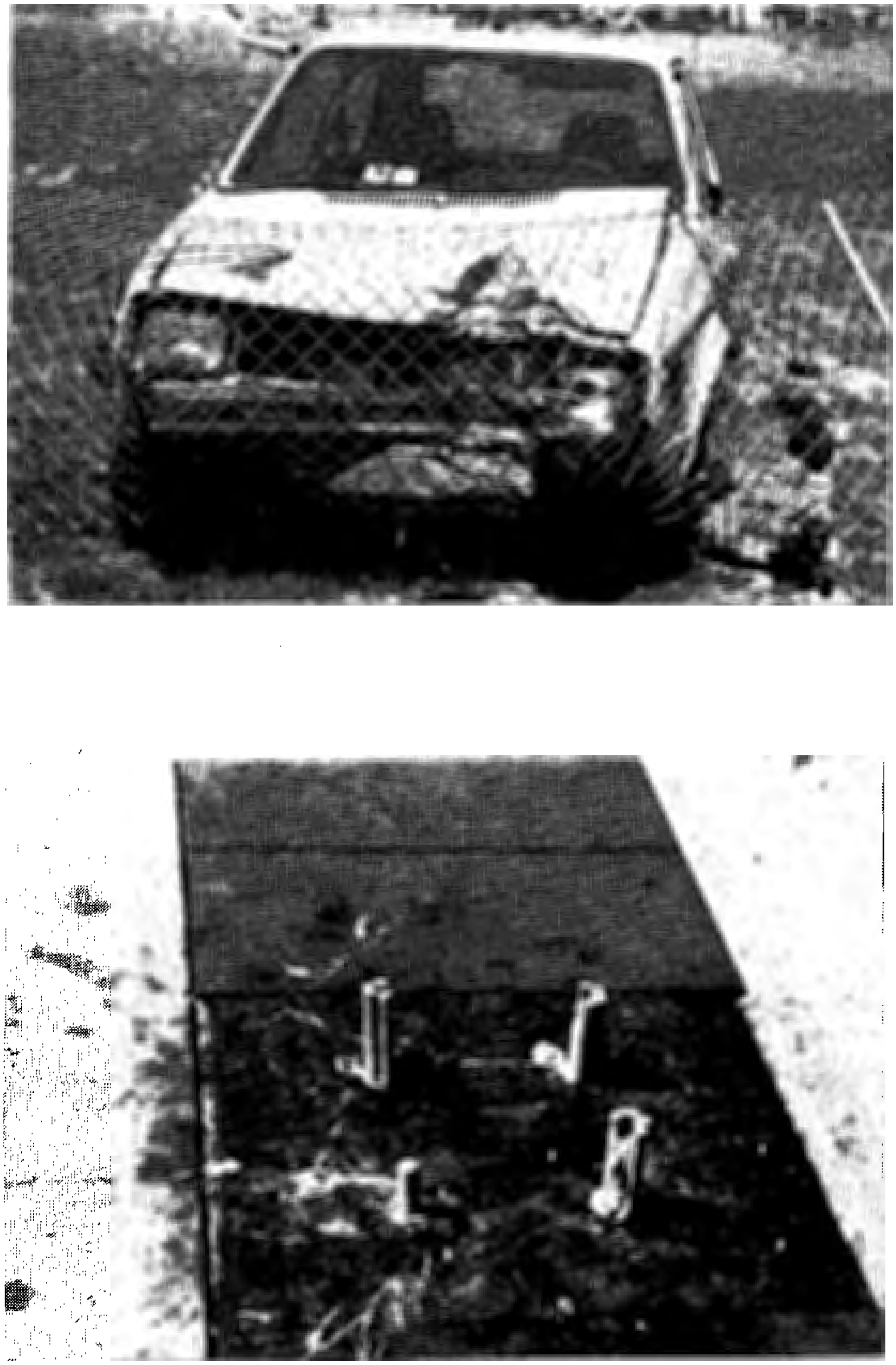
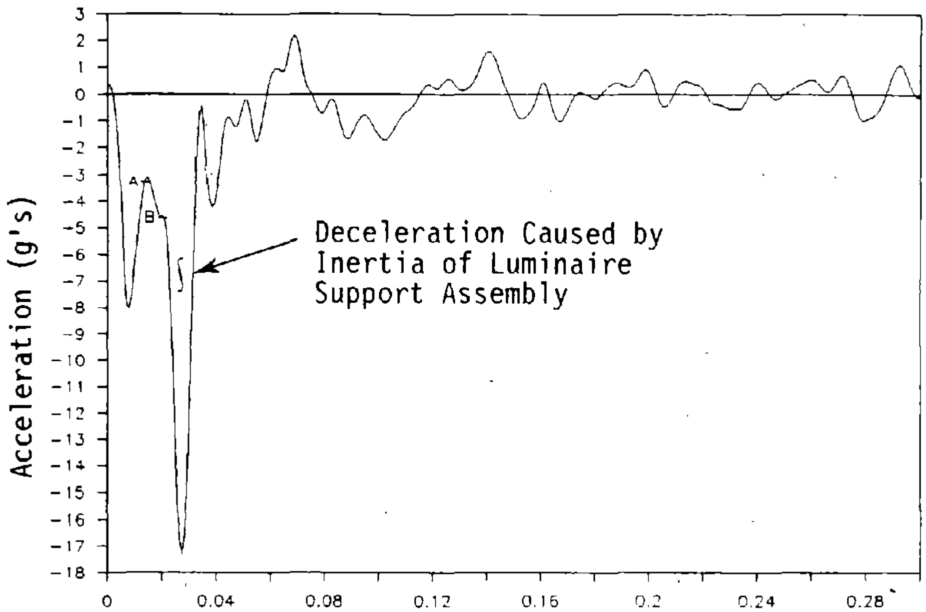


Figure 11. Post-test photographs, test 86F060.

Test 86F060



A - Breakaway Start B - Breakaway Finish

Figure 12. Acceleration vs time, cut-off frequency 100 Hz, test 86F060.

Test 86F060

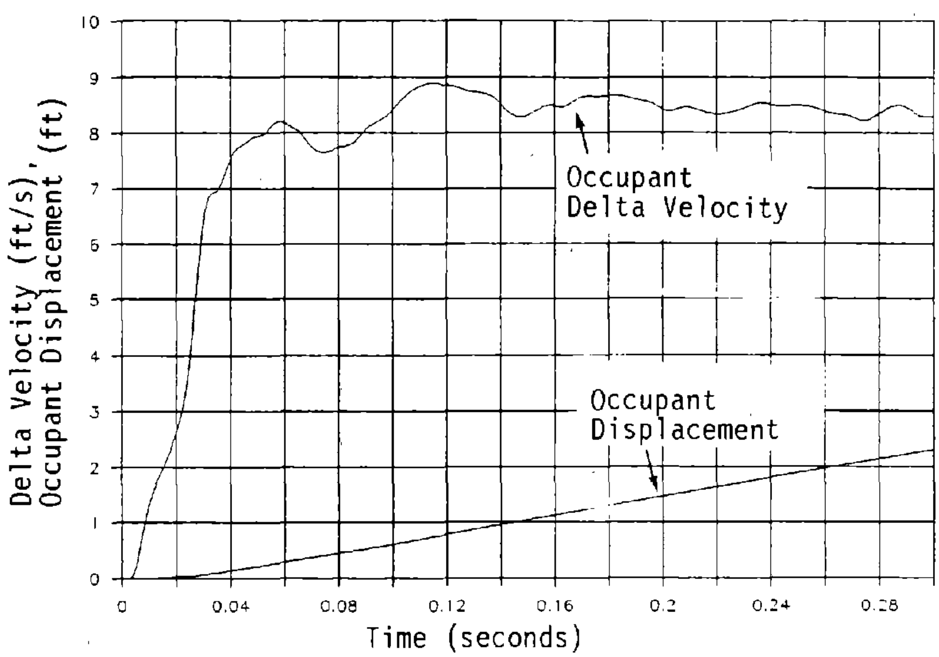


Figure 13. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F060.

d. TEST 86F061

Test Purpose: This test was conducted to determine the performance of the FOIL bogie vehicle relative to the automobile tests conducted at 60 mi/h (26.8 m/s). The bogie was configured to represent a 1979 Volkswagen Rabbit weighing 1850 lbs (839.9 kg). The planned impact was the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The bogie vehicle was accelerated to a velocity of 58.8 mi/h (26.2 m/s) before impacting the test article. The actual impact point was the vehicle's centerline. Upon impact the pole rotated, allowing the vehicle to pass under it.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f), the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **9.2 ft/s (2.81 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.190 s after impact and was determined to be **12.7 ft/s (3.87 m/s)**. In this test, the flail space change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury. This less accurate result (from a computational standpoint) is used because all of the appropriate conditions for use of the more accurate reported change in velocity were not met due to the location of the speed trap (it was too close to the impact point - see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

The data analysis summary sheet is given in table 11. Pre-test and post-test photographs are presented in figures 14 and 15. Graphs of the data are presented in figures 16 and 17.

Table 11. Data analysis summary sheet, test 86F061.

TEST NUMBER	86F061	TEST VEHICLE	Bogie
TEST DATE	06/22/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		

IMPACT SPEED (ft/s)	FILM 85.1
	SPEED TRAP 86.2 (58.8 mi/h)
EXIT SPEED (ft/s)	FILM 76.5
	SPEED TRAP 77.3
CHANGE IN VELOCITY (From INTEGRAL A_X)	X-ACC 1 13.1
	X-ACC 2 12.3
IMPACT-EXIT SPEED (ft/s)	FILM 8.6
	SPEED TRAP 8.9
	AVG. INTEGRAL A_X 12.7
REPORTED CHANGE IN VELOCITY (ft/s)	**DELTA V 9.2***
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	X-ACC 1 13.0* X-ACC 2 12.4*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	**AVG. FLAIL DELTA V 12.7***
MOMENTUM CHANGE (lb-s)	529
MAX FORCE (kips)	33.1
MAX ACCELERATION (g's)	17.9
VEHICLE CRUSH LENGTH (in)	MEASURED 24.3
	STRING POT 29.4**
IMPACT TIME (s)	
BREAKAWAY START	0.026
BREAKAWAY COMPLETE	0.044

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.
** Measurement is not accurate due to inertia overshoot of the mechanical mechanism.

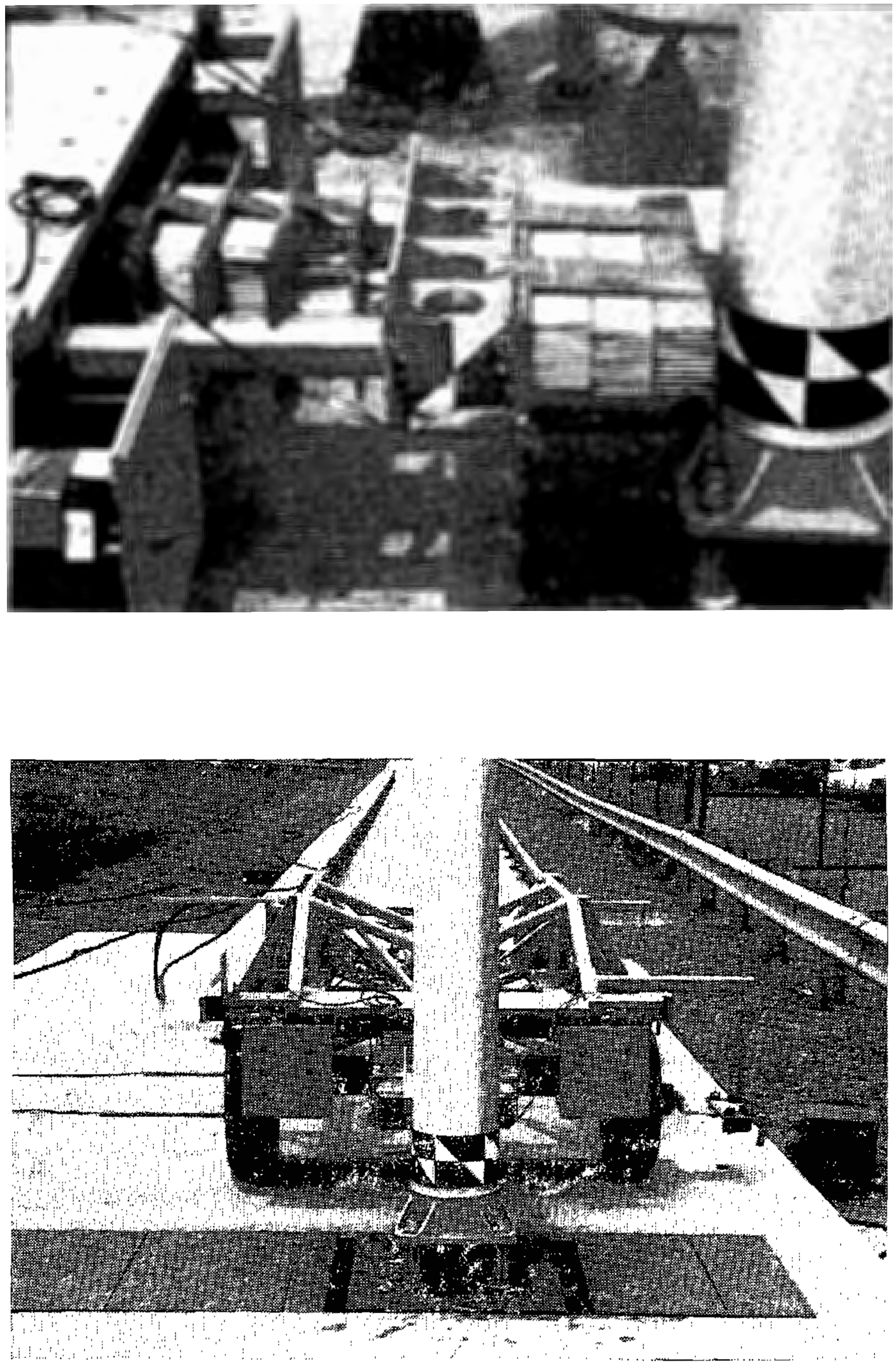
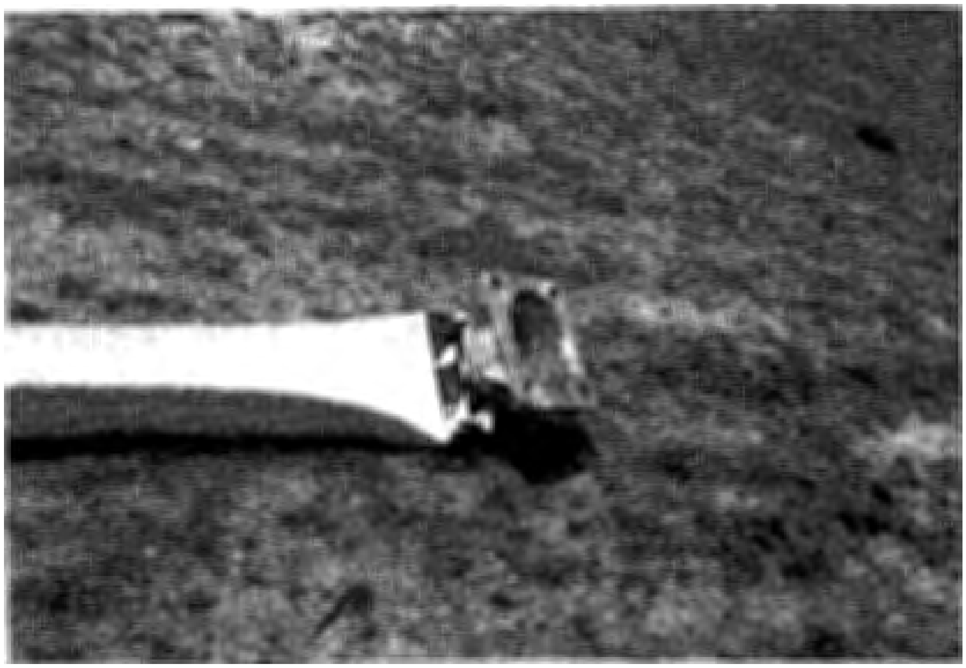


Figure 14. Pre-test photographs, test 86F061.



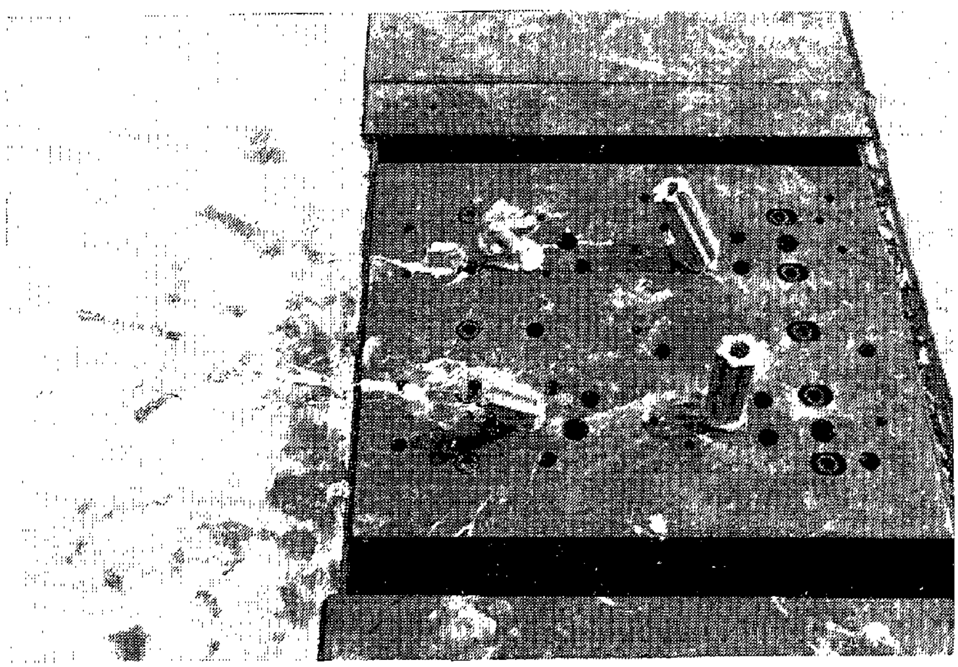


Figure 15. Post-test photographs, test 86F061.

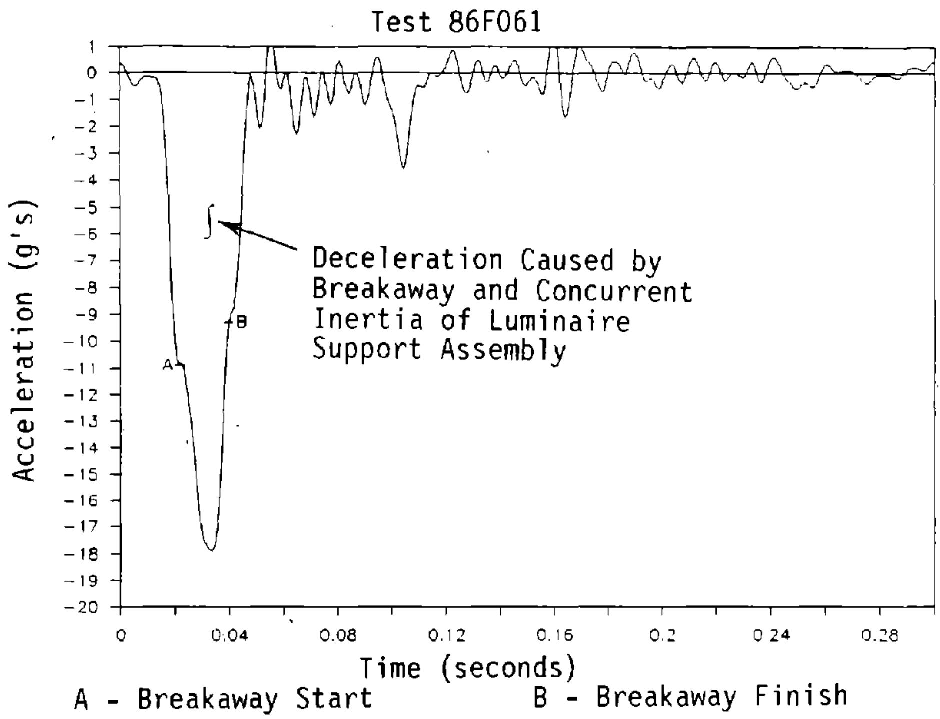


Figure 16. Acceleration vs time, cut-off frequency 100Hz, test 86F061.

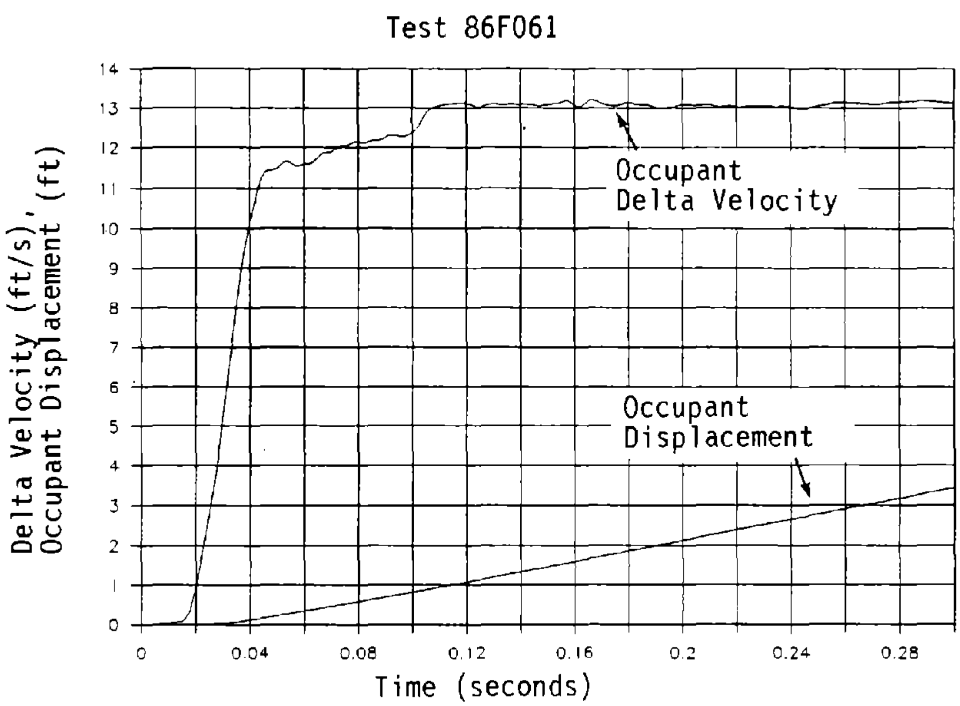


Figure 17. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F061.

e. TEST 86F062

Test Purpose: This test was conducted to determine the performance of the FOIL bogie vehicle relative to the automobile tests conducted at 20 mi/h (8.94 m/s). The bogie was configured to represent a 1979 Volkswagen Rabbit weighing 1850 lbs (839.9 kg). The planned impact was the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The bogie vehicle was accelerated to a velocity of 19.7 mi/h (8.81 m/s) before impacting the test article. The actual impact point was the vehicle's centerline. Upon impact, the couplings sheared away and the pole rotated, allowing the bogie to pass partially under it. The pole fell onto the bogie vehicle and rolled off before the vehicle stopped.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f) the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **19.2 ft/s (5.86 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.166 s after impact and was determined to be **20.3 ft/s (6.19 m/s)**. In this test, the reported change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury (see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

The data analysis summary sheet is given in table 12. Pre-test and post-test photographs are presented in figures 18 and 19. Graphs of the data are presented in figures 20 and 21.

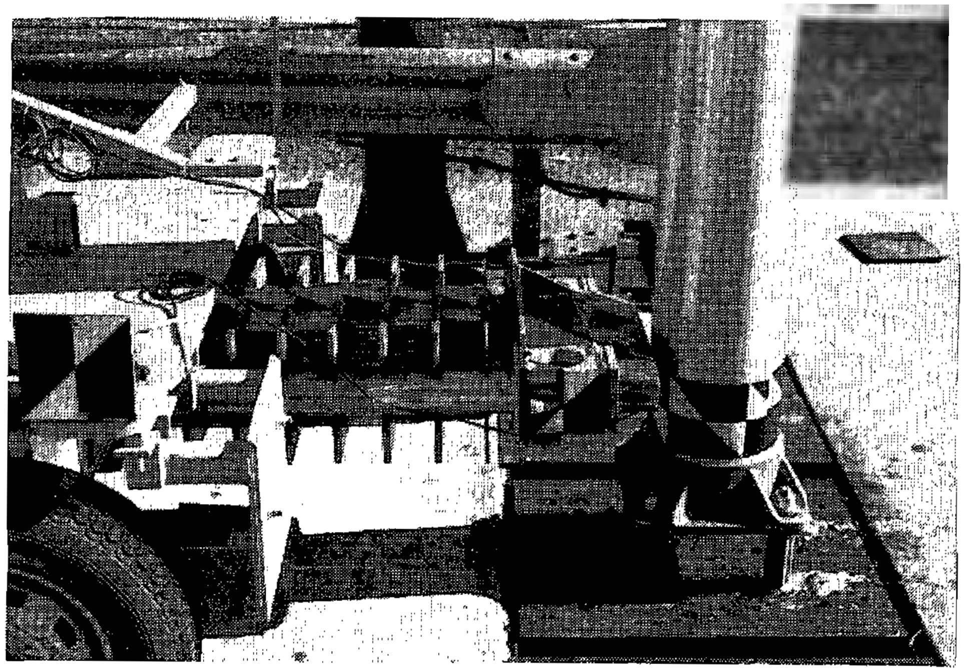
Table 12. Data analysis summary sheet, test 86F062.

TEST NUMBER	86F062	TEST VEHICLE	Bogie
TEST DATE	06/25/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		

IMPACT SPEED (ft/s)	FILM 30.1
	SPEED TRAP 28.8 (19.7 mi/h)
EXIT SPEED (ft/s)	FILM 11.0
	SPEED TRAP 10.4
CHANGE IN VELOCITY (From INTEGRAL A_X)	X-ACC 1 20.1
	X-ACC 2 20.7
IMPACT-EXIT SPEED (ft/s)	FILM 19.1 SPEED TRAP 18.4 AVG. INTEGRAL A_X 20.4
REPORTED CHANGE IN VELOCITY (ft/s)	**DELTA V 19.2***
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	X-ACC 1 20.0* X-ACC 2 20.6*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)	**AVG. FLAIL DELTA V 20.3***
MOMENTUM CHANGE (lb-s)	1103
MAX FORCE (kips)	23.0
MAX ACCELERATION (g's)	12.4
VEHICLE CRUSH LENGTH (in)	MEASURED 18.7 STRING POT 21.6**
IMPACT TIME (s)	
BREAKAWAY START	0.078
BREAKAWAY COMPLETE	0.084

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.
** Measurement is not accurate due to inertia overshoot of the mechanical mechanism.



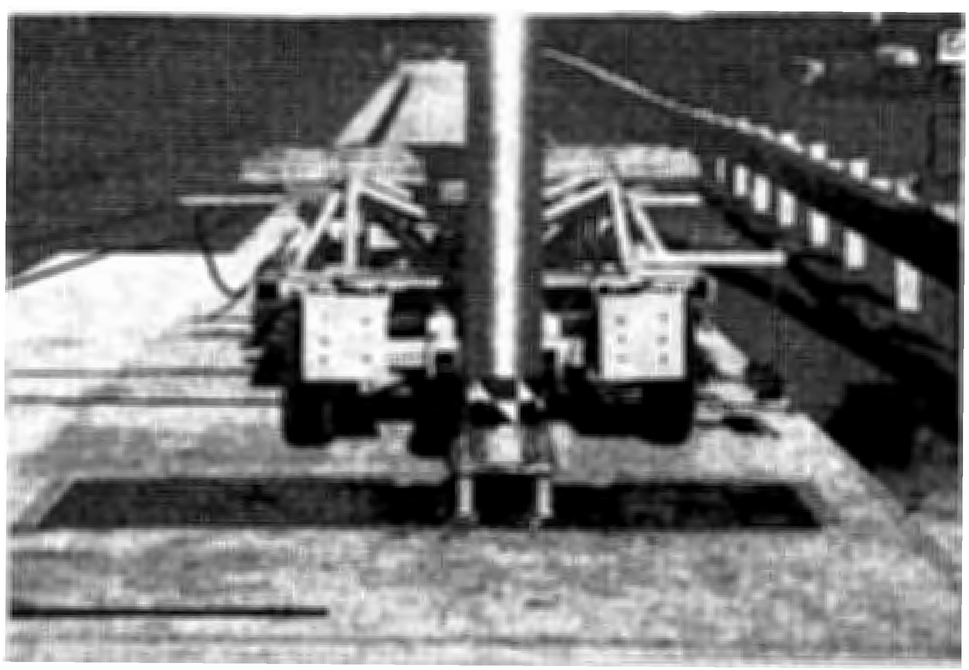


Figure 18. Pre-test photographs, test 86F062.

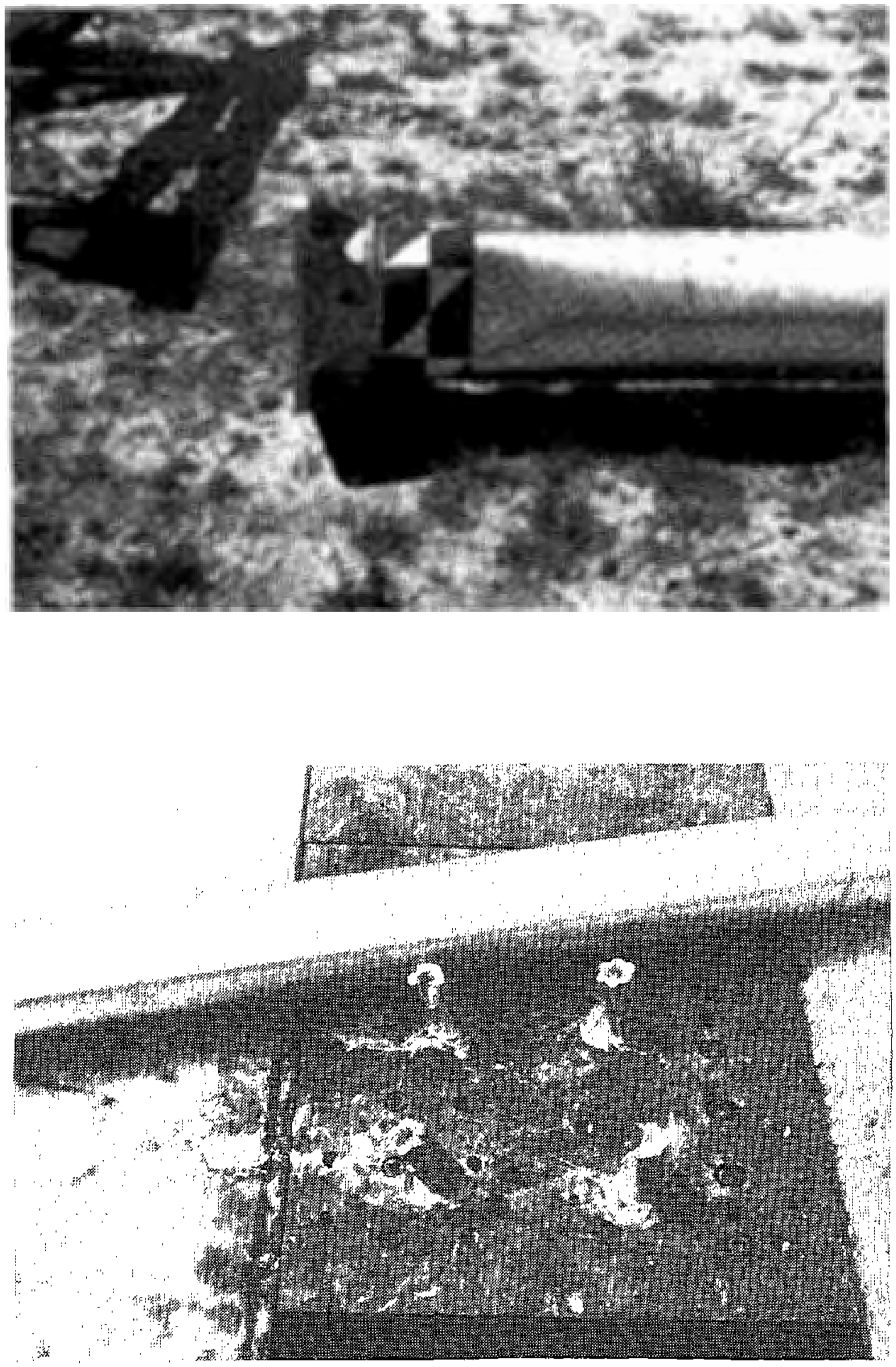
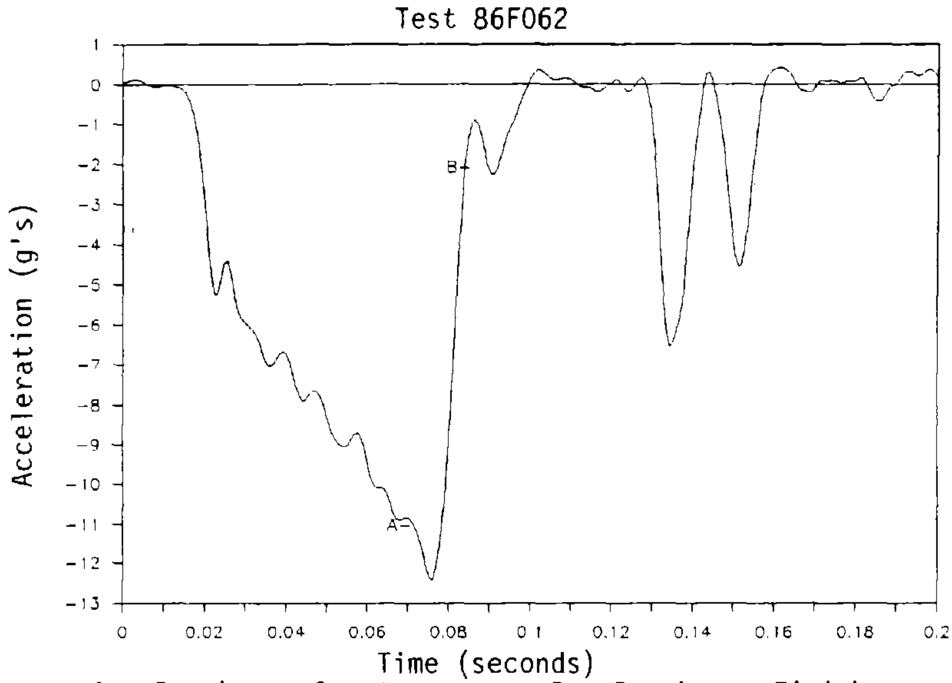


Figure 19. Post-test photographs, test 86F062.



A - Breakaway Start B - Breakaway Finish

Figure 20. Acceleration vs time, cut-off frequency 100 Hz, test 86F062.

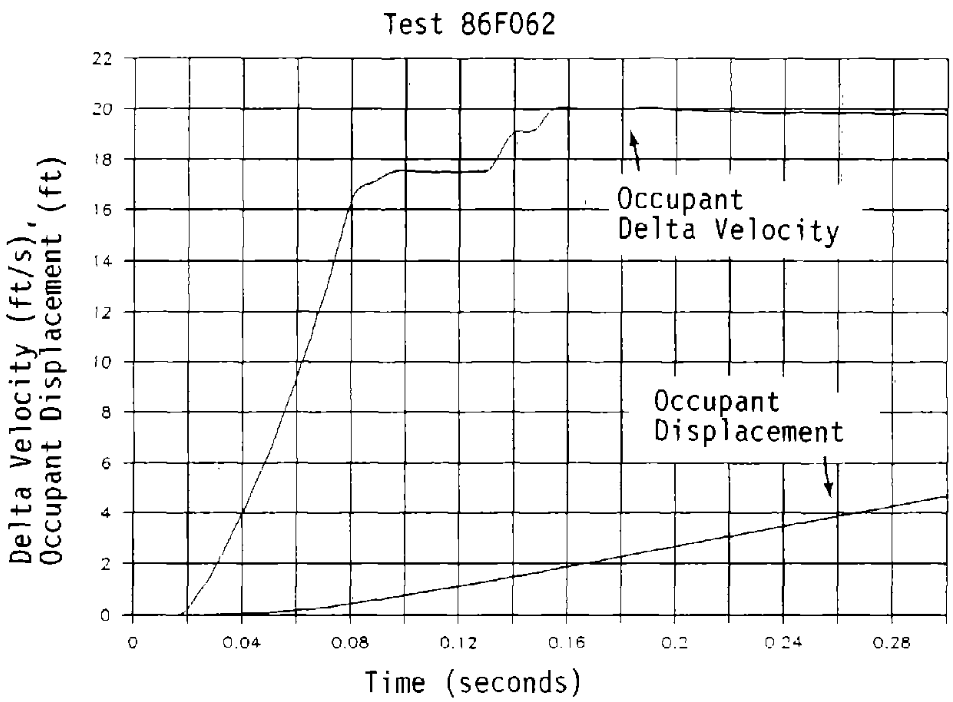


Figure 21. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F062.

f. TEST 86F063

Test Purpose: The purpose of this test was to provide an additional data point to compare with an automobile at 60 mi/h (26.8 m/s). The bogie vehicle was configured to represent a 1979 Volkswagen Rabbit weighing 1850 lbs (839.9 kg). The planned impact was the vehicle's centerline. The test article was a Union Metal Manufacturing Co., 40-ft (12.2 m) long aluminum pole weighing 250 lb (113.5 kg) with Alcoa couplings as its base. The couplings were mounted to the FOIL foundation plate using 1-8UNC studs. The pole was mounted to the couplings using the torque limited nuts supplied by the manufacturer.

Test Results: The bogie vehicle was accelerated to a velocity of 59.5 mi/h (26.6 m/s) before impacting the test article. The actual impact point was the vehicle's centerline. After impact, the couplings sheared away and the pole rotated, allowing the bogie to pass beneath it. The bogie continued in a straight trajectory into the run-out zone, where it was stopped by the catch net. During this test the high-speed cameras malfunctioned; therefore, all data from the film were lost.

Two changes in velocity are calculated and reported for this test, reported and flail space. Both are measures of occupant injury. Under appropriate conditions (see section 9f) the two velocity change values are reasonably the same, with the reported change in velocity considered the more accurate from a computational standpoint. The method for determining each is explained in section 7. The reported change in velocity was determined to be **10.9 ft/s (3.32 m/s)**. All calculations for determining this change in velocity were terminated after impact coincident with the test vehicle passing over the center of the exit speed trap. The flail space change in velocity occurred 0.212 s after impact and was determined to be **12.0 ft/s (3.66 m/s)**. In this test, the flail space change in velocity is considered the more appropriate of these two methods and is used as the primary predictor of occupant injury. This less accurate result (from a computational standpoint) is used because all of the appropriate conditions for use of the more accurate reported change in velocity were not met due to the location of the speed trap (it was too close to the impact point - see section 9f for explanation).

Data for all graphs were analyzed using the vehicle's primary X-axis accelerometer. Unless otherwise indicated, all graphs shown are plotted from accelerometer data.

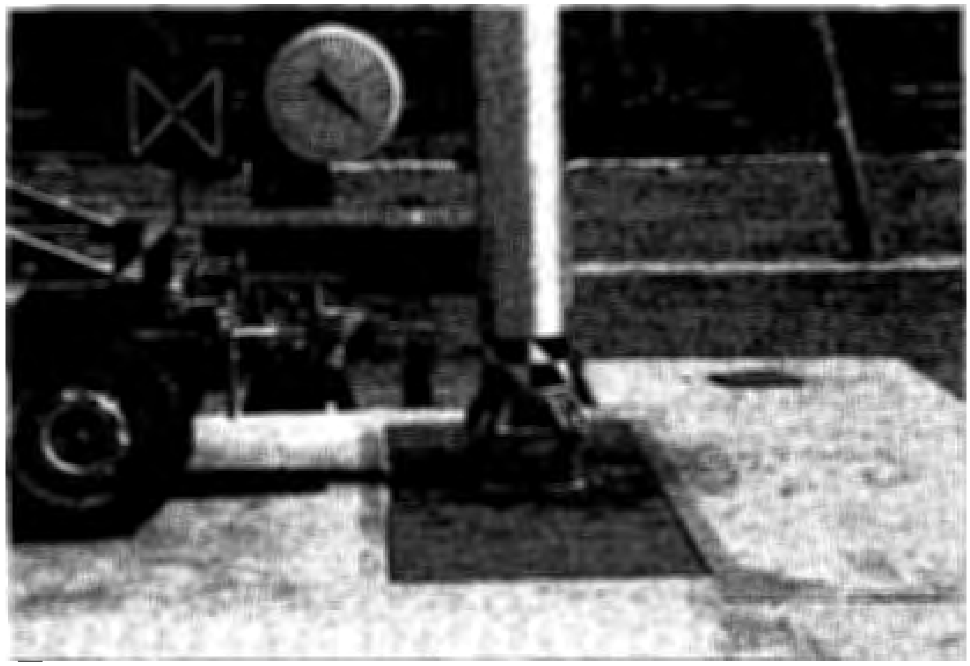
The data analysis summary sheet is given in table 13. Pre-test and post-test photographs are presented in figures 22 and 23. Graphs of the data are presented in figures 24 and 25.

Table 13. Data analysis summary sheet, test 86F063.

TEST NUMBER	86F063	TEST VEHICLE	Bogie
TEST DATE	06/27/86	VEHICLE WT (lbs)	1850
TEST ARTICLE	Luminaire Support	ARTICLE TYPE	Coupling
MANUFACTURER	Alcoa	MODEL NUMBER	100-1
LENGTH (ft)	40		
WEIGHT (lbs)	250		
IMPACT SPEED (ft/s)		FILM	No Data
		SPEED TRAP	87.2 (59.5 mi/h)
EXIT SPEED (ft/s)		FILM	No Data
		SPEED TRAP	77.3
CHANGE IN VELOCITY (From INTEGRAL A_X)		X-ACC 1	12.6
		X-ACC 2	11.4
IMPACT-EXIT SPEED (ft/s)		FILM	No Data
		SPEED TRAP	9.9
		AVG. INTEGRAL A_X	12.0
REPORTED CHANGE IN VELOCITY (ft/s)		**DELTA V**	**10.9***
FLAIL SPACE CHANGE IN VELOCITY (ft/s)		X-ACC 1	12.6*
		X-ACC 2	11.4*
FLAIL SPACE CHANGE IN VELOCITY (ft/s)		**AVG. FLAIL DELTA V**	**12.0***
MOMENTUM CHANGE (lb-s)		626	
MAX FORCE (kips)		45.3	
MAX ACCELERATION (g's)		24.5	
VEHICLE CRUSH LENGTH (in)		MEASURED	25.9

Metric Equivalents: 1 mi/h = .447 m/s 1 ft = .305 m 1 lb-s = 4.44 N·s
1 lb = 4.44 N

* See section 8, Test Results.



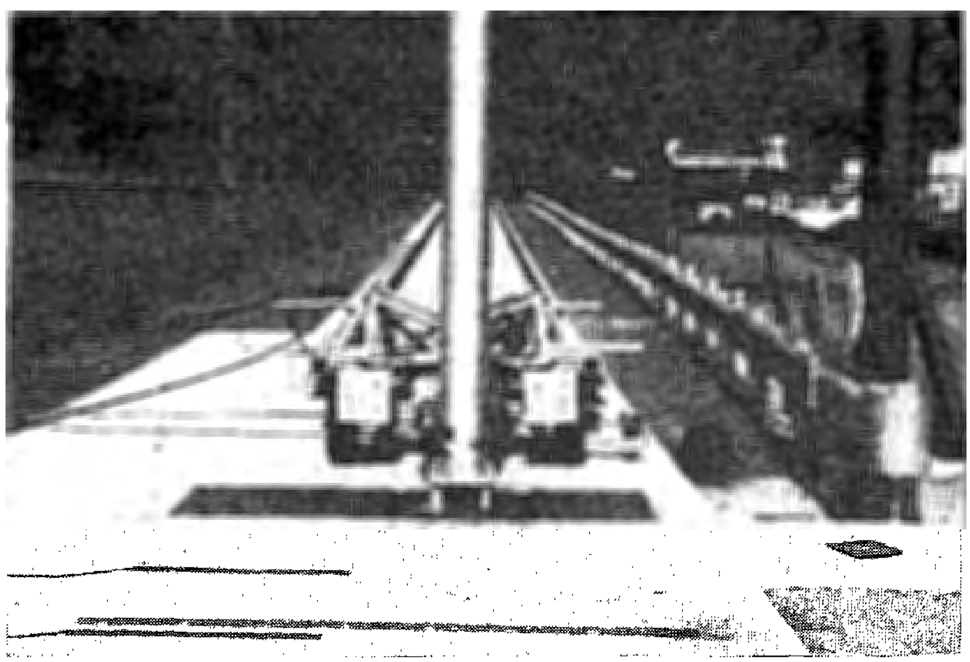
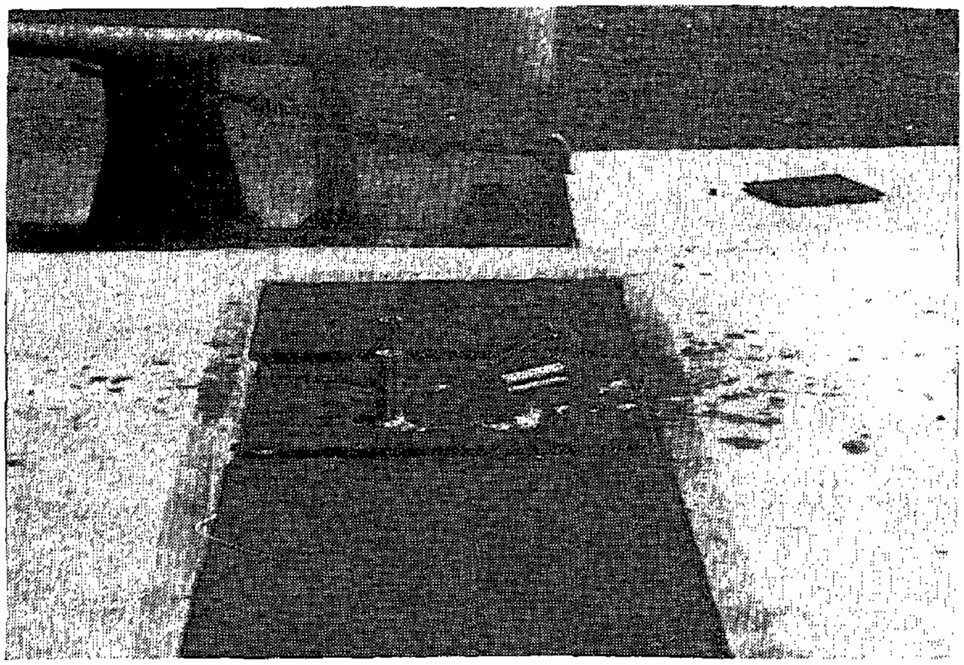


Figure 22. Pre-test photographs, test 86F063.



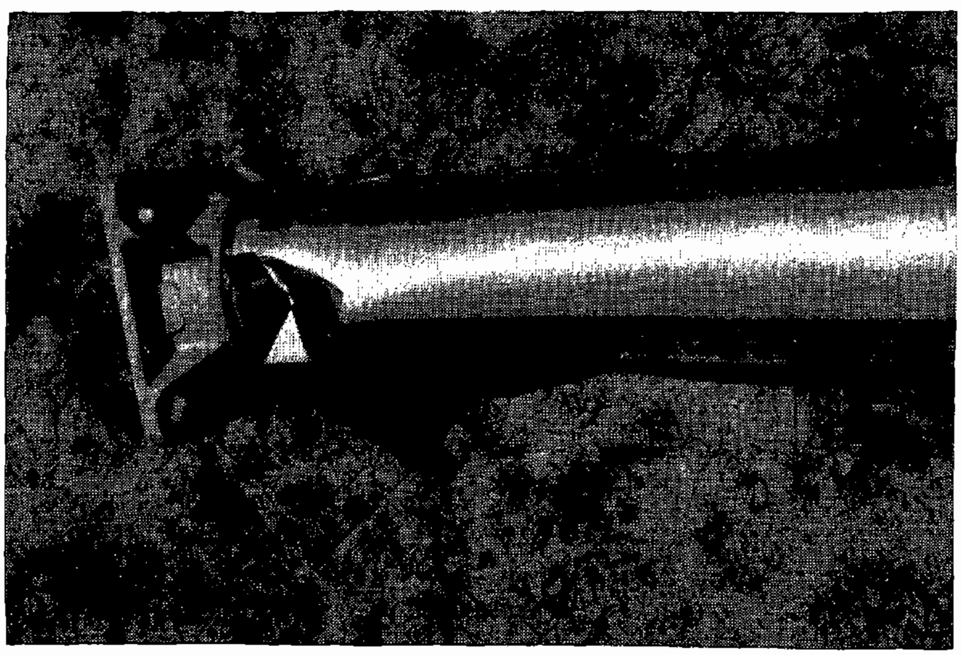


Figure 23. Post-test photographs, test 86F063.

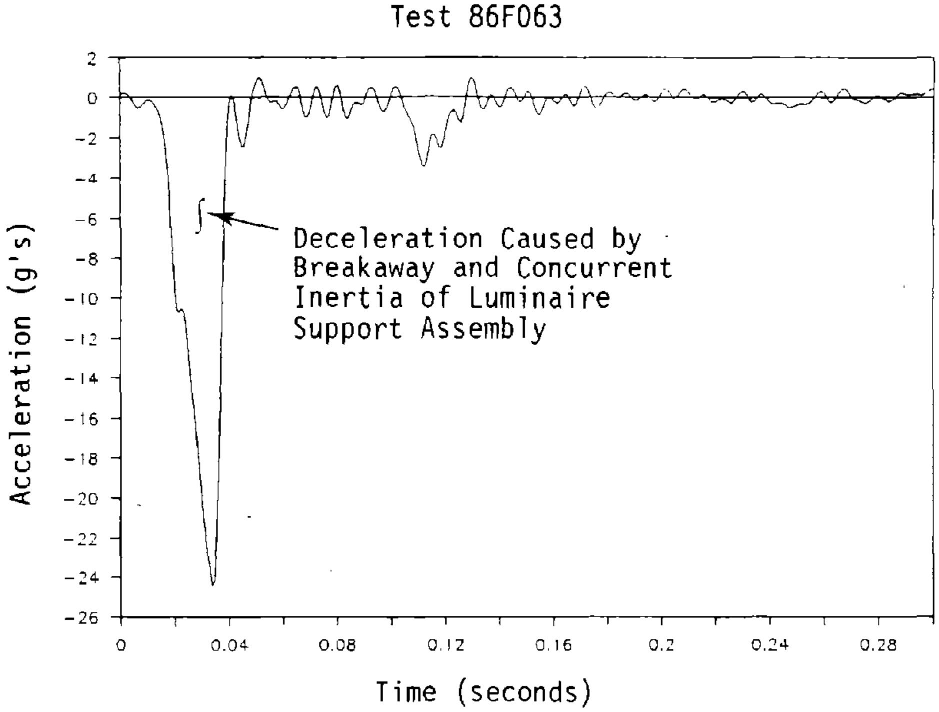


Figure 24. Acceleration vs time, cut-off frequency 100 Hz, test 86F063.

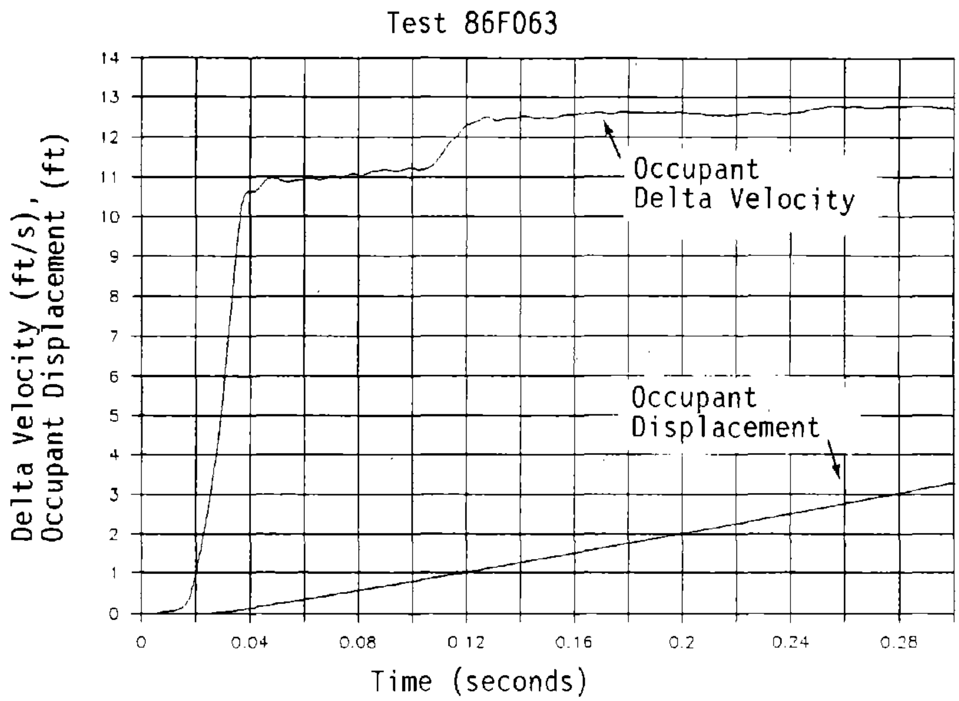


Figure 25. Occupant change in velocity and relative displacement vs time, cut-off frequency 100 Hz, test 86F063.

9. DISCUSSION

a. Validation of a Surrogate Vehicle: The validation of a bogie vehicle as a surrogate for assessing the safety performance of a breakaway luminaire support (that is, verification of agreement between surrogate vehicle results and actual automobile performance) can be segregated into four distinct levels of validation: (1) force-deflection curve comparison, (2) velocity change comparison, (3) crush-length comparison, and (4) physical modeling comparison. For each level of validation obtained, a higher overall level of validation is achieved. While it is desirable to obtain validation at all four levels, validation to a lesser level is appropriate for specific purposes, as discussed later. A discussion of the four levels of validation follows.

(1) Force-Deflection Comparison: The first level of validation is force-deflection curve comparisons. The bogie can be considered a reasonable loading device (as determined, for example, with low-speed (20 mi/h (8.94 m/s) rigid instrumented pole experiments) if the force-deflection curve of the bogie is similar to an automobile. That is, the force exerted by the bogie on the rigid instrumented pole (when plotted vs honeycomb aluminum crush) is equivalent to an automobile's loading pattern (when plotted against the automobile's actual frontal crush).

(2) Velocity Change Comparison: A second level of validation is based on velocity change comparisons. When combined with level 1, a higher level of validation is obtained. The bogie can be considered a reasonable predictor of velocity change when a series of tests (for example, into actual luminaire supports) indicates that the velocity change values of the bogie are similar to the automobile values at both low (20 mi/h (8.94 m/s)) and high (60 mi/h (26.8 m/s)) speeds. This would indicate that the areas under the respective acceleration-time traces are essentially equivalent for both the bogie and the automobile. It does not, however, indicate that the shape of the two traces are necessarily identical or even similar, merely that the velocity changes obtained are equivalent.

To be conservative, the bogie should either predict very closely or overestimate the velocity change, making it a "reasonable worst case" predictor.

This assures that no devices will be certified by the bogie that would fail tests using automobiles. Of course, a bogie also provides very repeatable, controlled conditions for certification testing, so that variations among different full-scale automobiles are eliminated.

(3) Crush-Length Comparison: A third (and even higher) level of validation couples the first two levels of validation with crush-length comparisons. A bogie can be used to predict the crush of a vehicle if the crush-length measurements (as determined from tests into actual luminaire supports) of the bogie and automobiles agree at both low and high speeds. That is, predictions of intrusion into the engine compartment of a vehicle can be made with a bogie which satisfies this criterion.

(4) Physical Modeling Comparison: The final and most complete level of validation includes physical modeling. Here, three interrelated phenomena must all agree between bogie and automobile: the impact dynamics, the chronology of breakaway, and the fracture patterns of the device (as determined from tests into actual luminaire supports). In addition, the lower levels of validation must also be achieved.

For the <u>impact dynamics</u> to be validated, the acceleration vs time history of the bogie and the automobile must be in agreement. That is, not only must the areas under the respective curves be reasonably the same, but the shape of the curves must also be reasonably similar. Because acceleration is proportional to force, this level of validation implies that the force applied to a breakaway device over a specific time period is essentially the same for a bogie and the corresponding automobile. It should be noted that this force is measured at the vehicle's c.g., not at the point of application between the vehicle and the breakaway device.

The <u>chronology of breakaway</u> is obtained by observing and comparing the breakaway of respective bases (when impacted by a bogie and an automobile) using high-speed film or other appropriate methods. Validation is achieved when the sequence of events during the breakaway of each device (i.e., initiate breakaway and complete breakaway) occur at approximately the same time for both the bogie and the automobile.

Finally, the resulting fracture patterns of each base can be obtained and compared after completion of the tests. Validation is achieved when the fracture patterns of bases impacted with the bogie and bases impacted with automobiles are reasonably similar.

Desired Level of Validation: The level to which a bogie surrogate must be validated is determined by the function which the bogie is to perform. Ideally, all levels of validation are obtained. However, for coupling mounted luminaire support certification testing, only levels 1 and 2 are necessary. This is because velocity change is the primary criterion for breakaway support acceptance. Therefore, a valid velocity change comparison must be obtained (level 2) as well as a valid force-deflection comparison (level 1). However, it is not necessary that the shape of the acceleration traces of the bogie and the automobile agree, nor, for that matter, that the breakaway chronology and fracture patterns agree (level 4). In addition, although desirable, it is not absolutely essential that the crush lengths closely correlate (level 3).

b. Impact physics: The physics of a vehicle impacting a breakaway type support can be analyzed using a three phase description, as shown in figure 26.[8]

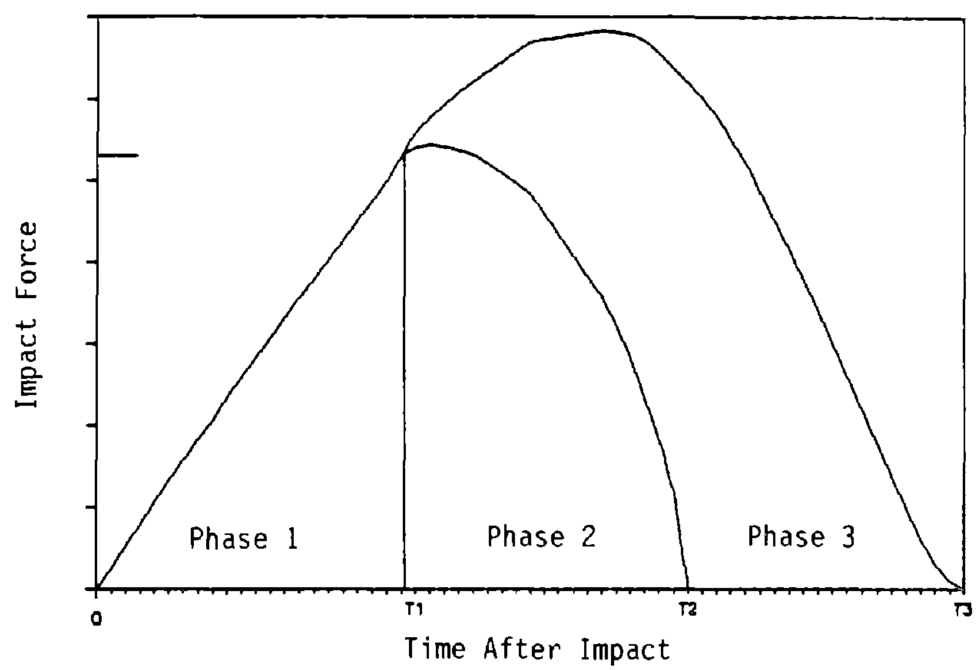


Figure 26. The three phase model of breakaway support behavior.

The first phase is defined by the vehicle crushing while the luminaire support remains relatively rigid. This phase lasts until the impact force becomes large enough to initiate fracture of the breakaway hardware. The second and third phases start at the initiation of fracture of the breakaway device. Phase 2 is associated with the completion of breakaway of the base, and phase 3 is associated with the acceleration of the luminaire support. Initiation of phases 2 and 3 takes place simultaneously since the base starts to move after initiation of fracture, thus accelerating the support while fracture continues and subsequently terminates. Note that the vehicle continues to crush during both phases 2 and 3 and that, after completion of phase 2 (i.e., breakaway), phase 3 (acceleration of the support) can continue for an extended period of time.

The impact force and the base fracture force are identical until the initial fracture of the device. After initiation of fracture, the base fracture force starts to decrease and is no longer the same as the impact force. During the combined phases 2 and 3, and even after completion of fracture when phase 3 exists solely, the impact force trace can continue to increase due to the inertia of the pole (particularly in high-speed tests). The impact force trace continues until the luminaire support is accelerated in translation and rotation to a velocity which is the same or greater than the velocity of the impact vehicle.

For 20 mi/h (8.94 m/s) impacts, the maximum value of the impact force and the force necessary to initiate fracture are thought to be approximately the same. This is because the force due to accelerating the support away from the vehicle is not significant (the luminaire support usually falls on the vehicle) and the force to complete fracture drops off rapidly. For 60 mi/h (26.8 m/s) impacts, however, this is not the case. The maximum impact force can often be much greater than the force to initiate fracture due to inertia forces caused by accelerating the support away from the vehicle.

c. Historic Data: During the developmental testing with the FOIL bogie vehicle, Alcoa aluminum couplings, model 100-1, were tested and the results were published in "Laboratory Procedures to Determine the Breakaway Behavior of Luminaire Supports in Mini-Sized Vehicle Collisions, Test Results Report - Task E Bogie Testing."(9)

Two tests were conducted at 20 mi/h (8.94 m/s). The tests utilized couplings from a manufacturer's processing lot other than that used for tests in this series. The first 20 mi/h (8.94 m/s) test, test 502, used couplings from the same lot, while the second test at 20 mi/h (8.94 m/s), test 505, used couplings from mixed lots.

The results (see table 14) of the 20 mi/h (8.94 m/s) tests show a significant difference in change in velocity. One possible explanation for this is that couplings from different lots can produce a large variation in change in velocity. Another possible explanation is that the difference shown is normal scatter. There are insufficient data, however, to draw a firm conclusion other than a significant difference in change in velocity is possible with identical coupling tests.

Table 14. Previous coupling tests.

TEST NUMBER	SPEED (mi/h)	CHANGE IN VELOCITY (ft/s)	VEHICLE CRUSH LENGTH (in)
502	20	15.5	18.4
505	20	19.6	19.6

d. Force-Deflection Comparison: With regard to level 1 validation, previous work by other researchers included a comparison of the force-deflection characteristics of the bogie vehicle with a 1979 Volkswagen Rabbit automobile, as shown in figure 27.(5) These tests were conducted by impacting each vehicle into a rigid, instrumented pole at low speed. The force-time histories were obtained from force gauges mounted on the pole, while the deflection-time histories were obtained from double integration of the same force-time histories (after dividing through by the vehicle mass) or from double integration of the vehicle (c.g.) accelerometer data. The resulting force vs deflection curves were then cross-plotted from these data.

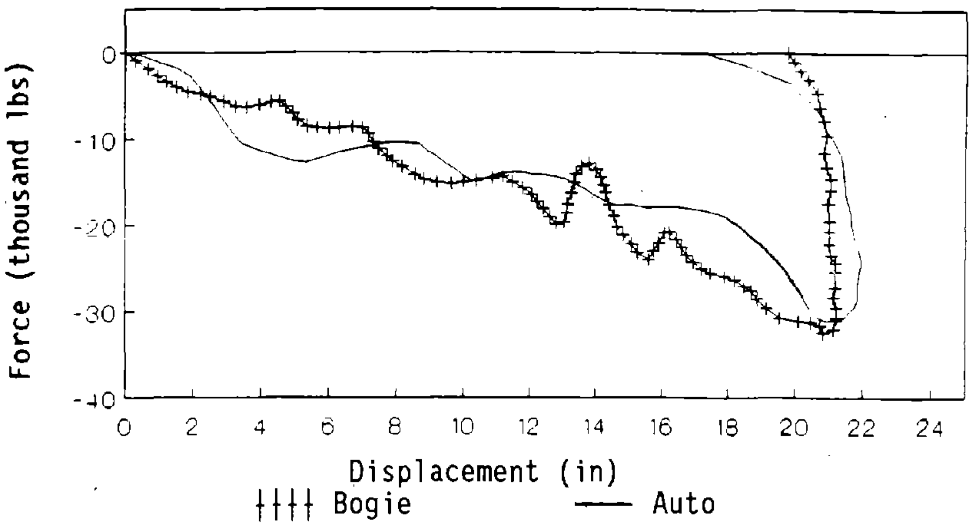


Figure 27. Force vs deflection, bogie and automobile, 20 mi/h.

The data presented in figure 27 indicate that the bogie vehicle's reported force-deflection characteristics are in reasonable agreement with the reported characteristics of a 1979 Volkswagen Rabbit automobile.

e. <u>Summary of Test Results</u>: Velocity change and crush-length data from all 20 mi/h (8.94 m/s) and 60 mi/h (26.8 m/s) tests conducted during this program are summarized in table 15. This table presents the velocity change collected from each independent measurement technique (speed traps, film and accelerometers) and the resulting reported change in velocity discussed in section 7. Also included is the flail space velocity computed from the accelerometer data in accordance with the procedures specified in NCHRP 230.

Table 15. Summary of test results.

	DELTA VELOCITY							
TEST VEHICLE	SPEED (mi/h)	TRAPS (ft/s)	FILM (ft/s)	ACC. (ft/s)	**REPORTED (ft/s)**	**FLAIL (ft/s)**	VEHICLE CRUSH LENGTH (in)	TEST NO.
Bogie	20	18.4	19.1	20.4	**19.2**	**20.3**	18.7	86F062
Auto	20	17.0	17.5	17.0	**17.2**	**16.7**	13.5	86F056
Bogie	60	8.9	8.6	12.7	**9.2**	**12.7**	24.3	86F061
Bogie	60	9.9	N/D*	12.0	**10.9**	**12.0**	25.9	86F063
Auto	60	7.1	7.7	8.2	**7.7**	**8.2**	16.5	86F058
Auto	60	8.2	7.7	8.5	**8.2**	**8.3**	16.0	86F060

*N/D = No Data

Highlighted in bold in table 15 are the columns containing the reported velocity change values and the flail space velocity change values. The reported velocity change is based upon measurements recording the change in velocity of the vehicle during the impact event. The flail space velocity change, on the other hand, is based upon a procedure which measures the relative difference between the velocity of the impacting vehicle and a theoretical occupant at the instant the occupant impacts an interior vehicular surface. For many impacts involving luminaire supports, the two velocity change values are essentially the same.

As discussed below, for purposes of comparison and validation, the reported velocity change values are considered more accurate and, therefore, more appropriate for the low-speed (20 mi/h, 8.94 m/s) test series. Thus, for low-speed, level 2 validation, the reported velocity change values are used. However, for the high-speed test series (60 mi/h, 26.8 m/s), the flail space velocity change values are considered more accurate and, thus, are used for the high-speed validation. The rationale for this is discussed below.

f. <u>Reported Versus Flail Space Velocity</u>: The reported change in velocity is calculated based on the weighted average of speed trap, high-speed film, and accelerometer velocity change values. All three measurements begin and terminate at the times coincident with the vehicle crossing the center of the pre-impact and post-impact speed trap, respectively. A weighted average technique is used in lieu of a simple average because the number of measurements (three) is small and a simple average does not necessarily yield the most accurate result, especially if one measurement tends to be grossly different from the others for no explainable reason (that is, one measurement is an outlier). The weighting factors used in the weighted average are calculated for each test using statistical distribution relationships.[7] These relationships are such that, if for any given test the three velocity measurements are essentially identical, the resulting weighting factors will also be identical (that is, a simple average results). However, if one velocity measurement tends to deviate from the other two for any reason, the corresponding weighting factor is automatically reduced relative to the other two (that is, the outlier is given less weight). The use of redundant measurements obtained from independent measurement techniques coupled with the weighted average statistical analysis procedure results in highly accurate vehicle velocity change values. These vehicle velocity change values, called the reported change in velocity, can be used for occupant impact velocity in place of the flail space velocity when correctly applied. Correct application depends upon the results of the test and is further discussed below.

Flail space velocity change values, on the other hand, are calculated using only accelerometer data. Because only one measurement technique is used, rather than three independent techniques, the flail space velocity change is less accurate, under many circumstances, than the reported velocity change. Flail space velocity change (in the longitudinal direction) is based upon an occupant movement or "flail space" concept. Given an impact, the occupant moves forward relative to the car until an interior surface is struck. This interior surface/occupant collision is assumed to occur at a relative distance (movement) of 2.0 ft (0.61 m). To determine the velocity of impact (the flail space velocity change), the longitudinal vehicle accelerometer trace is double integrated to determine the time at which movement of 2.0 ft (0.61 m) has occurred. The same trace is then single integrated to determine the velocity change occurring at that time. This velocity change is the flail space velocity change.

For low-speed tests, since all impact events (breakaway, separation and theoretical occupant impact) are completed prior to crossing the post-impact speed trap, the <u>reported</u> change in velocity is considered to be the more accurate representation of occupant impact velocity. As such, this representation is used for the low-speed, level 2 comparisons between the bogie and automobile. As noted above, the higher accuracy is due to the three redundant measurements (from speed traps, film and accelerometers) and to the statistical weighted averaging procedure.

To clarify why application of this method for calculating velocity change is valid, consider figure 28. For low-speed tests, breakaway, separation, theoretical occupant impact and post-impact speed trap crossing usually occur in the order stated, as shown in the figure. When this order of events is maintained and when contact between the vehicle and the luminaire support does

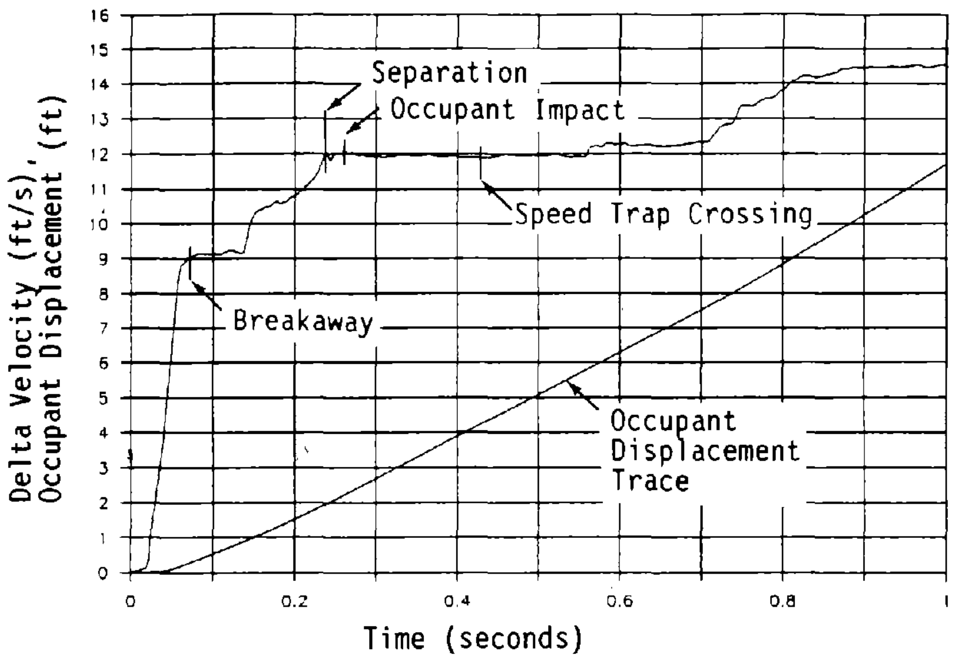


Figure 28. Occupant change in velocity and relative displacement vs time, typical low-speed test.

not reoccur, there is negligible difference in vehicle velocity at the time of theoretical occupant impact and at the subsequent time at which the vehicle traverses the post-impact speed trap. (As previously stated, the film and accelerometer data analyses are also terminated at this time to provide an identical time period for calculation as the speed trap data analysis.) This constant velocity condition is usually the case with low-speed tests. Therefore, when the above conditions are met, the reported method for calculating velocity change is more accurate and more appropriate than the flail space method. This calculation method is also valid for low-speed tests in which breakaway and separation do not occur (see figure 29).

As shown in figure 29, the order of the remaining events (theoretical occupant impact and, in this case, pre-impact speed trap recrossing) does not change. As in the previous case, the vehicle velocity during both events is essentially the same. Therefore, this calculation method is again valid and accurate.

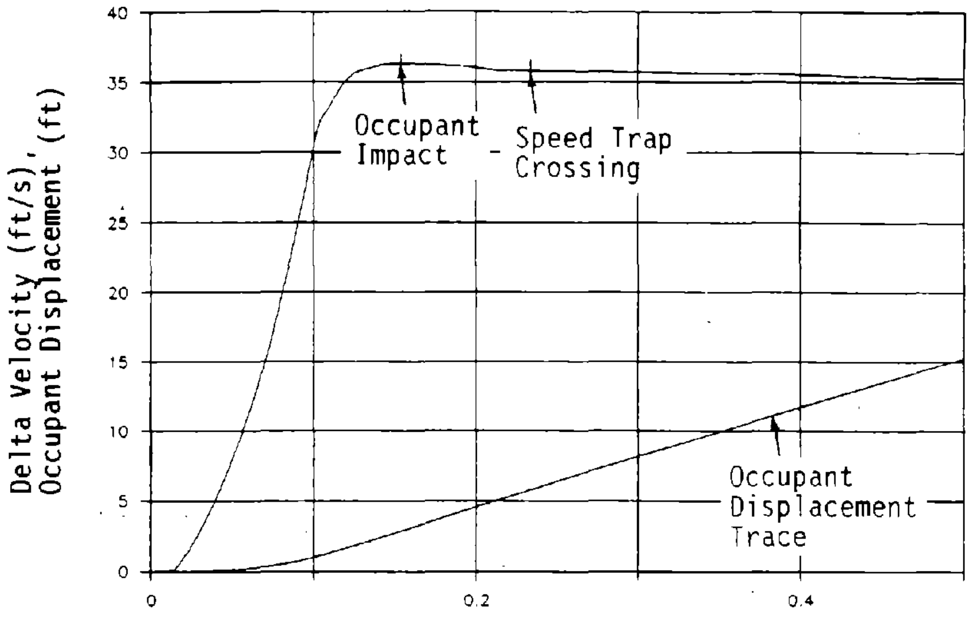


Figure 29. Occupant change in velocity and relative displacement vs time, typical low-speed test without breakaway.

The situation is different with high-speed tests, where frequently there is extended contact between the vehicle and the luminaire support. Because of this extended contact, and because the location of the post-impact speed trap for this series of tests was too close to the impact point (see figure 30), the vehicle was often still decelerating as it crossed the post-impact speed trap (again, the time at which all velocity change analyses are terminated under the reported velocity calculation method). As such, for this series of tests, the flail space change in velocity is considered to be the more accurate representation of occupant impact velocity. Therefore, for this series of tests, this representation is used for the high-speed, level 2 (velocity change) comparisons between the bogie and automobile.

To clarify why this method is used, in lieu of the reported method, consider figure 30. For high-speed tests, breakaway, separation, theoretical occupant impact and post-impact speed trap crossing <u>do not</u> usually occur in the order stated, as shown in the figure. Due to the relatively close proximity of the post-impact speed trap in this series of tests, both

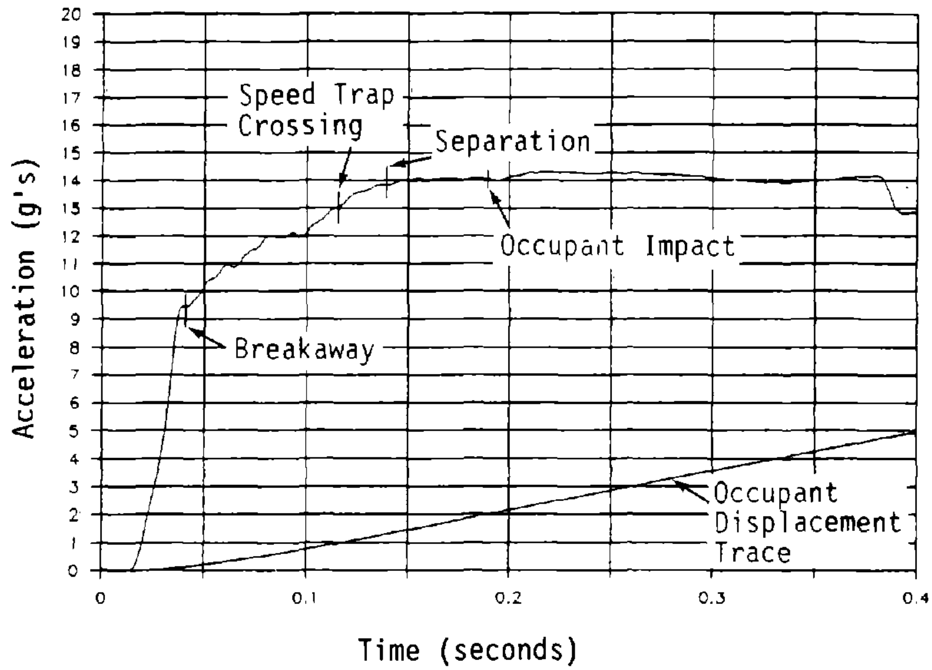


Figure 30. Occupant change in velocity and relative displacement vs time, typical high-speed test.

separation and theoretical occupant impact occur after the crossing of the speed trap. Because separation occurs after traversal of the speed trap, the vehicle is still undergoing deceleration; thus, its velocity at the time of theoretical occupant impact is less than during traversal of the post-impact speed trap. Therefore, because the order of impact events is changed (that is, separation occurs after speed trap crossing), the two velocities are not identical. As a result, the necessary conditions for application of the reported velocity change method are not satisfied, and the less accurate, one-measurement technique flail space method must be used.

This is particularly true when a very heavy luminaire support is impacted at high speed (see figure 31). As shown in this figure, the order of events again changes due to even greater extended contact between the vehicle and the luminaire support. In this case, the separation of the support occurs after both the theoretical occupant impact and the speed trap crossing. As before, the vehicle velocity at the time of occupant impact is different (here, much

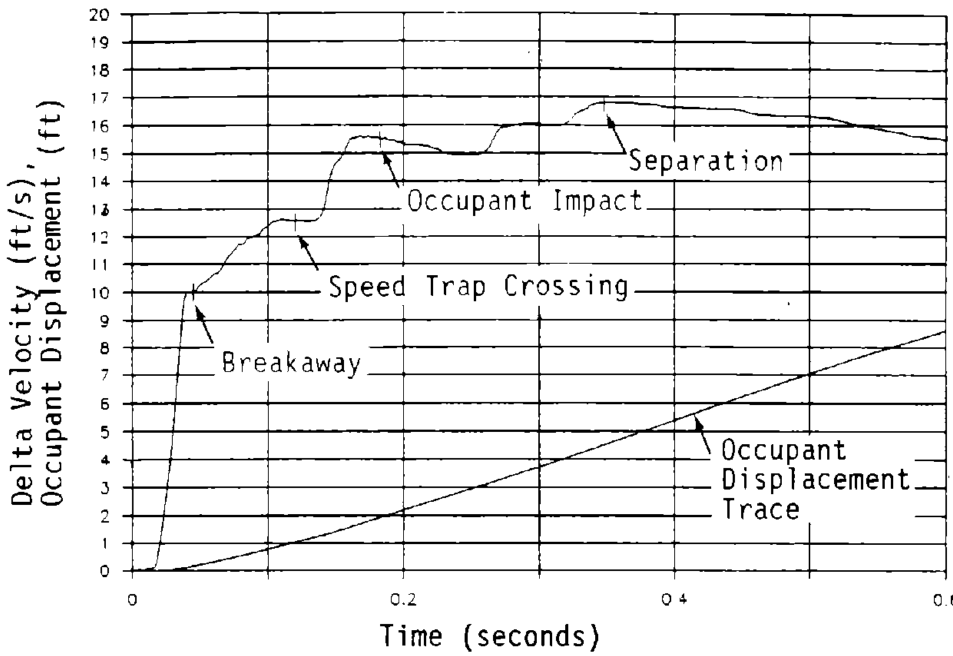


Figure 31. Occupant change in velocity and relative displacement vs time, typical high-speed test with heavy luminaire support.

less) than during crossing of the post-impact speed trap. Again, the necessary conditions for application of the reported velocity change method are not satisfied and the less accurate flail space method must be used instead.

g. <u>20 mi/h Comparison Test</u>: Two tests were performed with a 20 mi/h (8.94 m/s) test speed, one automobile and one bogie vehicle test. The following paragraphs discuss analysis of these 20 mi/h (8.94 m/s) tests with respect to level 2 (velocity change comparisons) and level 3 (crush-length comparisons) validation requirements.

(1) Velocity Change Comparison: The change in velocity for the two tests are compared in table 16 and figure 32. For these low-speed tests, the reported rather than the flail space velocity change values are used because they are considered to be the more accurate representation of occupant impact velocity and, hence, injury potential (see section 9f, Reported Versus Flail Space Velocity, for discussion).

Table 16. Summary of test results at 20 mi/h.

TEST VEHICLE	REPORTED DELTA VELOCITY (ft/s)	TEST NO.
BOGIE	19.2	86F062
AUTO	17.2	86F056

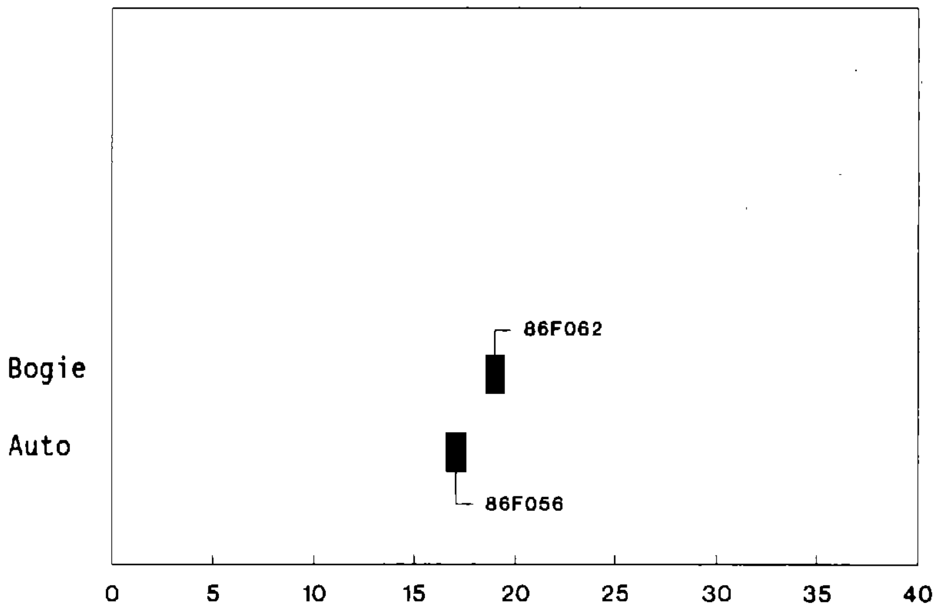


Figure 32. Range of velocity change values, bogie and automobile at 20 mi/h.

The velocity change values for the 20 mi/h (8.94 m/s) tests show that the bogie vehicle produces a slightly higher value than that of the automobile. However, this value is well within the range of expected deviation of couplings in general, as can be seen in section 9c.

(2) Crush-Length Comparison: Crush lengths for this series of tests are compared in table 17 and figure 33. Two crush-length columns are presented in the table. Measured crush length is taken from the crash test data sheets. Since the bogie honeycomb includes a "zero resistance" cartridge directly

behind the nose, the thickness of this cartridge (2 in (0.051 m)) for a low-speed test) is subtracted from the measured bogie values to obtain the actual crush lengths. The cartridge is a piece of very soft honeycomb which does not transmit a force to the bogie. Therefore, since no work is done on the bogie by the crush of this cartridge, the thickness of this cartridge can be ignored (see section 9i for additional discussion).

Table 17. Bogie and automobile crush-length comparisons at 20 mi/h.

TEST VEHICLE	REPORTED DELTA VELOCITY (ft/s)	MEASURED CRUSH LENGTH (in)	**ACTUAL CRUSH LENGTH (in)**	**NORMALIZED CRUSH LENGTH (in/ft-kip)**	TEST NO.
BOGIE	19.2	18.7	**16.7**	**.76**	86F062
AUTO	17.2	13.5	**13.5**	**.64**	86F056

1 ft/s = 0.305 m/s   1 in = 0.0254 m   1 ft-kip = 1354 N·m

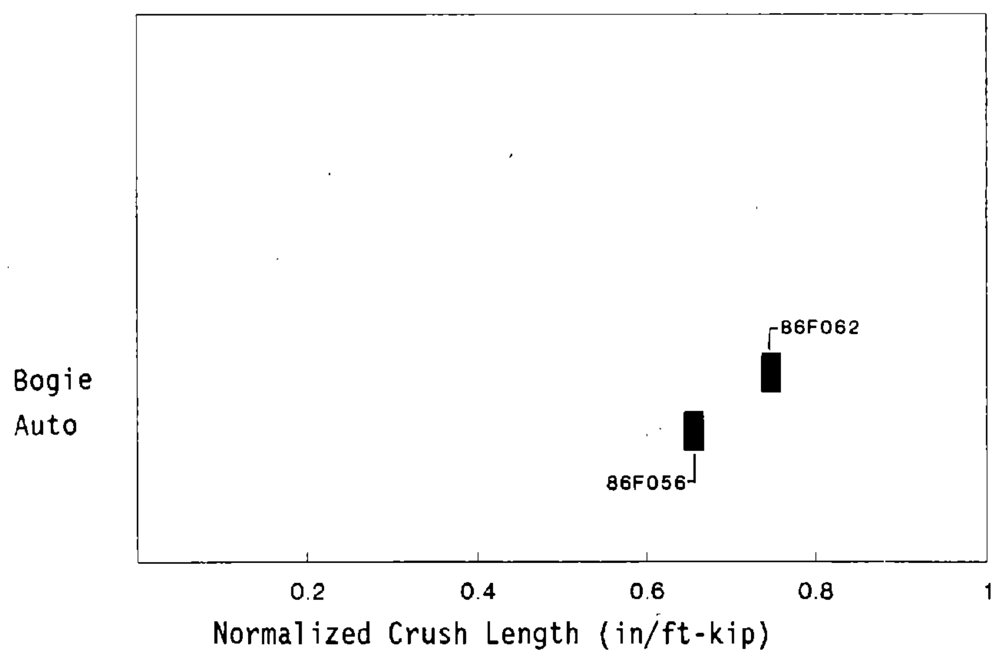


Figure 33. Range of normalized crush-length values, bogie and automobile at 20 mi/h.

The actual crush length (L_{crush}) has been normalized by the change in kinetic energy (Delta K.E.) of the vehicle. Since the work done on the vehicle is the integral of the force (F_{impact}) acting on the vehicle from the luminaire support times the crush (if the tire and aerodynamic forces are neglected), and since this work is equal to the change in the kinetic energy of the vehicle, this normalization is essentially a measure of the reciprocal of the average force (F_{avg}) acting on the vehicle. That is,

$$\begin{aligned} \text{Delta K.E.} &= \int F_{impact}\, dL_{crush} \\ &= F_{avg}\, L_{crush} \\ L_{crush,\ normalized} &= L_{crush} / \text{Delta K.E.} \\ &= 1 / F_{avg} \end{aligned}$$

Thus, normalized crush is equivalent to the reciprocal of the average force when all units of measure are correctly accounted for. However, in the following comparisons, the crush length is expressed in inches (meters) and the change in kinetic energy is expressed in ft-kips (N·m), consistent with common usage and convention for each.

The normalized crush lengths listed in table 17 above take into account the different force levels resulting from variations in the impact velocity and from variations in velocity change observed in the tests, and allow for a straightforward comparison of crush length.

At an impact speed of 20 mi/h (8.94 m/s), the crush length of the bogie is higher than that of the car. This suggests that the bogie normalized crush length at low speed (not including the length of the "zero resistance" cartridge) can be expected to be higher than the normalized crush of an automobile.

h. <u>60 mi/h Comparison Test</u>: Four tests were performed with a 60 mi/h (26.8 m/s) test speed, two with the bogie vehicle and two with an automobile. The following paragraphs discuss the analysis of these 60 mi/h (26.8 m/s) tests with respect to level 2 (velocity change comparisons) and level 3 (crush-length comparisons) validation requirements.

(1) Velocity Change Comparison: The changes in velocity of the four tests are compared in table 18 and figure 34. For these high-speed tests, the flail space rather than the reported velocity change values are used because they are considered to be the more accurate representation of occupant impact velocity and, hence, injury potential (see section 9f, Reported Versus Flail Space Velocity, for discussion).

Table 18. Summary of test results at 60 mi/h.

TEST VEHICLE	FLAIL SPACE DELTA VELOCITY (ft/s)	TEST NO.
BOGIE	12.7	86F061
BOGIE	12.0	86F063
AUTO	8.2	86F058
AUTO	8.3	85F060

1 ft/s = 0.305 m/s

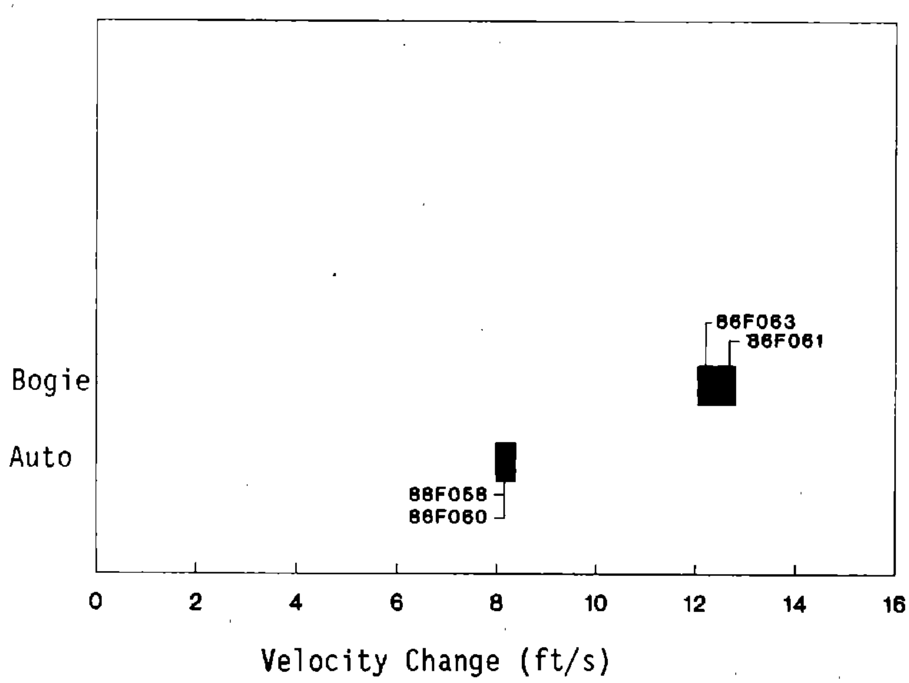


Figure 34. Range of velocity change values, bogie and automobile at 60 mi/h.

The changes in velocity for the bogie vehicle were 12.7 ft/s (3.98 m/s) and 12.0 ft/s (3.66 m/s), while the automobile changes were 8.2 ft/s (2.50 m/s) and 8.3 ft/s (2.53 m/s). The range of velocity change for the bogie vehicle is higher than that of the automobile. This may be due in part to the variation in the coupling's breakaway performance, though it appears that the bogie is more conservative than the particular automobile tested.

(2) Crush-Length Comparison: Crush lengths of this series of tests are compared in table 19 and figure 35. As with the low-speed data, two crush-length columns are presented in the table. Measured crush length is taken from the crash test data sheets. Since the bogie honeycomb includes "zero resistence" cartridges directly behind the nose, the thickness of these cartridges (5 in (0.13 m) for a high-speed test) is subtracted from the measured bogie values to obtain the actual crush lengths. As mentioned above, these cartridges are pieces of very soft honeycomb which do not transmit a force to the bogie. Therefore, since no work is done on the bogie by the crush of these cartridges, the thickness of these cartridges can be ignored. (See section 9i for additional discussion.)

Table 19. Bogie and automobile crush-length comparisons at 60 mi/h.

TEST VEHICLE	FLAIL SPACE DELTA VELOCITY (ft/s)	CRUSH LENGTH (in)	**ACTUAL CRUSH LENGTH (in)**	**NORMALIZED CRUSH LENGTH (in/ft-kip)**	TEST NO.
BOGIE	12.7	24.3	**19.3**	**0.33**	86F061
BOGIE	12.0	25.9	**20.9**	**0.37**	86F063
AUTO	8.2	16.5	**16.5**	**0.41**	86F058
AUTO	8.3	16.0	**16.0**	**0.41**	86F060

1 ft/s = 0.305 m/s 1 in = 0.0254 m 1 ft-kip = 1354 N·m

The actual crush length is normalized by the change in the vehicle's kinetic energy, as discussed in the previous section. At an impact speed of 60 mi/h (26.8 m/s), the normalized crush length of the bogie is somewhat lower than that of the automobile. This suggests that the bogie normalized crush length at high speed (not including the length of the "zero resistance" cartridge) can be expected to be lower than, though close to, that of an automobile.

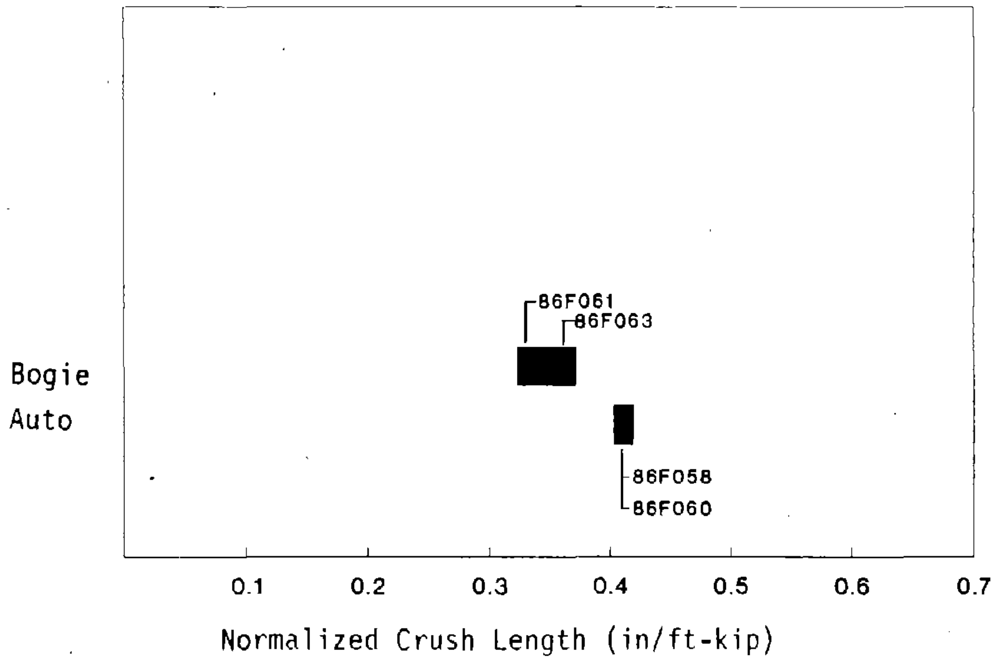


Figure 35. Range of normalized crush-length values, bogie and automobile at 60 mi/h.

i. Physical Modeling Comparison: This section analyzes both the 20 mi/h (8.94 m/s) and the 60 mi/h (26.8 m/s) tests with respect to level 4 (physical modeling comparison) validation requirements. However, prior to discussion of those elements comprising this validation level (i.e., impact dynamics, chronology of breakaway and fracture patterns), a discussion of typical low-speed and high-speed acceleration traces for each vehicle ensues, followed by an explanation of the breakaway mechanism found in Alcoa model 100-1 breakaway couplings.

(1) Low-Speed Test Acceleration Traces: A plot of a typical 20 mi/h (8.94 m/s) longitudinal acceleration vs time (from impact) trace from transducers located at each vehicle's c.g. is shown in figure 36.

A study of this figure indicates that the bogie vehicle's acceleration trace displays a short time delay (approximately .010 s) from impact to the onset of deceleration while the automobile's trace shows deceleration immediately subsequent to impact. This delay is due to the construction of the

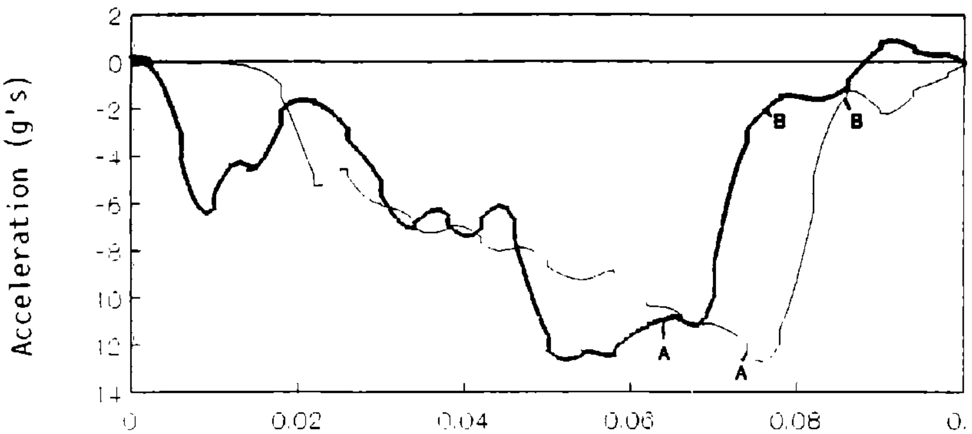


Figure 36. Acceleration vs time, bogie and automobile, 20 mi/h.

bogie's crushable front end. Aluminum honeycomb cartridges are placed in front of the striker surface (called the "nose") to eliminate "spiking" of the luminaire support by the striking nose surface. Immediately behind the nose, one or two (depending upon test speed) honeycomb cartridges with essentially "zero resistance" are inserted to allow the nose to decelerate to rest prior to compression of the remainder of the honeycomb cartridge stack and concurrent application of the full mass of the bogie on the luminaire support. Thus, prior to compression of the "zero resistance" cartridges, the support is acted on by a force which contains only the mass of the nose. After compression of the "zero resistance" cartridges, the force acting on the support is due to the full mass of the bogie vehicle.

Because no force transfer takes place between the striking nose surface and the body of the bogie vehicle until the "zero resistance" cartridges are completely crushed (at which time the nose is at rest against the pole), a delay results before the accelerometer at the bogie c.g. detects any measurable deceleration. However, the corresponding accelerometer placed at the c.g. of the automobile detects deceleration immediately following the instant of impact due to an integral connection between the bumper and the body of the automobile.

Following the two acceleration traces further in time, the deceleration of each vehicle continues to increase until coupling fracture begins. (The automobile trace decreases prior to peaking, probably because of a soft inner space between body components and engine components.) The maximum deceleration occurs near the point where the couplings begin to break away for both the bogie and the automobile. The relative difference in the peak acceleration between the vehicles (both in magnitude and in time) may be attributed in part to variations in the breakaway characteristics of each set of couplings.

(2) High-Speed Acceleration Traces: A plot of typical 60 mi/h (26.8 m/s) longitudinal acceleration vs time (from impact) traces from transducers located at each vehicle's c.g. is shown in figure 37.

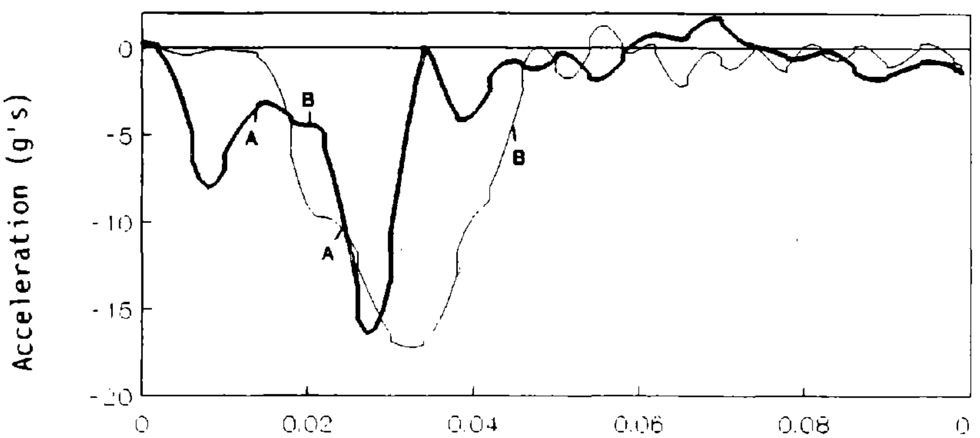


Figure 37. Acceleration vs time, bogie and automobile, 60 mi/h.

A study of this figure indicates that, as was the case in low-speed impacts, the bogie vehicle's acceleration trace displays a short time delay following impact (again, approximately .010 s), while the automobile's trace immediately decelerates. The reason for this delay is the same as that in the low-speed (20 mi/h, 8.94 m/s) impacts. That is, the delay is due to the design of the bogie vehicle's striking "nose" surface (see previous discussion of low-speed acceleration traces in this section). The bogie vehicle's deceleration increases and then the couplings begin to fracture. The bogie vehicle reaches its maximum deceleration simultaneously as the couplings are broken away from their mounting studs and the pole is accelerated in the direction of the impacting vehicle.

Following the automobile trace in time, deceleration starts the instant of impact and continues to increase. Just prior to the couplings breaking away, there is a momentary decrease in deceleration. Thereafter, deceleration continues to increase to its maximum value. The cause for this second increase is the inertial resistance supplied by the pole to the vehicle. After deceleration reaches its maximum value, the pole is accelerated away from the impacting vehicle and the accelerometer trace returns to zero.

The peak values of deceleration of the vehicles are roughly equivalent, although the bogie vehicle's peak occurs somewhat later in time. This equivalence in peak values is probably due more to the identical inertial characteristics of the two luminaire supports impacted than to the characteristics of the two impacting vehicles. (Following breakaway, it is reasonable to assume that, given the same luminaire support with the same weight and the same c.g. location, the peak deceleration (or force) caused by the inertia of the pole on each vehicle would be the same or similar.)

(3) Typical Breakaway Mechanism: To aid in the understanding of the impact dynamics of the breakaway couplings used in this series of tests, an explanation of their breakaway mechanism follows.

Failure of the Alcoa model 100-1 coupling is initiated when the impact force is high enough to begin fracture in the vertical grooves. When the pole is struck by the impacting vehicle, the front pair of couplings generally fractures first, and the studs connecting the base of the pole to the couplings lose their integrity and are pushed from the coupling. The same sequence then occurs with the rear pair of couplings. This phenomenon occurs when the pole is impacted at 20 mi/h (8.94 m/s) by both the bogie vehicle and the automobile. However, at an impact speed of 60 mi/h (26.8 m/s), the pole begins to buckle in the area struck by the impacting vehicle.

In tests using the bogie vehicle, the impact load is in a small region centered at a height of 17.5 in (0.445 m). With the impact load concentrated in a small area on the pole, the pole buckles significantly when struck at high speed and, in somes cases, tears from the mounting shoe to which it is welded, as shown in figure 38. This causes the breakaway event to be extended, thus consuming more of the vehicle's momentum.

Tests with the Volkswagen Rabbit created a load which initially was at bumper height, 18 in (0.458 m) above the ground, but subsequently was spread over a large area centered at a height of about 12 in (0.305 m). With the impact load spread over a larger area, the pole, when struck, only buckled slightly as in figure 39. The automobile continued to crush until it came in contact with the shoe to which the pole is welded and the couplings are mounted. The couplings then broke away in the manner described earlier. The differences in the frontal impact surfaces between the bogie and the automobile and the resulting differing load application heights lead to extended breakaway for the bogie, which causes the change in velocity for the bogie vehicle to be greater than that of an automobile.

(4) Impact Dynamics: The first part of physical modeling, as discussed in section 9a, is impact dynamics. The acceleration data presented in the previous discussion in this section indicate that the bogie interacts somewhat differently than the automobile when impacting coupling mounted luminaire supports at both low and high speeds. The bogie experiences a delay in sensing deceleration, while the automobile does not (due to the presence of a bumper).

(5) Chronology of Breakaway: At low speed, initiation of fracture occurs at a slightly later time with the bogie than with the automobile. However, the durations of fracture are very similar. At high speed, the time to initiate breakaway with the bogie is somewhat later as compared to the automobile. In addition, the duration of fracture is longer and the force levels experienced are greater with the bogie vehicle than with the automobile.

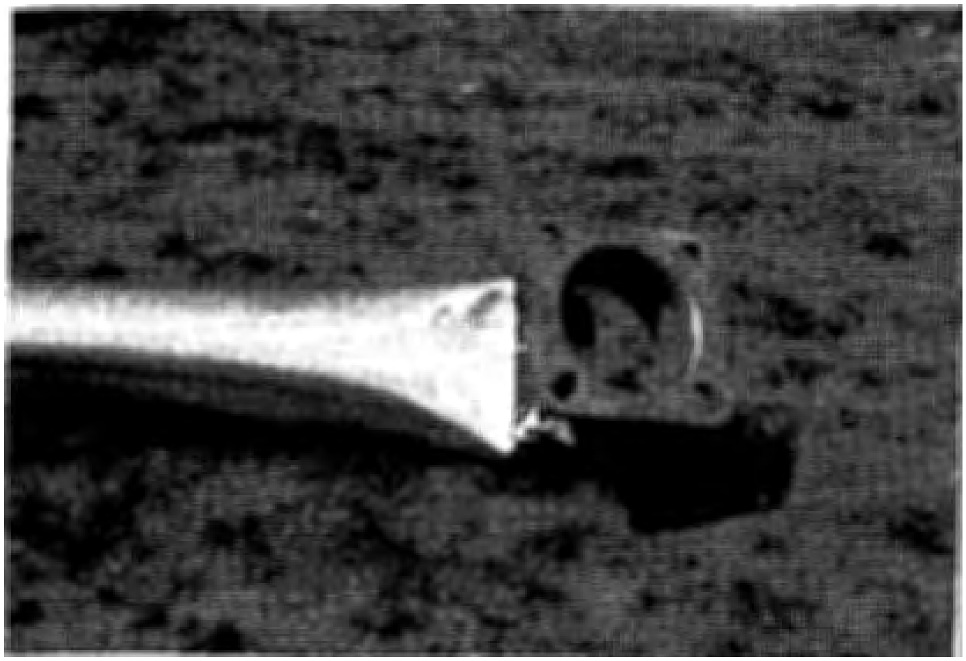


Figure 38. Pole when impacted by the bogie vehicle.

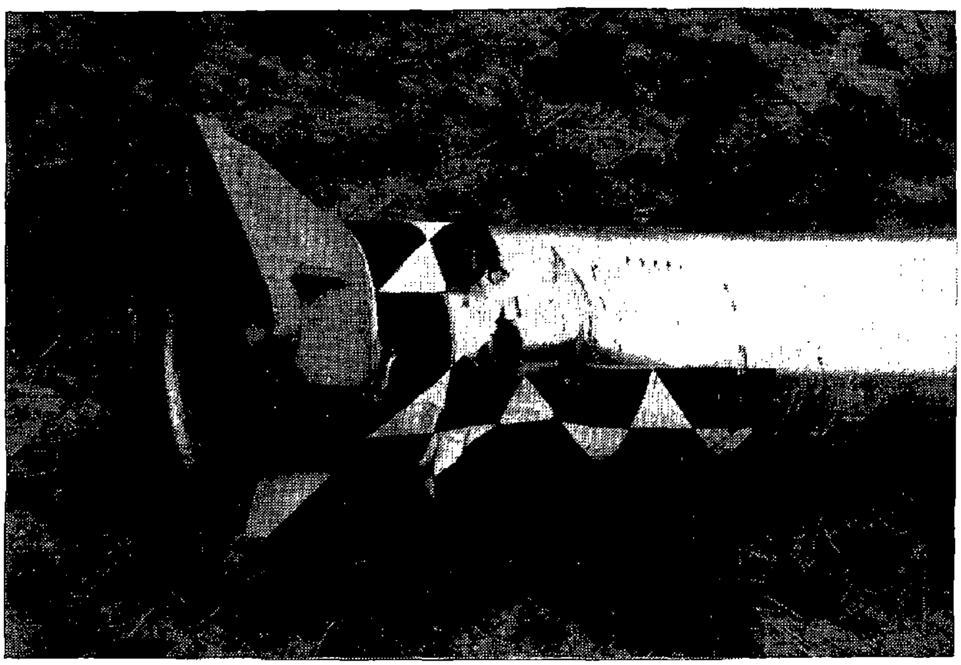


Figure 39. Pole when impacted by an automobile.

(6) Fracture Patterns: The third and final part of physical modeling is a comparison of fracture patterns of couplings impacted with the bogie and with an automobile. Figures 40 and 41 show photographs of coupling devices impacted with the bogie and with an automobile. These figures are typical of both low- and high-speed impacts. As can be seen in these photographs, the patterns are very similar, indicating that the bogie does model the automobile with regard to observed fracture patterns.

Figure 40. Typical coupling fracture patterns when impacted by an automobile.

10. CONCLUSIONS

a. Force-Deflection Comparison: The results of previous studies discussed in section 9d indicate that the bogie vehicle force-deflection characteristics reasonably model the characteristics of a 1979 Volkswagen Rabbit automobile.

b. Velocity Change Comparison: Historic data have shown that the repeatability of the breakaway couplings' performance is poor. Therefore, to expect extremely close correlation between tests is, perhaps, unrealistic. Correlation must be found by assessing the results of several tests made with

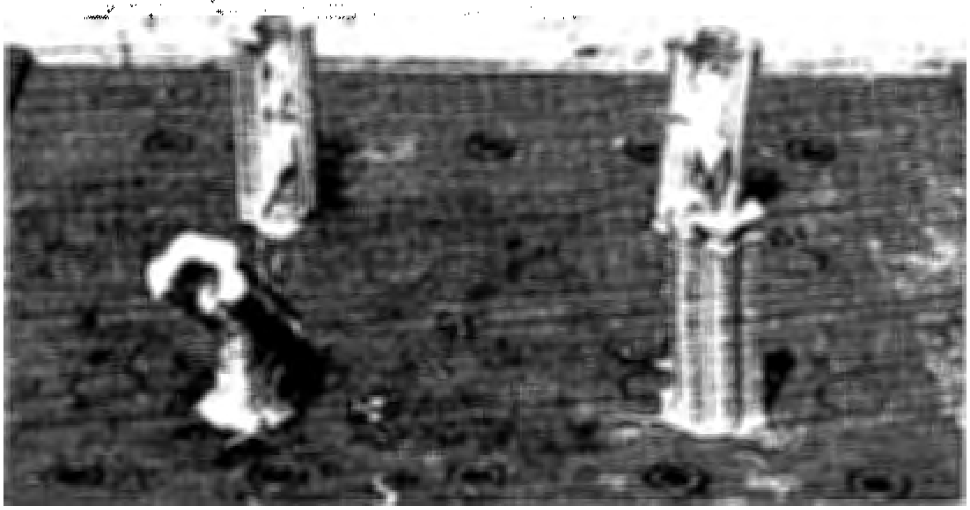


Figure 41. Typical coupling fracture patterns when impacted by the FOIL bogie vehicle.

the bogie and with the automobile. If the results are at least close, then correlation has probably been obtained.

The results of this study tend to indicate a trend toward a higher velocity change for the bogie vehicle, particularly for high-speed tests. During the high speed tests of this series, thin-walled aluminum poles were used. These poles deformed significantly when impacted by the concentrated load of the bogie vehicle's nose. This deformation contributed to the increased velocity change experienced by the bogie compared with the automobile. It is expected that the velocity change correlation would be better if stiffer and/or heavier poles were tested.

Based on these results, the bogie vehicle is a conservative predictor of change in velocity and is more accurate at low speed (20 mi/h (8.94 m/s)), where most devices which are unacceptable fail the change in velocity criterion.* Therefore, the bogie can be considered to be a reasonable surrogate for the testing of breakaway luminaire supports when mounted with coupling devices, though it is very conservative at high speed (particularly with lightweight, easily deformable poles).

c. Crush-Length Comparison: For high-speed tests, the normalized crush length of the bogie was slightly less than that of the automobile. At low speeds, the bogie crush was somewhat more than that of the automobile, though only one test with each vehicle was conducted. Thus, the bogie should be used only for crush-length comparisons at high speeds, where the bogie values are close to that of an automobile, unless additional tests at 20 mi/h (8.94 m/s) can be conducted which reveal that the bogie is a better model at low speed.

d. Physical Modeling Comparison: The bogie vehicle acceleration curves do not agree with the automobile curves because the dynamics of the breakaway are not the same. In addition, the chronology of the breakaway is not the same. However, the fracture patterns of couplings impacted with the bogie and with an automobile are similar.

e. Additional Conclusions: Based on previous efforts, the change in velocity determined using three independent measurement techniques and a statistical weighting function is more accurate than a simple integration of accelerometer data to obtain the flail space velocity. This is true if the duration of impact is short and the speed trap is correctly located. For the high-speed tests conducted during this study, the speed traps were too close to the impact point, so that the less accurate flail space results had to be used.

The time history of the velocity change should be checked after each test to determine when the impact event ends in relation to the 2-ft (0.61 m) occupant flail location and the speed trap location. If there is no substantial velocity change between the location of the speed trap and the 2-ft (0.61 m) flail point, then the weighted average of the three redundant measures of

* Only very heavy luminaire supports tend to fail the high-speed test (60 mi/h (26.8 m/s)) where the unacceptable changes in velocity are due to the high inertial properties of these supports.

velocity change should be used. If there is a substantial change in velocity between these two locations, then the flail space velocity determined from integration of the accelerometer should be used.

f. Closing Remarks: The bogie vehicle developed and evaluated at the FOIL has been shown to provide both low- and high-speed first level (force-deflection comparison) and second level (velocity change comparison) validation, and high-speed third level (crush-length comparison) validation. With regard to fourth level validation (physical modeling), the bogie produces similar fracture patterns when impacting coupling devices, but the impact dynamics and the chronology of breakaway are somewhat different.

Because the bogie vehicle has been validated at both the first and second levels, it can be used as a surrogate vehicle for determining the expected velocity change when a luminaire support mounted with couplings is impacted with a small, 1800 lb (817.2 kg) vehicle. In addition, since it has been validated for high speed at the third level, it can be used to estimate intrusion into the engine compartment when a small vehicle impacts at high speed a luminaire support mounted on coupling devices.

11. List of References

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