# Development of Variable Yaw Angle Side Impact System and Testing on Double Thrie Beam Median Barrier

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A side impact system for projecting crash test vehicles in side skids was developed and tested. The system incorporates a side impact carriage (SIC) that can be modified to position the test vehicle at different yaw angles, a guidance rail, an impact attenuator, a skid deck, and tow cable propulsion. The SIC is a modified lightweight test bogie designed to carry test vehicles weighing up to 1170 kg. The SIC is loaded with the vehicle and towed up to the skid deck by a 1-ton pickup truck pulling the cable through a pulley. The SIC hits the skid deck at the wheel supports for the test vehicle, causing them to collapse. The vehicle drops onto the lubricated skid deck, and skids in channels positioned to maintain the correct yaw angle. The SIC travels underneath the deck and slows to a stop after colliding with the impact attenuator. The vehicle skids off the deck and onto the ground surface in front of the test article. After several trial tests, the system was used to project a Honda Civic in a side skid at a counterclockwise yaw angle of 31 degrees, a trajectory angle of 22 degrees, and an impact speed of 66.5 km/hr into a double thrie beam median barrier. The side impact system needs modifications and more testing. The double thrie beam median barrier meets the occupant risk and structural adequacy (but not the vehicle trajectory) evaluation criteria for Test 2-10 of the National Cooperative Highway Research Program Report 350 guidelines. The test indicated the need to conduct more side-skid testing of the double thrie beam median barrier.

To improve the performance of roadside safety features in side-skidding collisions at various yaw angles, a crash-testing system must be developed to replicate this type of vehicle behavior. Although new roadside feature designs are tested adequately for crash worthiness in tracking collisions, side-skidding impacts can result in different occupant injuries, vehicle dynamics, and vehicle damage.

Typically, crash-worthiness tests for longitudinal barriers are performed with tracking vehicles having impact angles of 15, 20, and 25 degrees. In the report *Side Impact Crash Testing of Roadside Structures,* a comprehensive list of side impact tests conducted throughout the world reveals only tests with yaw angles of 90 and 45 degrees into narrow objects (*1*). A literature search revealed that no side skidding or side impact crash tests into longitudinal barriers had been conducted at yaw angles other than 90 degrees. The only operating side impact carriage in the U.S. is at the Federal Outdoor Impact Laboratory of the Federal Highway Administration in Virginia. It has only been used to project vehicles into narrow objects at 90 degree yaw angles.

The California Department of Transportation (Caltrans) Legal Division in Los Angeles requested the researchers to assist in defending a tort liability claim. The claim resulted from a cross-median accident involving a 1989 Honda Civic passing under a cable barrier. The Honda skidded sideways across the soil median center line along a trajectory angle of 22 degrees, at approximately 80.5 km/hr and in a counterclockwise yaw of 32 degrees. Hence, the apparent angle of impact with the barrier was 32 + 22 = 54 degrees. The vehicle was assumed to have translated with no rotation. Crash Test 523 was intended to replicate this accident at the same speed and angles, but with a double thrie beam barrier. The cable barrier at the accident site was subsequently replaced with a double thrie beam barrier.

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The objectives of this project were as follows:

1. Develop a side impact system capable of projecting a Honda Civic for Crash Test 523, as described previously. Although this was the only test budgeted for the project, it would be designed for any similarly sized vehicle to be projected into a smooth, translating side skid at any yaw angle and at speeds up to 100 km/hr.
2. Evaluate the performance of a double thrie beam median barrier in a side skid collision based on National Cooperation Highway Research Program (NCHRP) Report 350 guidelines.
3. Conduct a crash test with this system for the Caltrans Legal Division in defense of a legal case scheduled to start trial August 1, 1994. Because of the limited scope of this paper, details of this legal case will not be presented.

## TECHNICAL DISCUSSION

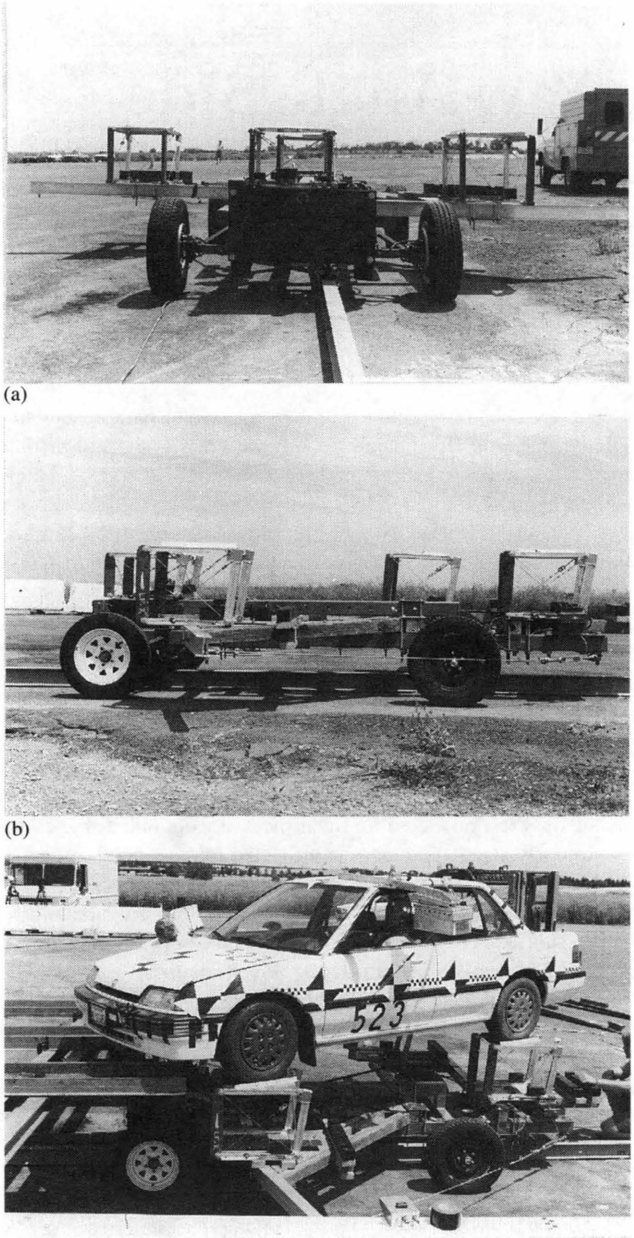
### Part A: Development of Side Impact System

*General*

The following design criteria were set for the side impact system:

1. The side impact carriage (SIC) would be the existing Caltrans lightweight crash test bogie, modified to support a vehicle weighing up to 1170 kg in various yaw positions (see Figure 1). It would be able to sustain design uniform accelerations of $-23.5g$.
2. The SIC would be towed by a 1-ton pickup truck with a 2:1 mechanical advantage pulley configuration.
3. An existing portable guidance rail would be used.

The test vehicle is carried on the SIC, supported by collapsible wheel supports. The SIC and vehicle are towed along the guidance rail up to a skid deck that stands at a height just below the wheels of the test vehicle. The skid deck comprises steel channels that receive each wheel as they drop from the collapsing wheel supports.




(a) (b) (c)

**FIGURE 1 SIC: (*a*) front view, (*b*) left side view, and (*c*) loaded with car at impact point with skid deck.**

The wheel supports hit the ends of the skid channels and collapse backward against the frame of the SIC. The SIC travels underneath the skid deck and is stopped by an impact attenuator, whereas the test vehicle skids above it on the lubricated deck. The test vehicle skids along the deck until the end, where it slides onto the pavement or soil surface in front of the test article.

### *Side Impact Carriage Design*

To support the test vehicle, the existing lightweight crash test bogie is fitted with 6061-T6 aluminum I-beams cantilevered from the frame. The beams are clamped to the tubular steel frame of the bogie with steel plates and bolts. The locations of the beams can be changed to accommodate vehicles of different sizes and various yaw angles.

For additional strength during the collision with the impact attenuator, wheel struts brace the connection between the axles and the frame and an extra steel plate is bolted to the existing impact plate. In addition, wire rope cables connect the ends of the two longer beams to the bogie frame.

These modifications turned the test bogie into a side impact carriage. A structural dynamic analysis revealed that the SIC can resist horizontal accelerations of $-23.5g$.

### *Test Vehicle Wheel Supports*

The test vehicle wheel supports hold the wheels of the test vehicle above the skid deck, allowing a smooth transition as the vehicle is transferred onto the skid channels (see Figure 2). The wheel supports collapse on impact with the upstream ends of the skid channels. They remain attached to the SIC and can be reused after minor repairs.

The basic design consists of two collapsing four-bar linkages held together in parallel by two plates. The top plate supports the vehicle tire and the bottom plate is bolted onto the aluminum I-beam of the SIC. The two front columns are the only steel members on the supports. All other members are 6061-T6 aluminum. The top and bottom plates are each supported with two solid aluminum bars. The rear columns are two aluminum square tubes welded together. The members are held together by eight bolts that act as hinges. The four-bar linkages are restrained laterally with two diagonal steel cables. Since the supports must collapse during the impact with the skid deck, one cable on each of the sides is spliced with a pin connection that fails when the supports hit the skid channels.

### *Tow Cable System*

The tow cable pulls the SIC along the length of the guidance rail. After the test vehicle is transferred to the skid deck, the tow cable pulls the SIC underneath the skid deck and is released. One end of the cable behind the SIC trails freely, the middle is connected to the SIC, and the other end is attached to a deadman anchor. Between the SIC and dead end of the cable, a 1-ton pickup truck pulls the cable through a pulley attached to the rear bumper.

### *Guidance System*

The guidance rail is composed of sections of aluminum I-beam 127 mm deep. The rails are anchored with brackets and steel spikes set in holes drilled in the asphalt pavement and filled with magnesium-phosphate concrete. The guidance mechanism connecting the SIC to the rail features roller blade wheels, four on each side and four on the top of the rail (see Figure 3).

### *Impact Attenuator*

The impact attenuator brings the SIC to a controlled stop after the test vehicle is released and is skidding above on the skid deck. The attenuator dissipates the energy in the SIC by crushing a fiber-reinforced plastic (FRP) tube (see Figure 4). This design is based on the box-beam guardrail terminal developed for the Wyoming

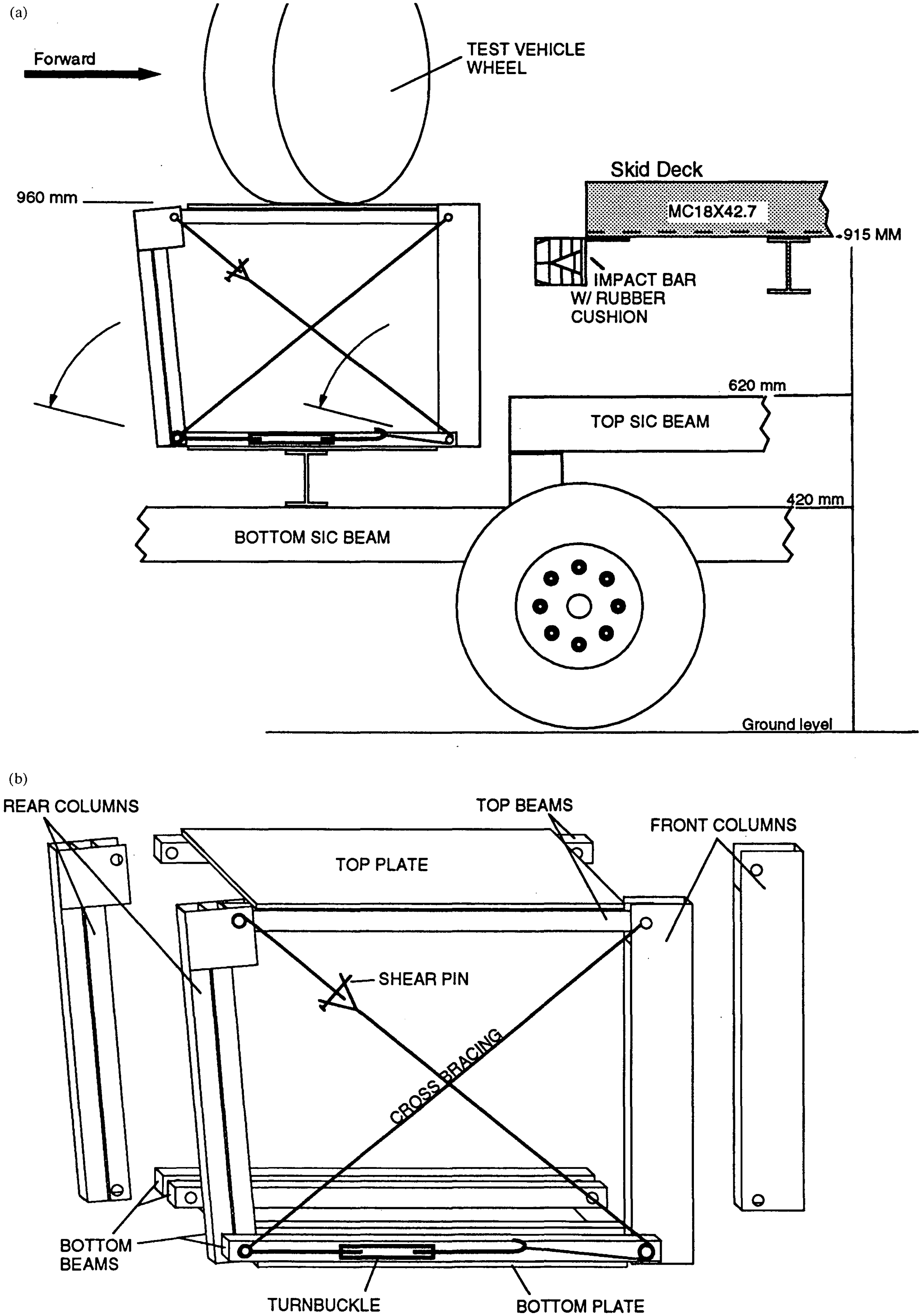



**FIGURE 2** SIC wheel support schematic: (*a*) wheel support assembly and (*b*) exploded detail of wheel supports.

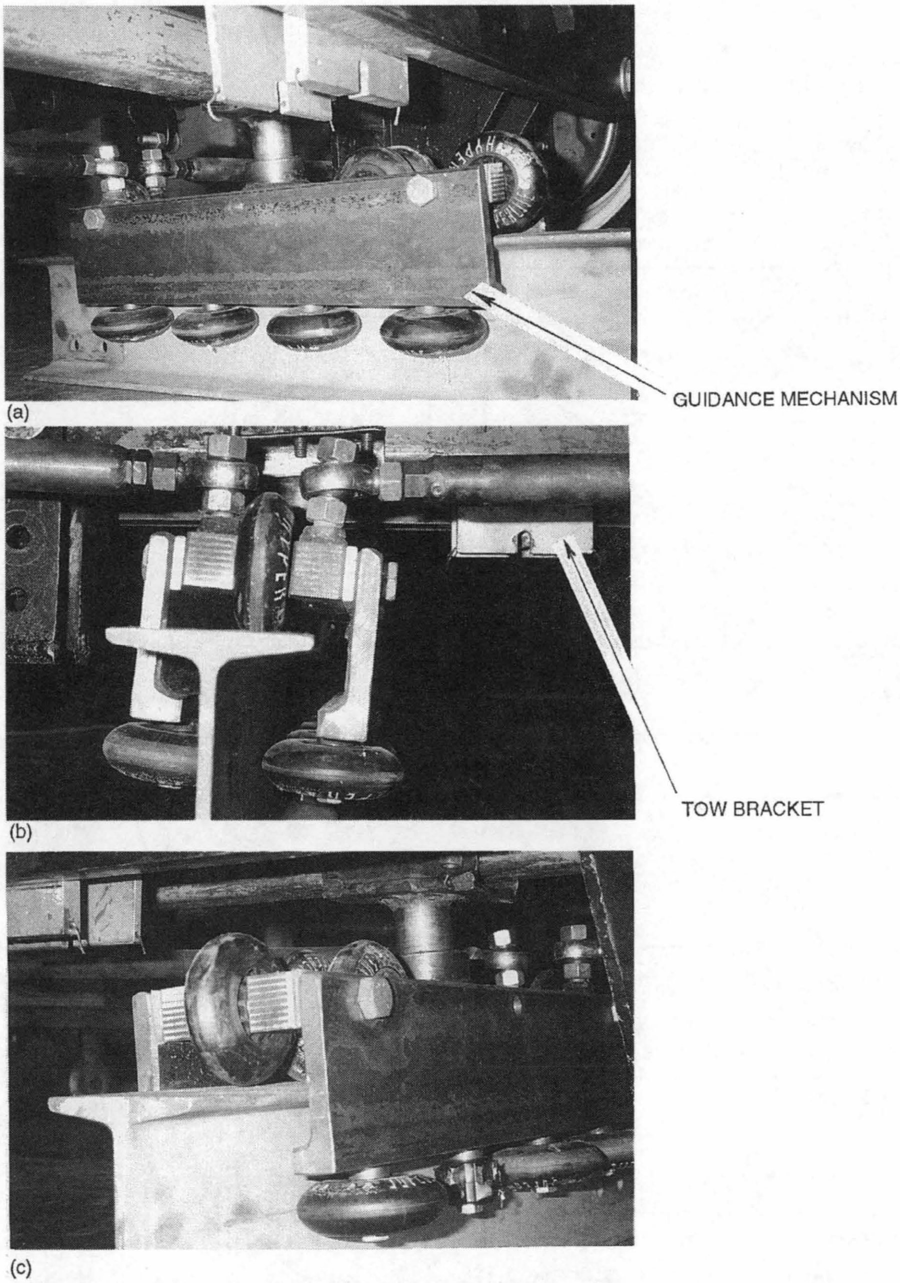



**FIGURE 3 Guidance mechanism and tow bracket: (*a*) right side view from front, (*b*) rear view, and (*c*) left side from front (lateral guide wheel is damaged).**

Department of Transportation by the Texas Transportation Institute (*2*). The optimum tube size was determined to be a wall tube, 152 mm diameter × 6 mm thick, manufactured with the same specifications as the tube samples in the development of the Wyoming box-beam end terminal.

### *Skid Deck*

The skid deck consists of two, three, or four steel channels supported on four steel wide-flange beams and the median embankment (see Figure 5). For the particular yaw angle of this project, the left channel received the left front wheel of the test vehicle, the middle channel received the right front and left rear wheels, and the right channel received the right rear wheel. They were positioned so that the left front, right rear, and right front wheels dropped onto the skid deck simultaneously, and later hit the dirt median all at the same time. The left rear wheel trailed, skidding in the same channel as the right front wheel.

The webs of the channels are coated with liquid soap, and the inside flange faces are coated with grease. This allows the test vehicle wheels to skid smoothly and with very little friction.

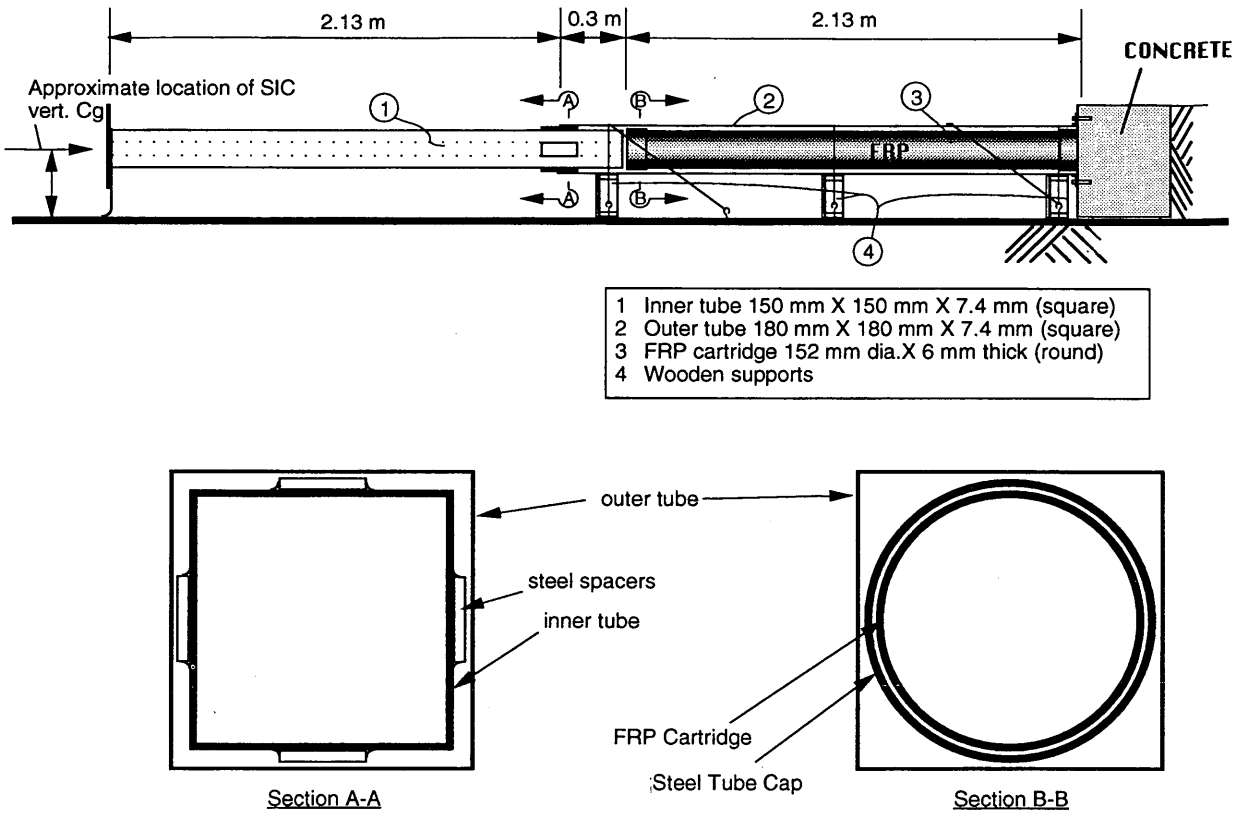



**FIGURE 4 Impact attenuator.**

*Results of Trial Test 1*

The purpose of this test was to tow the SIC, without a crash car loaded onto it, into the skid deck and impact attenuator at an estimated final speed of 48 km/hr. Stability of the SIC at this speed, performance of the wheel support collapse mechanism, and performance of the impact attenuator were focal points. In this test, the SIC had an earlier version guidance mechanism and the front wheels were fixed. The guidance rail anchor plates were not attached adequately to the pavement.

Approximately 70 m from the impact attenuator, the guidance rail shifted out of alignment, the guidance mechanism broke off, and the SIC was pulled into the skid deck without guidance. Consequently, the SIC did not reach the skid deck at the correct position and speed.

*Results of Trial Test 2*

This test had the same purpose as the first, with the addition of testing a modified guidance system. The fixed SIC front wheel connections were rebuilt with hinges to the axle, controlled by two tie rods connected to the guidance mechanism. The guidance mechanism incorporated a larger and stronger frame. The guidance rail anchor plates were fixed securely to the pavement.

The SIC was towed into the skid deck at approximately 48 km/hr with no problems. The wheel supports collapsed properly and the SIC hit the end of the impact attenuator squarely, pushing it in approximately 30–50 cm.

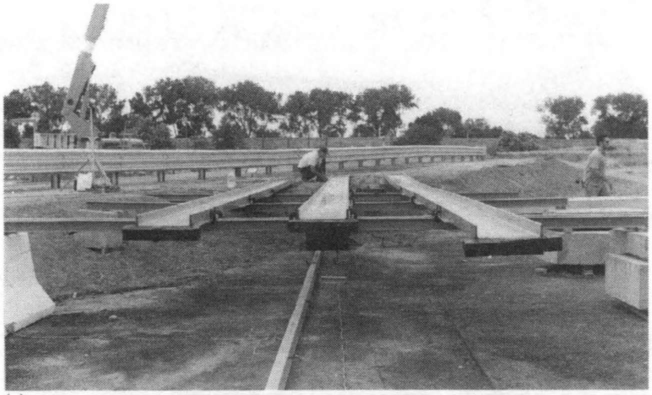
*Results of Trial Test 3*

A 1975 Toyota Celica hit a temporary cable barrier at an estimated speed of 42 km/hr with a trajectory angle of 25 degrees, and a counterclockwise yaw angle of 35 degrees. The system worked well, except that the test vehicle rotated slightly counterclockwise while translating in a side skid. This resulted in trajectory and yaw angles larger than desired. No signs of vehicle roll were noted; however, the Celica did pitch downward in front on making contact with the dirt. The SIC hit the attenuator squarely, crushing the FRP tube approximately 150 mm.

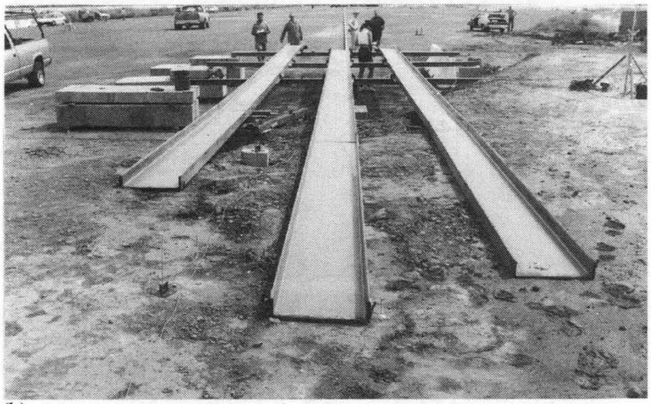
The Celica's undesired rotation was due to the unrestrained front wheels partially rolling and side skidding, whereas the rear wheels only side skidded since the transmission was in park. With the steering locked in a straight-ahead position, the partial rolling of the front wheels caused the front of the vehicle to track slightly in the direction of the initial yaw angle, whereas the rear translated along the initial trajectory path.

*Results of Trial Test 4*

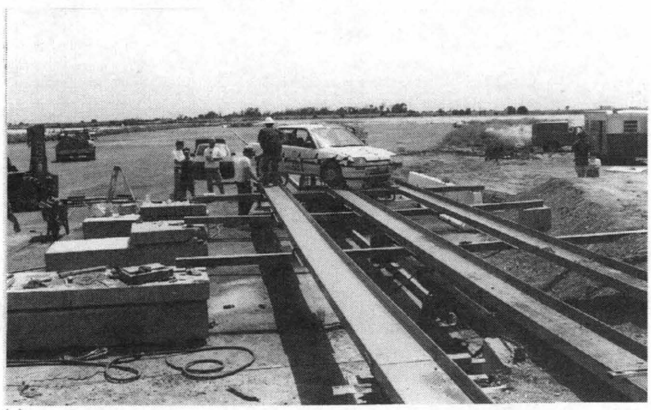
The Celica from Trial Test 3 was used again in Trial Test 4. It hit the temporary cable barrier at an estimated speed of 70 km/hr with



(a)



(b)



(c)

**FIGURE 5 Skid deck: (*a*) looking downstream, (*b*) looking upstream, and (*c*) looking upstream with car at impact point.**

a trajectory angle of 22 degrees and a counterclockwise yaw angle of 32 degrees. As the SIC hit the attenuator, the larger rear tube slipped up and off the reaction block, which in turn deflected the center skid channel upward approximately 60 cm. This caused the Celica's front left and right rear wheels to lift off of the skid channels for several feet. The car, however, stayed very close to the intended trajectory and yaw angles as it skidded onto the dirt median. This produced some instability in the car's motion, but it stabilized by the time it hit the temporary barrier.

The results of this test indicated that after modifying the impact attenuator connection to the reaction block the system was ready to be used to conduct Test 523.

*Results of Test 523 Pertaining to Side Impact System*

This was the final test of the project, using a 1989 Honda Civic hitting a double thrie beam median barrier. The performance of the barrier is covered in Part B.

The SIC loaded with the Honda was towed along the guidance rail without incident, until near the midpoint of the rail, the front wheels of the SIC started to turn to the right. The guidance mechanism was not able to keep the front wheels in proper alignment, probably because it was attached to the SIC frame in only one location (see Figure 3). Lateral forces transmitted from the SIC wheels to the guidance mechanism via the tie rods forced the guidance mechanism connection to the SIC frame to shift 3.18 cm laterally to the left. With the guidance mechanism shifted out of alignment, the SIC wheels were allowed to turn. Hence, the SIC remained on the guidance rail, but slightly out of alignment. The front wheels skidded as the SIC was towed into the skid deck.

The Honda slipped off the wheel supports smoothly and skidded onto the deck. The right front wheel support collapsed properly, but the other three did not, and were damaged beyond repair. The wheel supports hit the skid channels too high at the top plates, snagging and ripping them instead of making contact with the front columns and initiating collapse. The misaligned SIC caused the right front column of the right rear wheel support to miss the skid channel completely, so that the impact force initiating collapse was on only the left column.

The Honda skidded across the skid deck, made contact with the dirt median, and side skidded into the barrier at the desired 22 degrees trajectory angle. The yaw angle was 31 degrees counterclockwise, one degree off the desired 32 degrees. Impact speed was 66.5 km/hr, well below the desired 80.5 km/hr. The lower speed is attributed to the SIC not being towed fast enough because of the added drag on the tow vehicle from the misaligned SIC front wheels.

The SIC hit the attenuator squarely, slowing from 72.4 km/hr to 0 km/hr in 0.457 m, an average acceleration of $-45.2g$. Although this is significantly higher than the design acceleration of $-23.5g$, the SIC frame did not sustain any damage. The FRP tube crush strength was higher than anticipated.

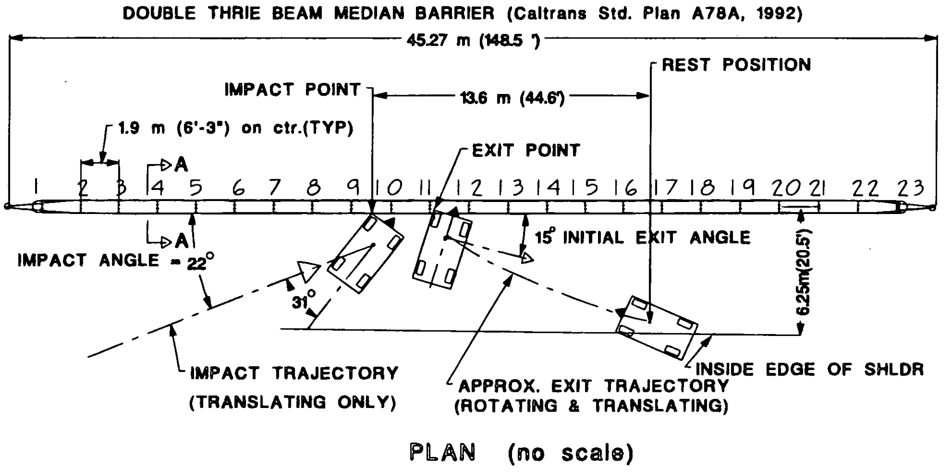
The guidance mechanism problem can be eliminated if it is restrained from lateral movement by connecting it to the SIC frame in an additional location. The problem of the too-high impact with the wheel supports can be corrected by adjusting the skid deck elevations. Crushing tests of the FRP tubes should be conducted to select a smaller size that will allow the SIC to decelerate over a longer distance and decrease the acceleration at a rate closer to the design value.

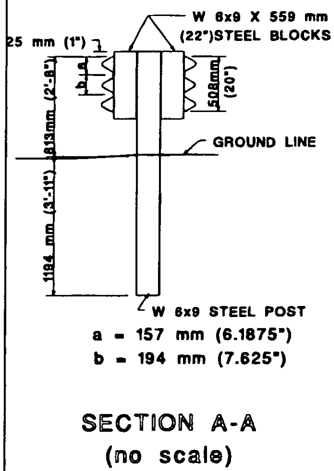
## Part B: Test 523—Performance of Double Thrie Beam Median Barrier in Side Skid Collision

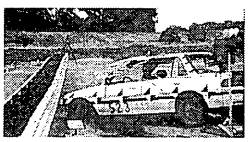
*Test Parameters*

**Test Article Design and Construction** The test article was a double thrie beam median barrier built with W 6 × 9 steel posts in accordance with Caltrans Standard Plan A78A (*3*) (see Figure 6 (*a*). This barrier is the same type that was installed at the legal case accident site after the accident. The median was replicated by surveying the accident site area and building the test median to the same dimensions and elevations.

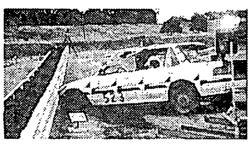
# DATA SUMMARY SHEET, TEST 523



t = -0.005 s



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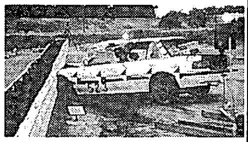

t = +0.070 s

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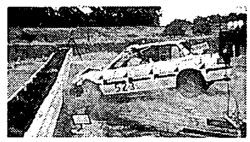


t = +0.300 s

| | | |
|---|---|---|
| GENERAL INFORMATION | | |
| Test Agency: | | California Dept. of Transportation |
| Test No. | | 523 |
| Test Date: | | July 21, 1994 |
| TEST ARTICLE | | |
| Type: | | Double Thrie Beam Median Barrier |
| Length: | | 45.27 m |
| Key elements: | | W 6 x 9 steel posts, 12 gage rail |
| SOIL TYPE | | sandy clay (SC) replicated from accident site |
| TEST VEHICLE | | |
| Type: | | Production model |
| Designation: | | Exemplar vehicle for legal case |
| Model: | | '89 Honda Civic |
| Mass: | Curb: | 925 kg |
| | Test inertial: | 1095 kg |
| | Dummy: | 74.8 kg |
| | Gross Static: | 1170 kg |
| IMPACT CONDITIONS | | |
| Speed: | | 66.5 km/hr |
| Trajectory Angle: | | 22° |
| Yaw Angle: | | 31° Counterclockwise |
| EXIT CONDITIONS | | |
| Speed: | | 43.4 km/hr |
| Trajectory Angle: | | 15° initially (rotating) |

| | |
|---|---|
| OCCUPANT RISK VALUES (calculated from flail space model) | |
| Theoretical Impact Velocity: | |
| longitudinal (x): | 9.8 m/s |
| lateral (y): | No theoretical impact |
| Theoretical Ridedown Acceleration: | |
| longitudinal (x): | -6.3 g |
| lateral (y): | No theoretical impact |
| TEST ARTICLE MAXIMUM DEFLECTIONS | |
| Lateral: | |
| dynamic: | 0.056 m post #10 |
| permanent: | 0.032 m post #10 |
| Longitudinal: | |
| dynamic: | not measured |
| permanent: | 0.016 m post #10 |
| VEHICLE DAMAGE | |
| Exterior: | |
| VDS: | FL4: |
| CDC: | 01FLEW5 |
| Interior: | |
| OCDI: | LF0010000 |
| POST IMPACT VEHICLE ROTATIONS | |
| Max Roll Angle: | negligible |
| Max Pitch Angle: | approximately 5° |
| Max Yaw Angle: | 103° |

**FIGURE 6 Data summary sheet Test 523.**

The barrier dynamic lateral deflections were measured with eight displacement transducers attached to Posts 8 through 15 (see Figure 6(*a*) for post locations). Permanent deflections were measured longitudinally and laterally from benchmarks placed in the ground before impact. Strain gauges were installed on the four anchor rods.

**Test Vehicle** The test vehicle was a 1989 Honda Civic, similar to the one that was involved in the legal case. With a test inertial mass of 1095 kg, it did not meet the NCHRP 350 requirements for an 820C vehicle (*4*).

The car was instrumented with seven triaxial sets of accelerometers and three rate gyros. High speed cameras were installed outside the driver's door and on the rear window shelf. The transmission of the test vehicle was placed in park, the steering was locked in the straight position, the emergency brake was engaged, and the wheels were restrained from rolling by wire cables. The engine was not running during the test. These actions were taken so that a translating side skid at the designated trajectory and yaw angles could be maintained.

**Soil Conditions** The test article median was built in an embankment constructed of imported fill that closely replicated the soil conditions at the accident site. Triaxial stress tests on the completed embankment indicated an average shear strength from 96 kPa at a normal stress of 0 kPa to 110 kPa at a normal stress of 24 kPa (depth of 1.2 m).

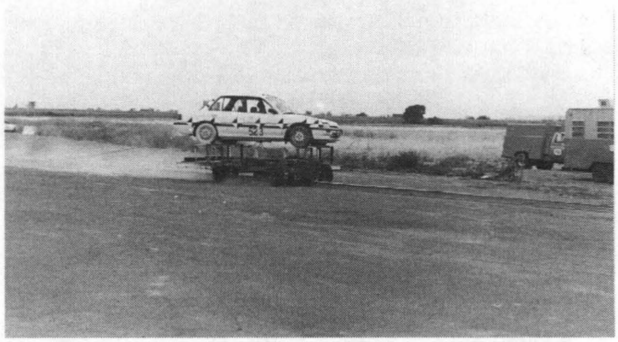
### *Test Conditions and Results*

**Impact Description/Vehicle Behavior** The Honda side skidded into the barrier at a 22 degree trajectory angle and 31 degree counterclockwise yaw angle. Impact speed was 66.5 km/hr (see Figure 7).

The vehicle was pitched down slightly as it hit the dirt median, causing the front bumper to drop lower than the bottom of the thrie beam rail. It passed underneath it as the left headlight and hood made first contact with the rail approximately 0.8 m upstream of Post 10. About ³⁄₄ of the front-end width crushed and slid against the rail for approximately 3 m before the vehicle left the barrier at an angle of 15 degrees and a speed of 43.4 km/hr. The Honda began to rotate as it exited the barrier, and continued to rotate and translate to a point approximately 14 m downstream, straddling the edge of shoulder 6.25 m from the barrier center line. Total change in yaw from impact was 103 degrees counterclockwise.

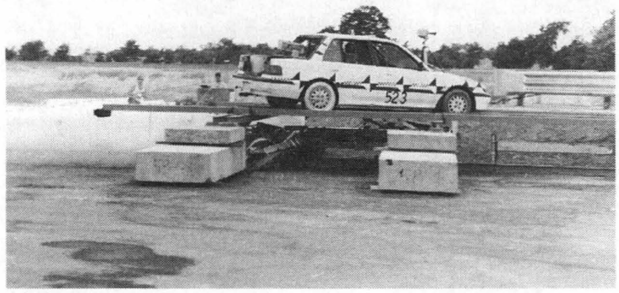
Maximum 50-m/sec average accelerations were $-10.7g$ longitudinal, $2.5g$ lateral, and $-2.7g$ vertical. The theoretical occupant impact velocity and ridedown acceleration in the longitudinal direction were 9.8 m/sec and $-6.3g$. There was no theoretical impact in the lateral direction.

**Barrier Damage** The test article deflected very little (see Figure 6(*b*) for data). Only Post 10 and its front block were damaged significantly. The thrie beam rail on the impact side was bent, but would not require immediate replacement (see Figure 8). The anchor rod on the upstream impact side resisted 28.6 kN of tension, and the anchor rod on the downstream impact side resisted 18.1 kN of tension.



(a)

(b)

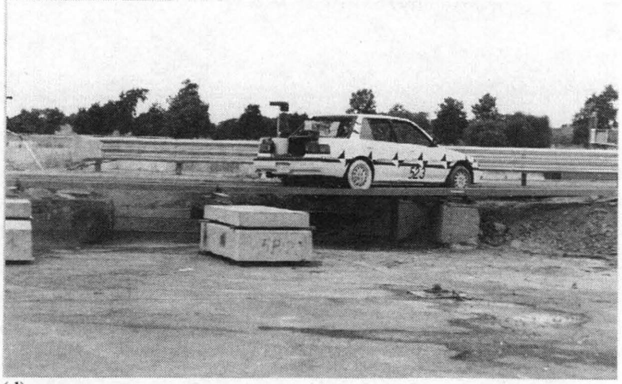


(c)

**FIGURE 7 Test 523 Sequential Photos: (*a*) 1.940 sec before impact, (*b*) 1.025 sec before impact, (*c*) 0.855 sec before impact, (*d*) 0.500 sec before impact, (*e*) 0.075 sec after impact, (*f*) 0.265 sec after impact, (*g*) 0.465 sec after impact, (*h*) 0.805 sec after impact, and (*i*) 2.260 sec after impact.** (*continued on next page*)

**Vehicle Damage** The vehicle could not be driven after the impact, but most of the damage was confined to the front left corner of the vehicle (see Figure 9). Debris scatter amounted to pieces of plastic from the Honda's lights. A portion of the plastic bumper was ripped off the Honda and got stuck at Post 10. See the Data Summary Sheet, Figure 6(*b*), for damage ratings.

**Dummy Behavior** A recently calibrated Hybrid III dummy was placed in the driver's seat of the test vehicle. It was restrained with a lap and shoulder belt. The head and chest each had one set of triaxial accelerometers.



(d)

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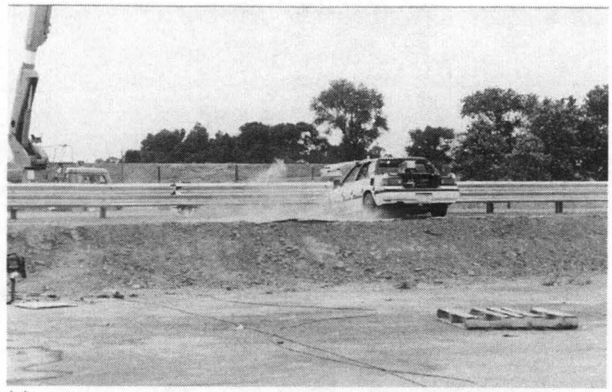
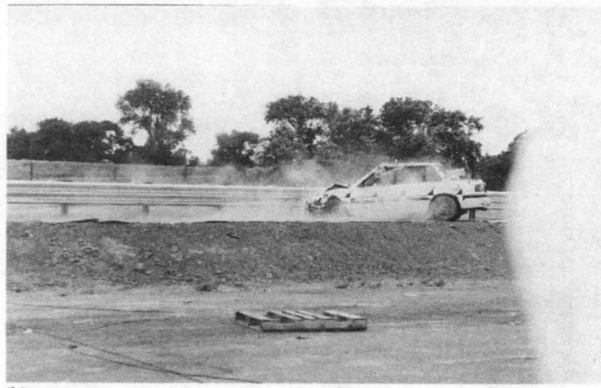


(g)



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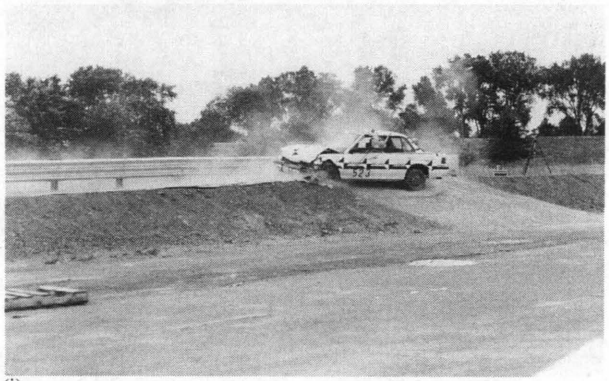

(i)

**FIGURE 7** (*continued*)

After impact, the dummy rotated forward about the lap belt, but the head did not hit the steering wheel or the windshield. It rotated backward and swung slightly to the left before coming back to rest against the headrest. The head injury criteria rating was 78.8, and maximum chest accelerations were $-27g$ longitudinal, $6g$ lateral, and $6g$ vertical. The maximum head accelerations were $-15g$ longitudinal, $4g$ lateral, $18g$ vertical, and $20g$ resultant.

### *Assessment of Test Results*

This test was assessed against standard Test 2-10 criteria of NCHRP Report 350 (*4*). Although the conditions for Test 2-10 include a smaller, tracking vehicle, they are the closest to those of Test 523, which were determined by the accident replication.

**Occupant Risk** The test satisfies all of the occupant risk criteria. The occupant impact velocity was 9.8 m/sec, over the preferred 9 m/sec but less than the maximum of 12 m/sec. No parts or flying debris entered the occupant compartment.

**Structural Adequacy** The barrier was structurally adequate: it was not penetrated and it redirected the vehicle. It received only minor damage.

**Vehicle Trajectory** This test did not meet the vehicle trajectory criteria. The vehicle came to rest straddling the median side shoulder line 6.25 m from the barrier center line. With a shoulder width of 0.61 m, the rear of the vehicle projected into the traveled

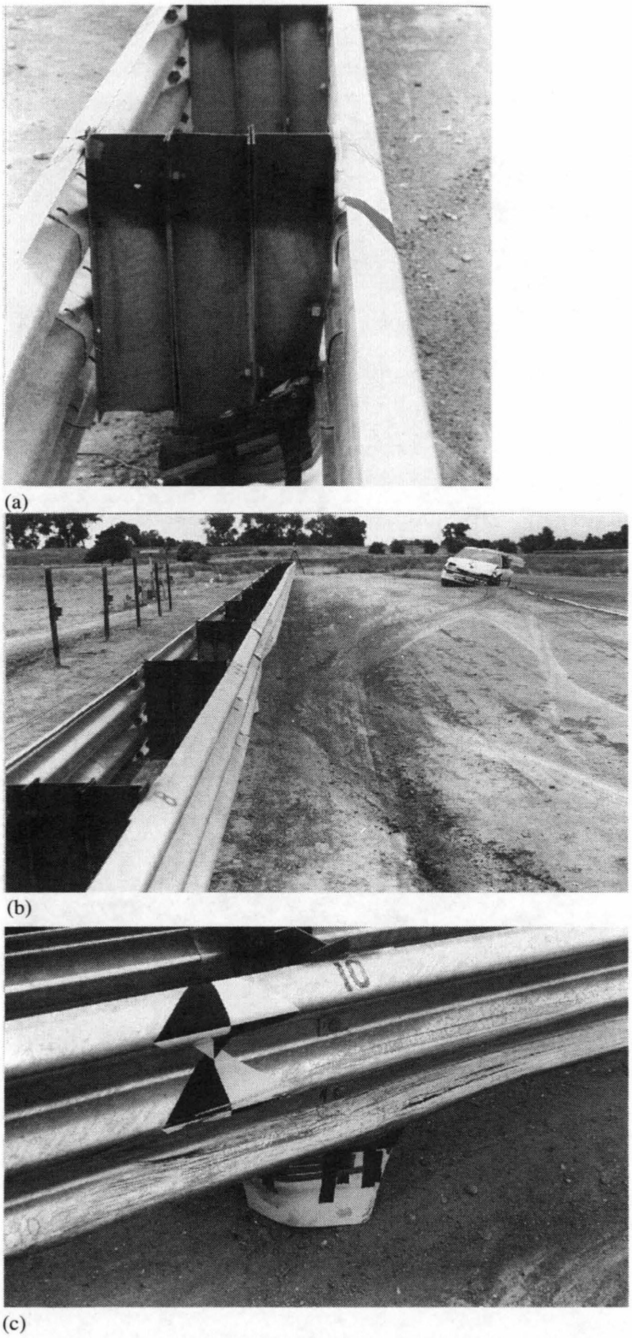


**FIGURE 8 Test article damage: (*a*) Post 10 looking downstream, (*b*) looking downstream, and (*c*) impact side of barrier.**

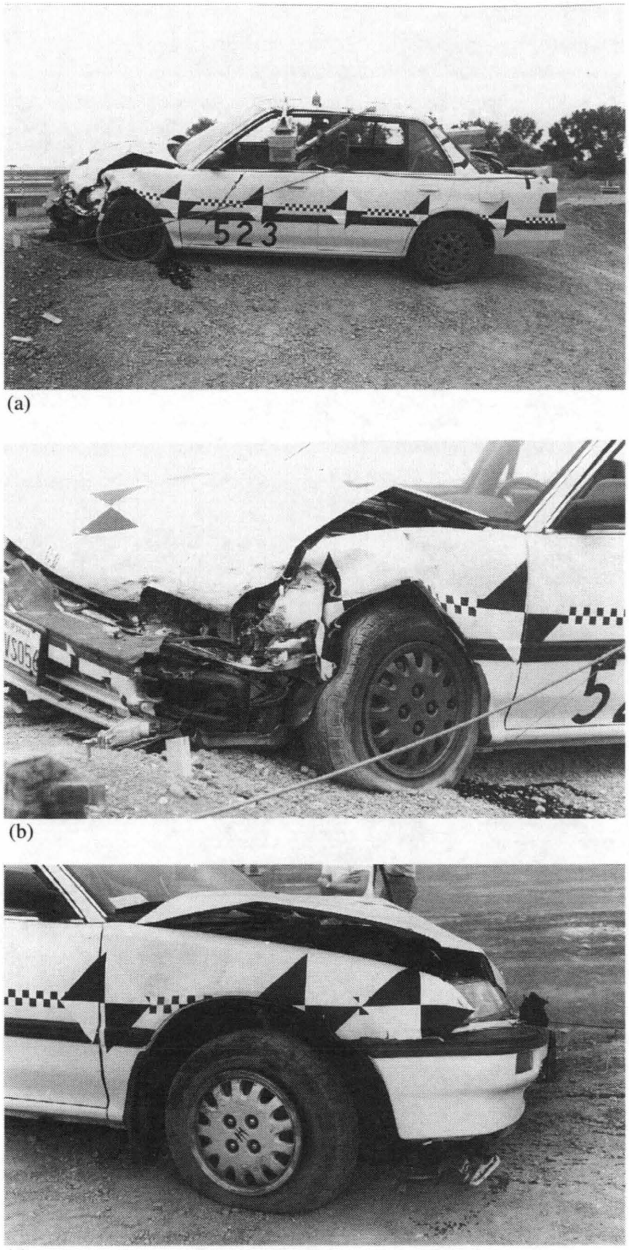


**FIGURE 9 Test vehicle damage: (*a*) left side view, (*b*) left front view, and (*c*) right side view.**

way. The exit angle of 15 degrees was also not less than 60 percent of the impact angle of 22 degrees.

**Overall Assessment** On highways with speed limits approximately 70 km/hr, the double thrie beam median barrier may be considered conditionally crashworthy in side skid collisions of the type in this test. In tests with a median width equal to that of Test 523 or smaller, the vehicle could reenter the traveled way. However, this type of barrier is installed typically in freeway medians, where speed limits are approximately 100 km/hr. At this speed, the occupant risks could be unacceptably high. Larger yaw angles could also cause higher decelerations and put the vehicle in more vulnerable positions, in which occupants would be at a higher risk of injury.

## CONCLUSIONS AND RECOMMENDATIONS

The side impact system performed well enough to project the Honda properly in Test 523 at a speed of 66.5 km/hr. With an improved guidance mechanism, impact speeds of 100 km/hr should be attainable. Different yaw angles can be achieved by simply relocating the cross beams on the SIC and repositioning the skid deck channels. With more extensive trial testing this system could be quite useful in a wide variety of side skid crash tests.

This side-skidding test at NCHRP Test Level 2 conditions indicates that the double thrie beam median barrier meets the structural adequacy and occupant risk criteria, but does not meet the vehicle trajectory criterion for medians with widths of approximately 15 m or less. More extensive testing at different yaw angles and in strict adherence to NCHRP Report 350 Test Level 3 conditions would be required to define fully the impact performance limits of the barrier in side skid collisions.

Test 523 was successful in providing information to Caltrans attorneys making decisions pertaining to the defense of the vehicle accident lawsuit.

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