REPEATABILITY OF FRONTAL OFFSET CRASH TESTS

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ABSTRACT

The Insurance Institute for Highway Safety publishes crashworthiness evaluations of passenger vehicles based on their performance in a 40 mi/h (64 km/h) frontal offset crash test. This paper describes the repeatability of vehicle and Hybrid III driver dummy responses for several pairs of vehicles in this type of crash test. Vehicle responses that were compared include interior intrusion measurements and vehicle accelerations. Driver dummy responses include dummy movement during the crash and electronic injury measures from the head, neck, chest, and upper and lower legs. The seven models that were tested twice are the 1997 Dodge Neon, 1997 Hyundai Elantra, 1994/95 Saab 900, 1995 Ford Taurus, 1997 Pontiac Trans Sport, 1996 Nissan Quest, and 1997 Infiniti Q45. Structural measures in the repeated tests were similar to those in the first tests for most models. Among injury measures, head injury criteria, neck tensions, chest compressions, femur and tibia axial forces, upper tibia indices, and foot accelerations also were similar in the repeated tests for most models. Neck bending moments and lower tibia indices were less consistent. Implications of these comparisons for the Institute's crashworthiness evaluations are discussed.

BACKGROUND

Crash tests are performed for a variety of reasons that include checking whether new designs meet engineering expectations and safety regulations, re-creating real-world crashes to study injury mechanisms, and comparing crashworthiness offered by different model designs. Because conducting a full-scale crash test is time consuming and costly, each of these endeavors relies on generalizing the results of a few tests, in many cases only one, to make inferences about other crashes under similar circumstances. Hence the issue of repeatability, or how closely the results of replicated tests resemble one another, is important.

Relatively little has been written on the subject of crash test repeatability. The most extensive study was reported by the National Highway Traffic Safety Administration (NHTSA), which conducted 12 full-overlap frontal crashes at 35 mi/h against a rigid barrier at three test sites.[1] In this study of the reliability of the agency's New Car Assessment Program (NCAP), the test vehicles were 1982 Chevrolet Citations identically equipped and built during the same shift at a single plant. The seats were welded in the correct adjustment position to minimize test setup differences. Head injury criterion (HIC) and chest acceleration were the two test results examined most closely.

Driver dummy HICs ranged from 522 to 954, and passenger dummy HICs ranged from 542 to 793, with one site consistently reporting the highest results and another consistently reporting the lowest. Reported chest accelerations were highest from the test site with the highest HICs and lowest from the site with the lowest HICs. Slight test procedure differences among the sites were noted, but none of these differences explained the particular pattern of results. For example, dummy head calibration results did not correlate with differences in crash test HICs.

Other differences among the tests were examined to try to explain some of the differences in the dummy injury measures. For instance, differences in dummy head contacts apparently explained some of the HIC variation observed. On the driver side, the head contacted the steering wheel rim in most tests because the 1982 Chevrolet Citations were not equipped with airbags. However, steering column intrusion varied enough among tests that the dummy's head contacted different parts of the steering wheel rim, and in two tests the dummy's head missed the steering wheel altogether. On the passenger side, the dummy's head sometimes contacted the right knee, which was pushed upward by floorboard buckling. The authors also noted that variation in torso rotation for both driver and passenger dummies may have been due to differences in seat belt placement.[1] However, a multivariate regression analysis did not find statistically significant relationships among vehicle response variables (amount of dynamic crush, floor buckling pattern, steering column movement) and dummy injury measures (HIC and chest acceleration). The many potential sources of test variability (procedure, test dummy condition, test vehicle) made it impossible to identify the specific contribution of any one source to the differences in dummy injury measures. Nevertheless, the authors made several recommendations that were intended to improve the reliability of NCAP results.

The need for a new frontal crash test standard in Europe led to the development by the European Experimental Vehicle Committee (EEVC) of the frontal offset crash test using a deformable barrier. The authors reasoned that offset tests with a deformable barrier face should be more repeatable than offset tests with a rigid barrier, in part because the weak edge of the soft barrier face would be less sensitive to lateral alignment.[2] The authors also suggested that the deformable barrier would reduce initial accelerations and increase the amount of time over which the acceleration is applied, compared with a rigid barrier. This increase in the duration of acceleration peaks would allow for more predictable onset of failure in structural components than the short, high acceleration peaks produced in rigid barrier tests. In support of these suggestions, the authors presented the results of three vehicles crashed into a deformable barrier at the same speed (56 km/h) with a 40 percent barrier overlap. Peak vehicle accelerations in these tests varied little and occurred at about the same time. Driver dummy injury measures were described as repeatable with HICs ranging from 374 to 427, maximum chest accelerations ranging from 70 to 96 g, maximum left femur loads ranging from 5 to 10 kN, and maximum right femur loads ranging from 5 to 8 kN.

The Bundesanstalt für Straßenwesen (BAST) submitted data on the repeatability of frontal offset deformable barrier tests to EEVC.[3] Three 1994 Volkswagen Golf VR6 A3s were tested at 56 km/h with a 40 percent barrier overlap. The authors reported good repeatability for the "classical" dummy measurements of HIC, chest acceleration, and chest compression, with coefficients of variation (standard deviation as a percent of the mean measured value) ranging from 2 to 8 percent. In addition, maximum head and chest accelerations as well as maximum chest compressions were recorded at about the same time in each of the repeated tests (within a range of 10 ms). The report stated that the dummies' leg measurements were more variable. Coefficients of variation calculated for the BAST leg injury data ranged from 2 to 108 percent, with most greater than 10 percent. Also, peak values from different tests were recorded at considerably different times, of which some occurred 50 ms apart. BAST also found that intrusion measurements were quite variable. Coefficients of variation for two of the measurements — vertical movement of the brake pedal and rearward movement of the left toepan — were comparable with those for the "classical" dummy measures. However, other toepan measures, steering column movement, and instrument panel rearward movement had coefficients that ranged from 12 to 185 percent.

The Japan Automobile Standards Internationalization Center (JASIC) also submitted data on the repeatability of frontal offset deformable barrier crash tests to EEVC.[4] Four midsize cars with two dummies, weighing approximately 1,400 kg per test setup, were tested at 56 km/h with a 40 percent barrier overlap. A measurement was judged repeatable if its range of observed values was no larger than 80 percent of its mean value. The JASIC tests showed good repeatability for all intrusion measurements except steering column vertical movement (range/mean = 3.2). HIC and chest acceleration results also were judged repeatable, but other injury measures (axial femur force, knee displacement, and neck extension moment) had range/mean values greater than 0.8.

INSTITUTE TESTS

The Insurance Institute for Highway Safety conducted two tests of each of seven vehicles at a nominal impact speed of 64.4 km/h (40 mi/h) and a nominal 40 percent overlap with a deformable barrier. Table 1 lists the vehicle weight, impact speed, and barrier overlap for each test. Although not conducted for the purpose of repeatability assessment, test conditions were similar enough for each pair of vehicles to provide further information about the repeatability of occupant protection performance in frontal offset deformable barrier crash tests.

Vehicle Response Measures

Vehicle acceleration and velocity history, occupant compartment intrusion, and action of restraint system components were compared between the first and second tests of each model. Vehicle acceleration was measured by

Table 1.
Repeated Frontal Offset Crash Tests

	Test Weight (kg)		Impact Speed (km/h)		Measured Overlap (%)	
Make/Model	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
Dodge Neon	1,312	1,308	64.0	64.3	41	41
Hyundai Elantra	1,340	1,355	64.4	64.8	45	40
Saab 900	1,476	1,489	64.5	64.2	40	40
Ford Taurus	1,565	1,599	64.5	64.5	41	40
Pontiac Trans Sport	1,836	1,852	63.4	64.2	41	41
Nissan Quest	1,846	1,862	64.2	64.0	40	40
Infiniti Q45	1,944	1,944	64.0	64.5	40	40

accelerometers inside the occupant compartment, and velocity history was either calculated from acceleration measures or obtained through film analysis from overhead cameras. Occupant compartment intrusion was characterized by the differences between precrash and postcrash positions of measurement targets on the instrument panel, toepan, and steering wheel hub. The maximum amount of seat belt spool-out was measured by stitching one end of a string to the belt webbing and attaching the other end to the B-pillar with tape so that as the webbing was pulled out of the retractor, the string was pulled out from under the tape. Airbag deployment time was characterized by noting when the airbag first was observed outside the module in the high-speed film.

Driver Dummy Responses

Hybrid III dummy injury measures and observed dummy kinematics were used to assess the repeatability of driver dummy responses. Dummy head contact locations, in addition to gross dummy kinematics, were used to compare dummy movement. Dummy injury measures include HIC, neck extension bending moment, neck tension force, chest compression, femur axial force, tibia-femur displacement, upper and lower tibia indices, tibia axial force, and foot acceleration.

RESULTS

Vehicle Responses

Table 2 lists the maximum vehicle longitudinal accelerations for the first and second tests of six models (vehicle acceleration was not recorded in the first Nissan Quest test). Acceleration differences in the repeated tests of the Saab 900, Pontiac Trans Sport, and Dodge Neon were less than 5 g, and the velocity histories calculated from the acceleration measurements in these tests follow each other closely. Despite somewhat larger peak acceleration differences (8-14 g) in the repeated tests of the Ford Taurus, Infiniti Q45, and Hyundai Elantra, these cars' occupant compartments experienced largely similar crash forces, as indicated by their occupant compartment velocity histories (Figures 1-3).

Table 2.
Maximum Vehicle Longitudinal Acceleration (g)

Make/Model	Test 1	Test 2
1997 Dodge Neon	35	33
1997 Hyundai Elantra	38	46
1994/95 Saab 900	32	28
1995 Ford Taurus	39	29
1996 Pontiac Trans Sport	24	25
1997 Infiniti Q45	30	44

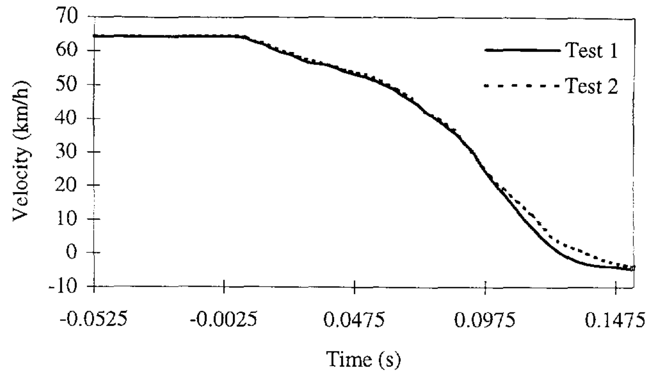
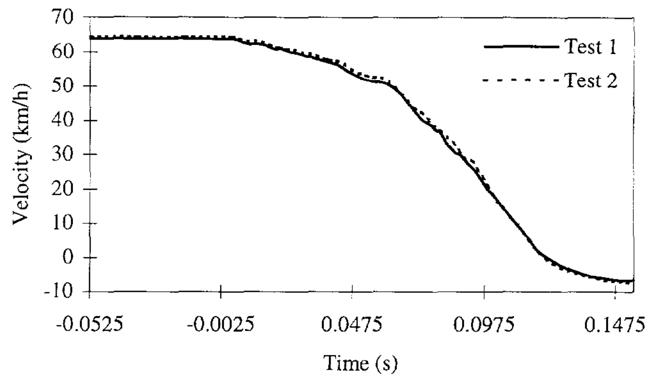


Figure 1. 1995 Ford Taurus Vehicle Longitudinal Velocity.



Figue 2. 1997 Infiniti Q45 Vehicle Longitudinal Velocity.

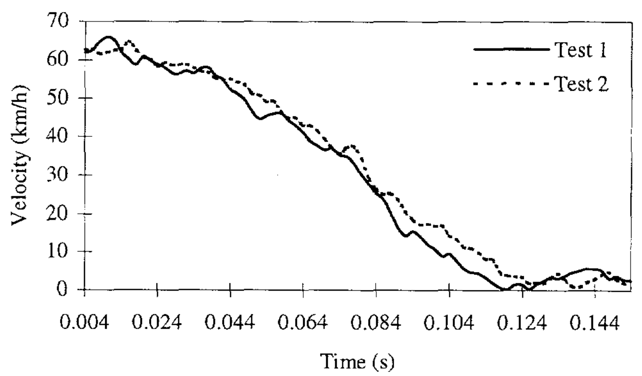
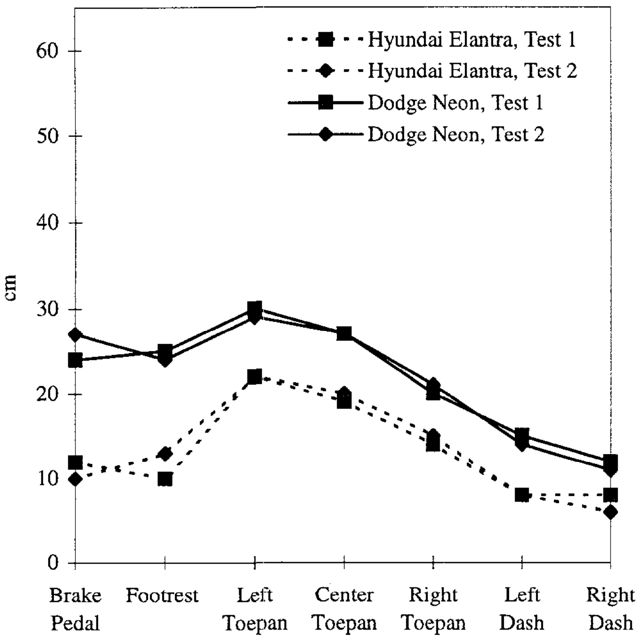


Figure 3. 1997 Hyundai Elantra Vehicle Longitudinal Velocity.

The peak vehicle acceleration differences in the repeated tests of the Ford Taurus and Infiniti Q45 were due to variation in high-frequency oscillations experienced by the accelerometers and did not indicate differences in the gross decelerations of the occupant compartments. Similarly, the apparent large acceleration difference in the Hyundai Elantra tests likely was due to differences in local accelerations caused by deformation of the occupant compartments near the accelerometer mounting locations, which were slightly different in the two tests. These differences developed later in the crashes as occupant compartments deformed. Acceleration histories for the first 60 ms of both crashes were quite similar. Because the accelerometer mounting locations were slightly different in the two tests, film analysis from an overhead camera was used to compute the velocity history shown in Figure 3.

Intrusion measurements in the repeated tests of the Dodge Neon and Hyundai Elantra, two small cars, as well as those in the Pontiac Trans Sport and Nissan Quest, two passenger vans, were very similar (Figures 4 and 5); some measures were exactly the same, and the largest differences were only 2-3 cm.

Intrusion differences among these models were much greater than differences between each model's first and second test. Intrusion measurements in the repeated tests of the Saab 900 and Ford Taurus, two midsize cars, were not very similar (Figure 6). Intrusion measurements in the repeated test of the Infiniti Q45 (Figure 7), a large luxury car, were not as similar as those for small cars and passenger vans but more similar than those for the Saab 900 and Ford Taurus.



Figue 4. Small Car Intrusion.

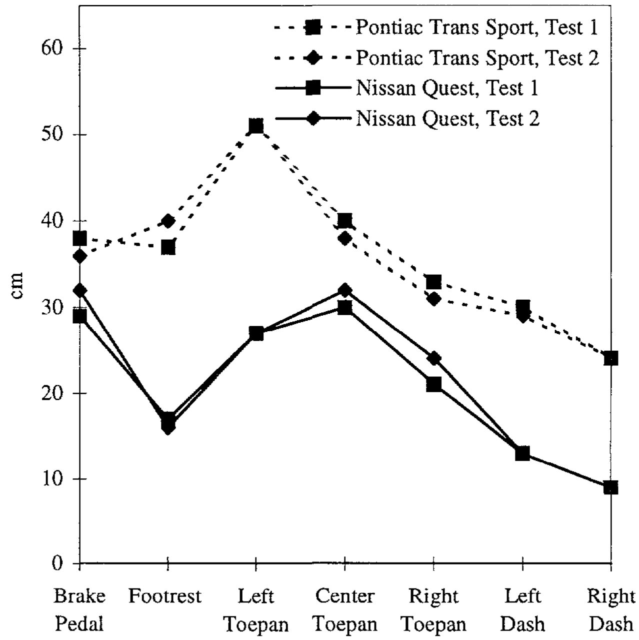


Figure 5. Passenger Van Intrusion.

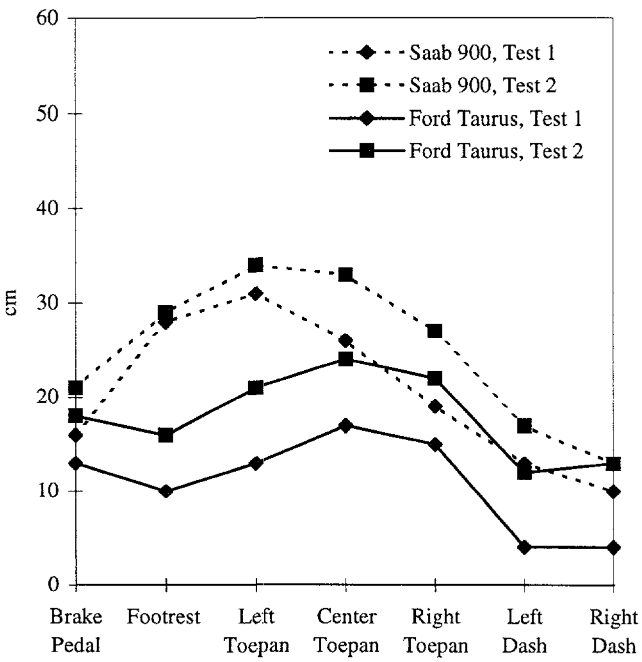


Figure 6. Midsize Car Intrusion.

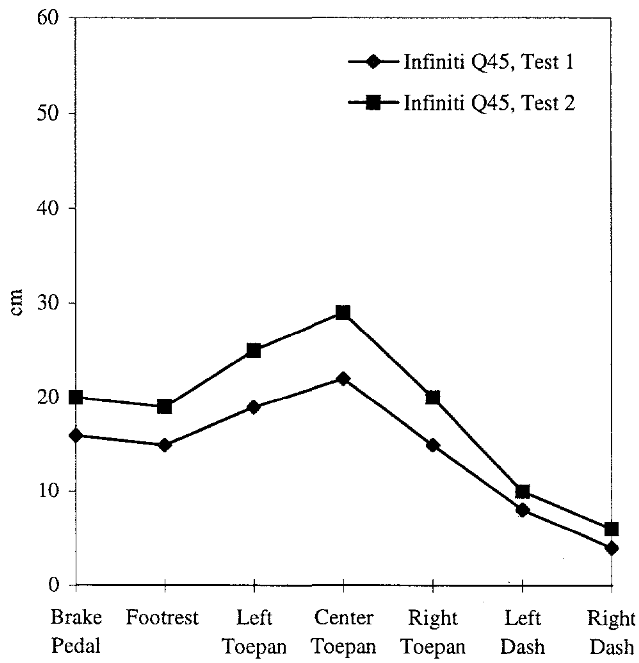


Figure 7. Large Luxury Car Intrusion.

Examination of underbody structures of the many models with repeatable intrusion measurements shows that crush zone components deformed in similar ways. For example, the engine cradles of the Pontiac Trans Sports did not deform but rather were pushed back into the occupant compartments, causing the same extreme level of intrusion in both tests (Figure 8). In contrast, the Infiniti Q45 tests show clear differences in the deformation patterns of crush zone components (Figure 9). The left side rail did not buckle in the second test, as it had in the first test, but remained straight and was driven rearward into the toepan, producing more toepan intrusion than in the first test.

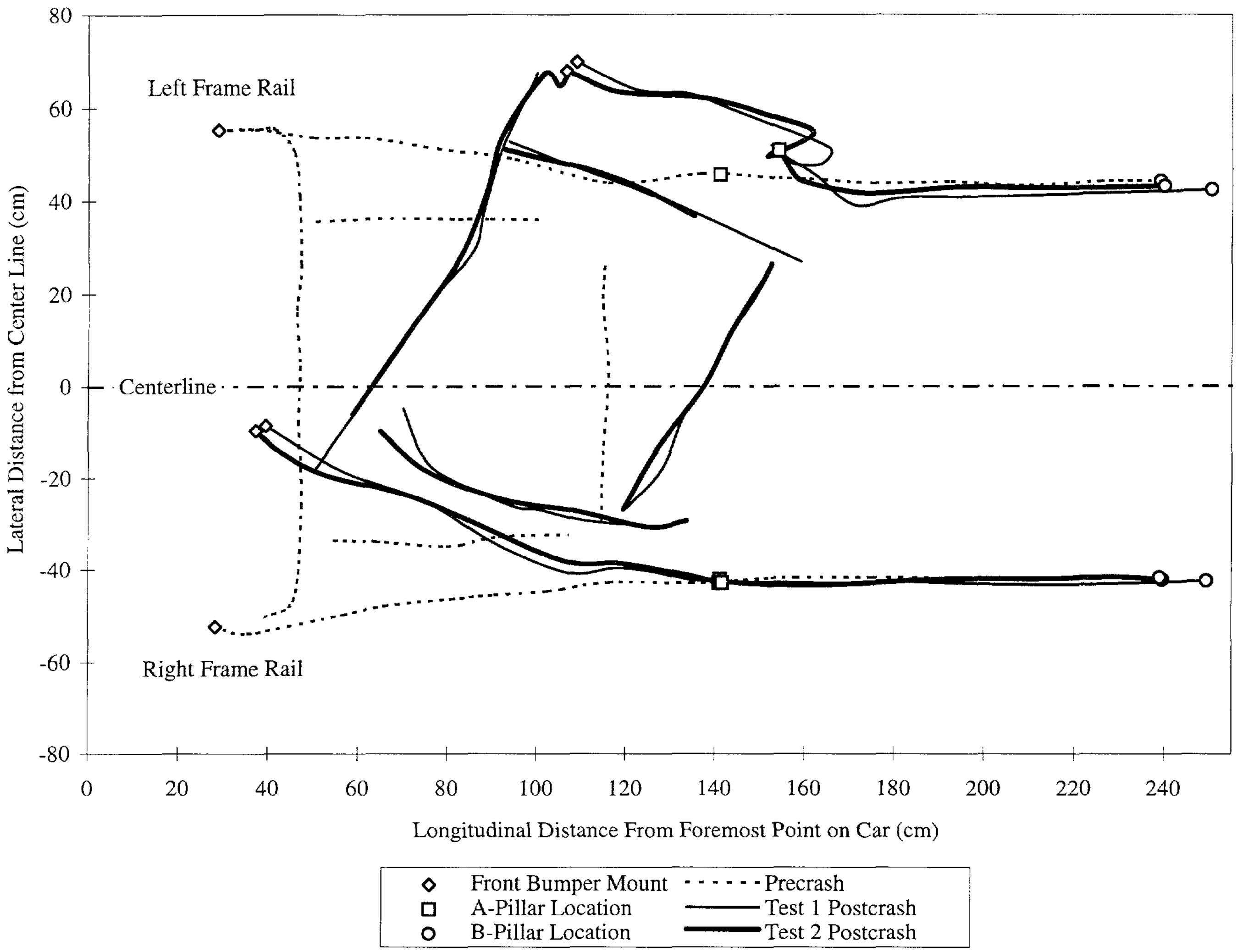
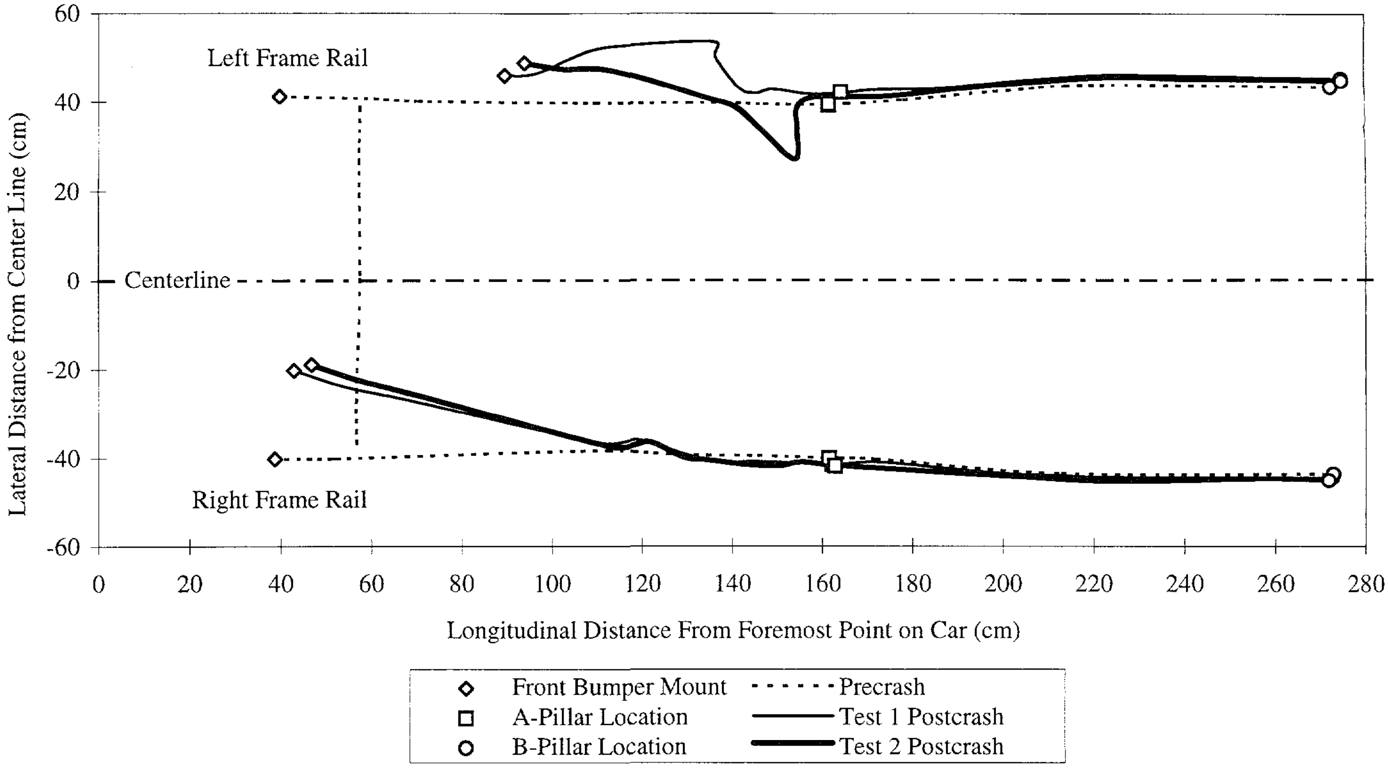


Figure 8. 1997 Pontiac Trans Sport Frame Rail Deformations, View from Below.



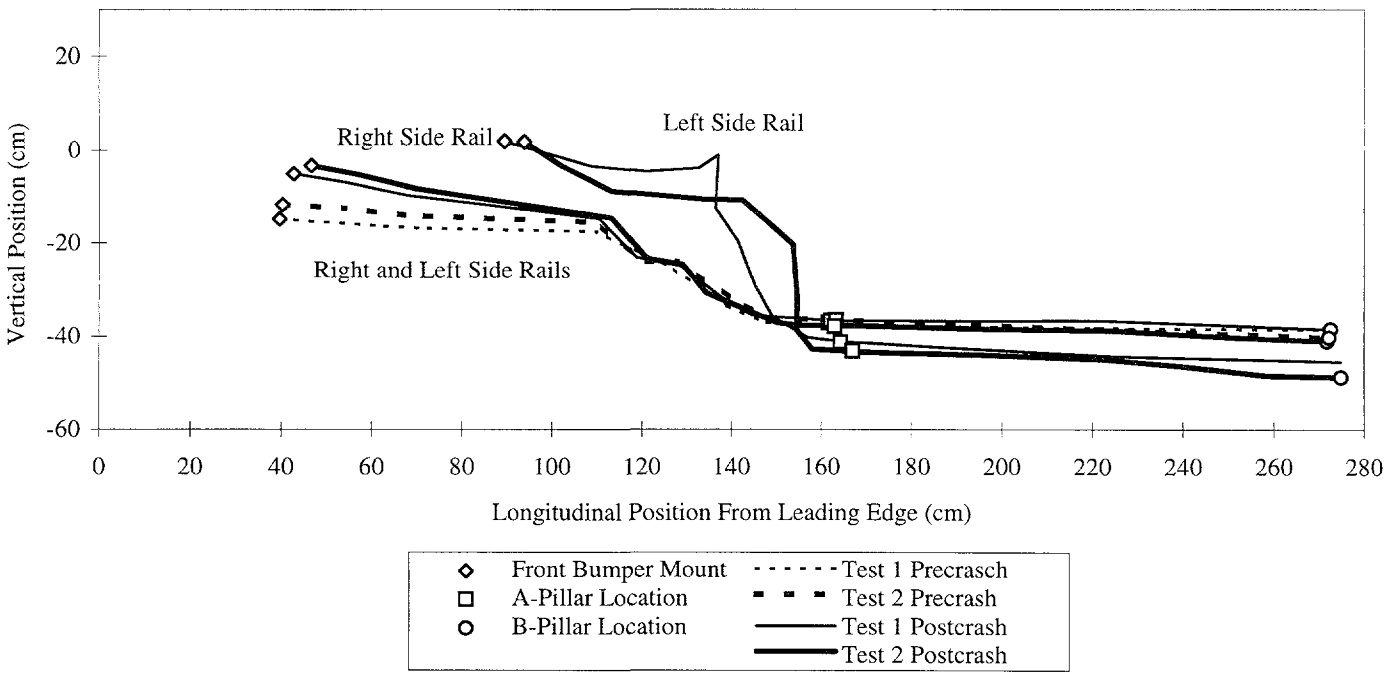


Figure 9. 1997 Infiniti Q45 Frame Rail Deformation, Views from Below and Side.

Longitudinal and vertical steering column movements were very similar (within 3 cm) in the repeated tests of all models except the Ford Taurus and Pontiac Trans Sport (Figures 10 and 11). Vertical movement was similar in the Ford Taurus tests, but longitudinal movement in the second test was 10 cm greater than in the first test. The Pontiac Trans Sport tests produced similar longitudinal steering column movement, but vertical measures differed by 5 cm.

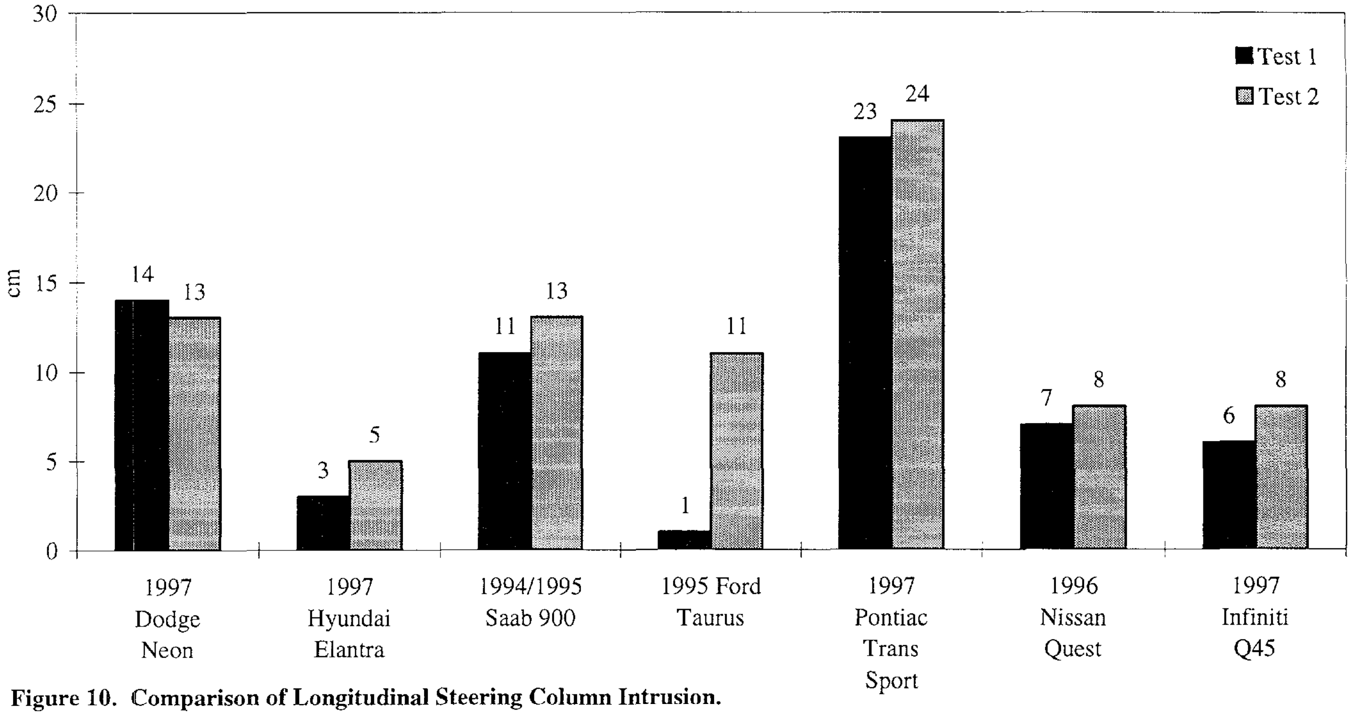


Figure 10. Comparison of Longitudinal Steering Column Intrusion.

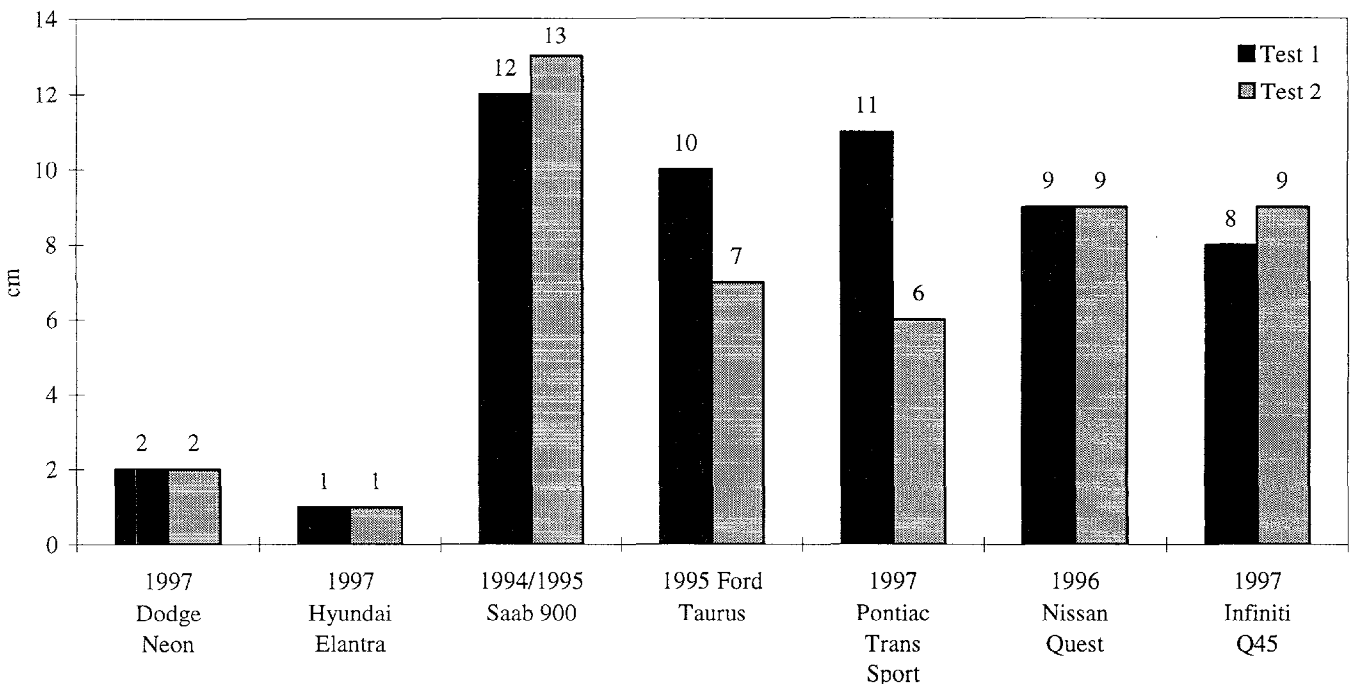


Figure 11. Comparison of Vertical Steering Column Intrusion.

Seat belt spool-out measures in the repeated tests of five models were very similar (differences of 2 cm or less), thus indicating seat belt system performance is repeatable (Table 3). The Saab 900 tests were not included in this comparison because retractor and pretensioner designs were changed between the 1994 and 1995 model years. The Infiniti Q45 tests were not included because spool-out measurements were not made in the first test.

Table 3.
Seat Belt Spool-out (cm)

Make/Model	Test 1	Test 2
1997 Dodge Neon	7	7
1997 Hyundai Elantra	6	7
1995 Ford Taurus	6	6
1997 Pontiac Trans Sport	6	8
1996 Nissan Quest	3	1

Airbag deployment times in the repeated tests of five models also were very similar (within 4 ms), but deployment times were 12 ms apart in the Hyundai Elantra tests (Table 4). A small difference in occupant compartment accelerations in the Hyundai Elantra tests may account for the larger difference in deployment times. Accelerations were slightly higher in the second test (average 8.1 g through 22 ms) than in the first test (average 6.1 g through 22 ms). The Saab 900 tests were not included in this comparison because the airbag sensor module was changed between the 1994 and 1995 model years.

Table 4.
Airbag Deployment Time (ms)

Make/Model	Test 1	Test 2
1997 Dodge Neon	40	42
1997 Hyundai Elantra	34	22
1995 Ford Taurus	26	26
1997 Pontiac Trans Sport	25	27
1996 Nissan Quest	20	18
1997 Infiniti Q45	52	56

Driver Dummy Responses

Table 5 lists the driver dummy head contact locations in the tests of five models. Despite head contact differences between the first and second tests, overall dummy movement patterns were very similar. For example, the dummy's head contacted the B-pillar in the first Ford Taurus test but narrowly missed contacting the B-pillar in the second test. Similarly, the dummy's head probably contacted the steering wheel through the airbag in the second Dodge Neon test, but this contact could not be verified because it was less forceful than in the first test. Dummy movement in the Hyundai Elantra tests also was very similar; however, after contacting the B-pillar, the dummy in the first test moved upward somewhat higher and brushed against the roof rail. The Saab 900 tests were not included in this comparison because of airbag and seat belt differences between the 1994 and 1995 models. The Pontiac Trans Sport tests were not included because of different driver seating positions.

Table 5.
Head Contacts Other Than Airbag
(in order of severity)

Make/Model	Test 1	Test 2
1997 Hyundai Elantra	B-pillar, roof side rail	B-pillar
1997 Dodge Neon	Steering wheel	None
1996 Ford Taurus	B-pillar	None
1996 Nissan Quest	None	None
1997 Infiniti Q45	B-pillar, side airbag	B-pillar, side airbag

Figures 12-16 show the upper body injury measures (HIC, neck tension force, neck extension bending moment, and chest compression) in the Dodge Neon, Hyundai Elantra, Ford Taurus, and Infiniti Q45 tests. Figures 17-22 show the lower body injury measures (axial femur force, tibia-femur displacement, upper and lower tibia indices, lower tibia axial force, and foot acceleration) in the Hyundai Elantra, Ford Taurus, and Infiniti Q45 tests. The Saab 900 tests were not included in these comparisons because of airbag and seat belt differences between the 1994 and 1995 models. The Nissan Quest tests were not included because data were not recorded in the first test. The Pontiac Trans Sport tests were not included because of different driver seating positions. The Dodge Neon tests were not included in the comparisons of leg injury measures because the first test was conducted using a dummy with ankles that had hard stops at the limits of the joint range of motion. The second Dodge Neon test was conducted using a newer foot/ankle design that had soft stops at the limits of the joint range of motion.

In the repeated tests of the Dodge Neon, Hyundai Elantra, Ford Taurus, and Infiniti Q45, HICs were very similar (Figure 12). The time intervals over which the HICs were calculated had the same duration to within 1 ms, and the largest difference between HIC-interval start times was 5 ms (Hyundai Elantra tests). Maximum neck tension forces also were similar and occurred at about the same time (Figure 13); the largest difference in maximum force was 0.3 kN (Hyundai Elantra tests), and the largest difference in the occurrence of maximum force was 7 ms.

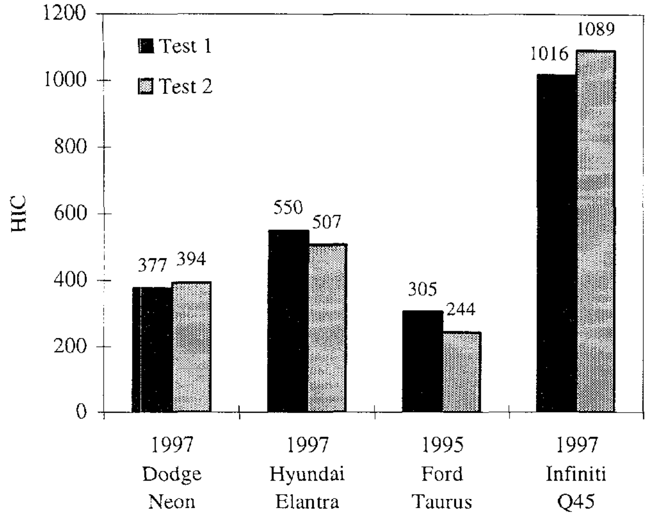


Figure 12. Comparison of HIC.

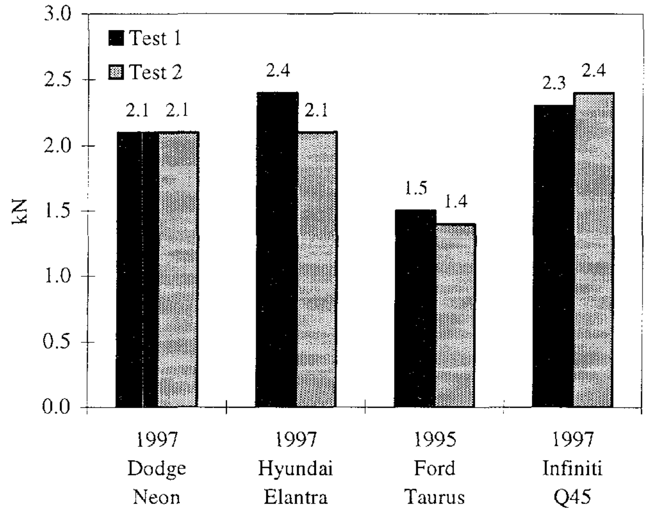


Figure 13. Comparison of Neck Tension.

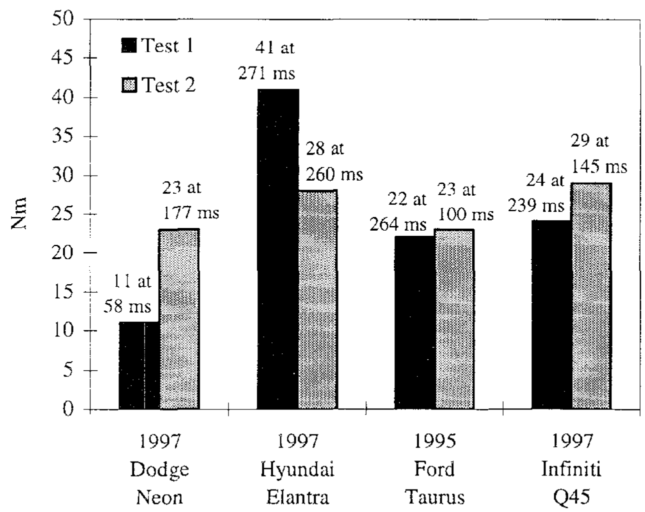


Figure 14. Comparison of Neck Extension Bending Moment.

Neck extension bending moments were more variable (Figure 14). The maximum values were similar but did not occur at the same time in the Ford Taurus and Infiniti Q45 tests. The maximum extension bending moment in the first Infiniti Q45 test occurred (at 239 ms) when the dummy's head contacted the B-pillar during rebound, but this measure in the second test was recorded (at 145 ms) before the head contacted the B-pillar (Figure 15). In the Hyundai Elantra tests, the maximum bending moments were recorded near the same time, but slight differences in the way the dummy's head contacted the B-pillar produced relatively large differences in the magnitude of the bending force. Extension bending moments in the Dodge Neon tests differed both in magnitude and time of occurrence.

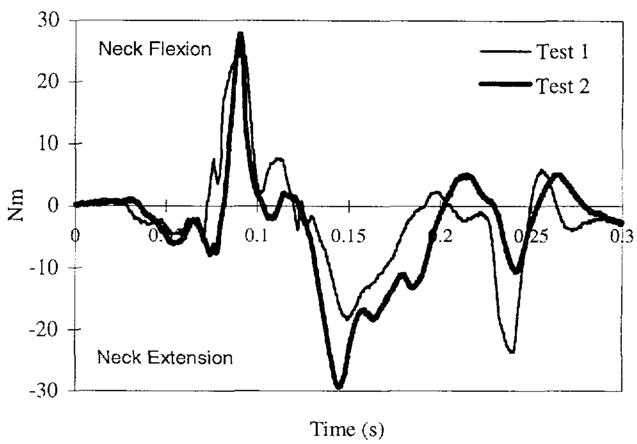


Figure 15. Neck Bending Moment - Infiniti Q45 Tests

Maximum chest compressions were very similar and occurred at about the same time (Figure 16); the largest difference in maximum compression was 6 mm, and the largest difference in the occurrence of maximum compression was 3 ms (Dodge Neon tests).

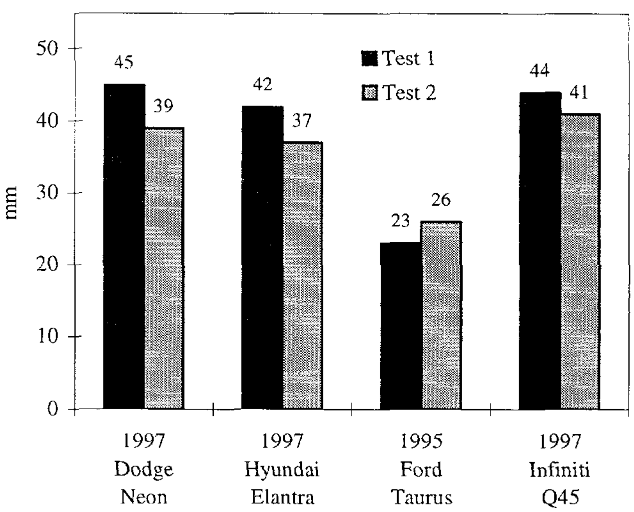


Figure 16. Comparison of Chest Deflection.

In the repeated tests of the Hyundai Elantra, Ford Taurus, and Infiniti Q45, the largest difference in femur forces (0.8 kN) occurred on the dummy's right leg in the Ford Taurus tests (Figure 17). Maximum femur forces occurred at about the same time except in the Ford Taurus tests, where maximum loads were recorded 43 ms apart. The largest difference in tibia-femur displacements (4 mm) occurred on the dummy's right leg in the Ford Taurus tests (Figure 18). Maximum tibia-femur displacements occurred at about the same time in the repeated tests. Upper tibia indices were similar, and the largest difference (0.13) was recorded on the dummy's left leg in the Infiniti Q45 tests (Figure 19).

Tibia axial forces were similar, and the largest difference (0.9 kN) was observed on the dummy's left leg in the Ford Taurus tests (Figure 20). Although the magnitudes of maximum tibia axial forces were similar, they did not occur at the same time. Maximum right tibia forces were recorded 38 ms apart in the Ford Taurus tests, and left tibia forces were recorded 41 ms apart in the Hyundai Elantra tests.

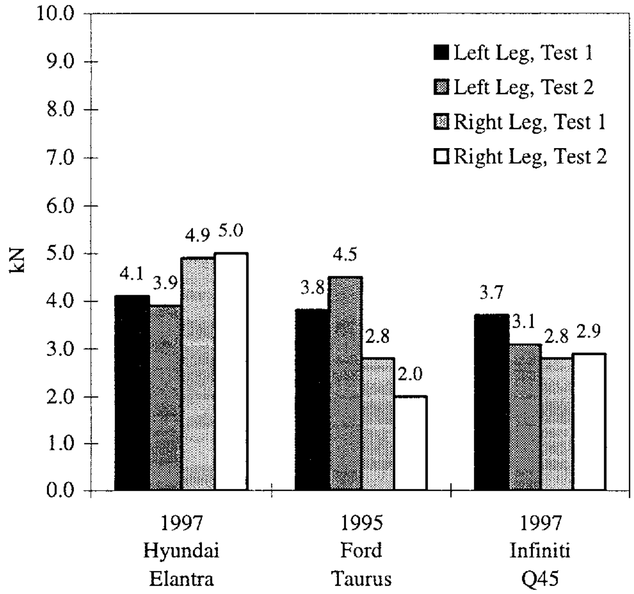


Figure 17. Comparison of Axial Femur Force.

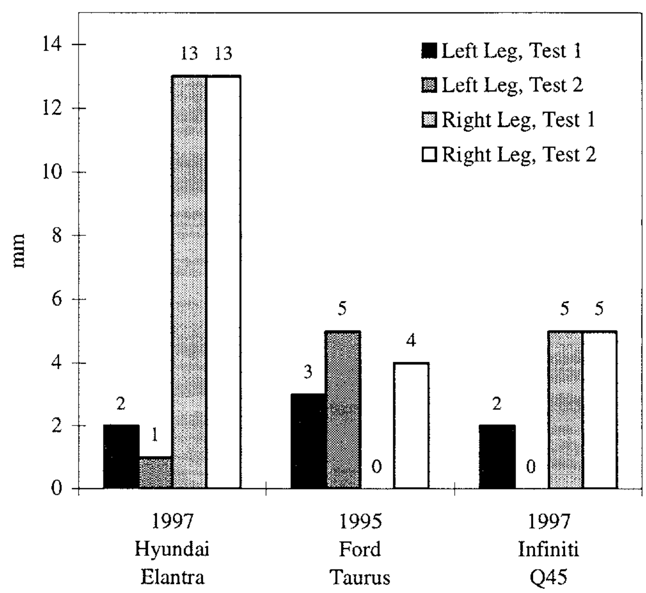


Figure 18. Comparison of Tibia-Femur Displacement.

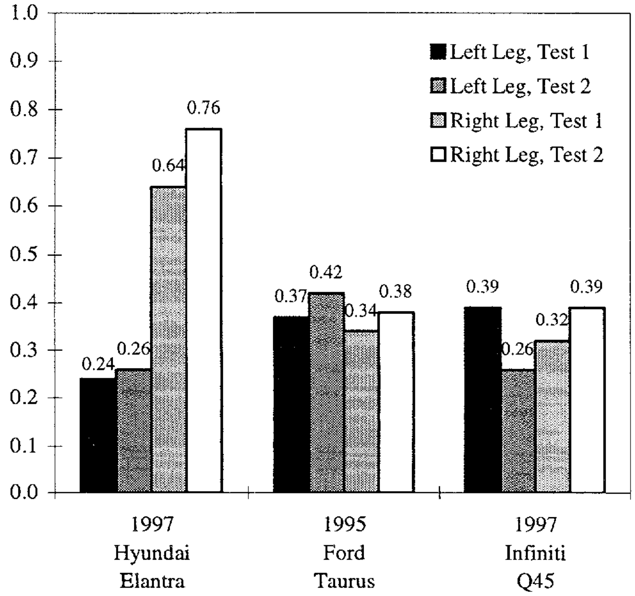


Figure 19. Comparison of Upper Tibia Index.

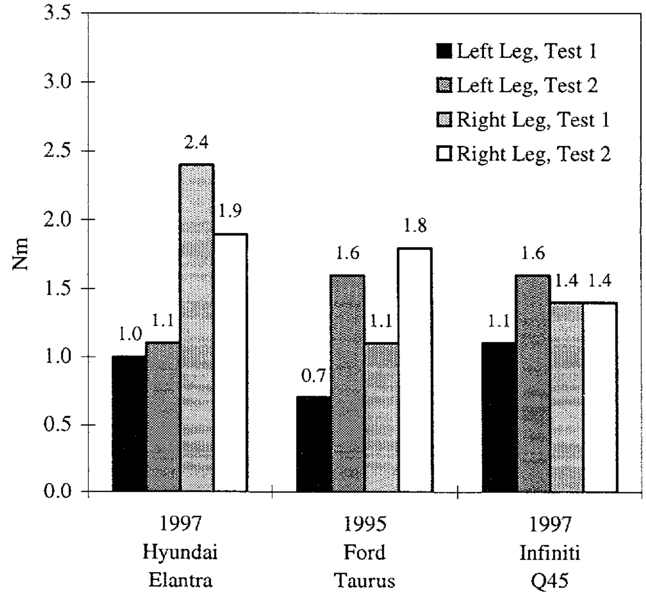


Figure 20. Comparison of Lower Tibia Axial Forces.

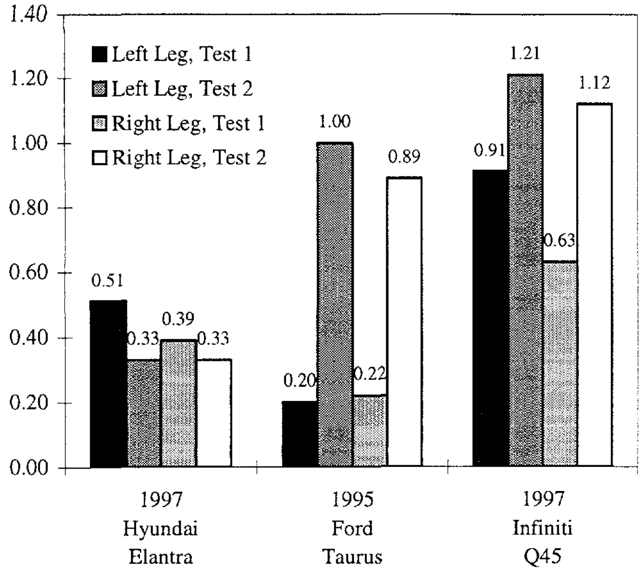


Figure 21. Comparison of Lower Tibia Index.

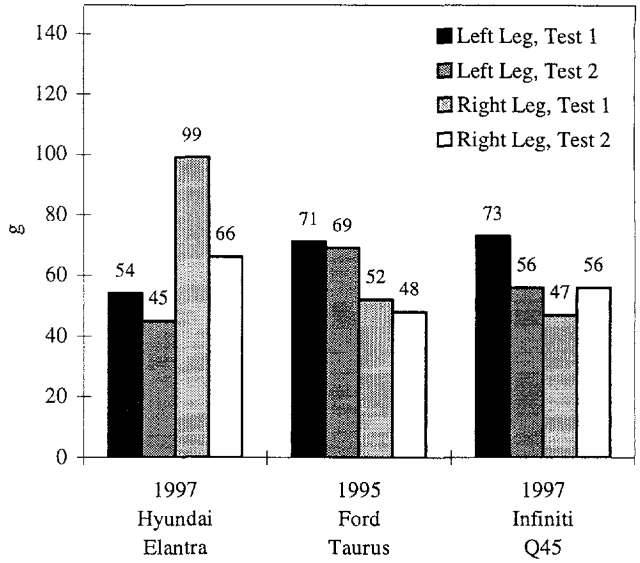


Figure 22. Comparison of Foot Accelerations.

Lower tibia indices show somewhat large differences in repeated tests (Figure 21). The smallest difference (0.06) was observed in the Hyundai Elantra tests, and the largest difference (0.80) was observed in the Ford Taurus tests. The occurrence of maximum tibia indices also was quite variable. Only the left indices occurred within 10 ms in the repeated tests of the Hyundai Elantra and Infiniti Q45. Foot accelerations were similar except in the Hyundai Elantra tests, where the difference between right foot accelerations was 33 g (Figure 22). Maximum foot accelerations occurred at about the same time except in the Ford Taurus tests, where maximum accelerations were recorded about 25 ms apart.

DISCUSSION

The results of repeated crash tests of the same vehicle model were very similar in this study. Vehicle accelerations, and hence the forces acting upon the occupants, were highly replicable, as were the performances of airbag and belt systems. Measurements of intrusion, a primary focus of offset crashes, were especially repeatable. Differences between pairs of vehicles in repeated tests were much smaller than the range of intrusion measurements seen for different vehicles of the same class. The Ford Taurus and Saab 900 showed the most intrusion variation, and only the Taurus intrusion difference would have given it a different rating in the Institute's evaluation of offset crash test performance (acceptable versus good). Similarly, occupant kinematics were highly similar, despite some minor differences in head contacts. Only the rearward steering column movements in the Ford Taurus tests and the airbag deployment times in the Hyundai Elantra tests exhibited appreciable differences. Because all seven models tested were equipped with driver airbags, differences in dummy head contacts with steering wheels, described in the NHTSA study, were not observed.

Dummy injury measures were reasonably repeatable as well. Only a few of the observed differences in the repeated tests would change the Institute's rating for the applicable body region. The greatest variability was observed for the lower tibia index. Interestingly, the vehicles with large differences, the Ford Taurus and Infiniti Q45, also exhibited less repeatable structural responses. A correlation between intrusion measurements and lower extremity injury measures has been established for this frontal offset test configuration,[5] and results from the Ford Taurus and Infiniti Q45 tests were consistent with this relationship. For each model, the test with greater intrusion also produced higher lower tibia bending forces. Toepan intrusion measurements in the Hyundai Elantra tests were considerably more repeatable, and the repeatability of the lower tibia index followed.

The Institute's crashworthiness evaluation combines results for three aspects of a vehicle's performance in an offset frontal crash test — structure/safety cage, injury measures (head/neck, chest, and left and right legs), and restraints and dummy kinematics — to derive an overall rating. The reliance on a combination of component ratings makes the overall evaluation even more consistent than component ratings alone. In the Institute ratings, even vehicles with a poor rating for one leg still can receive an acceptable rating if there is no other reason to rate the vehicle marginal or poor. In this test series, the vehicle showing the least repeatability (although performance still was reasonably similar) was the 1995 Ford Taurus. Nevertheless, intrusion measurements in the second test still would have been rated acceptable, and the leg injury ratings would have been acceptable and marginal. Dummy kinematics were similar, and good, in both tests, as was restraint system performance — airbags, belts, steering column, and seats. Overall, the rating for the Taurus in the second test would have been acceptable, only one category lower than its initial rating of good. For all other vehicles for which comparable information was available for all the rating components, the overall evaluation for the repeated test would have been the same as for the first test.

In summary, because differences between intrusion measurements, restraint system observations, and dummy injury measures in repeated tests generally were small compared with differences between rating categories, the Institute's overall crashworthiness evaluations would not be expected to change as a result of repeated tests. In cases where there is somewhat greater variability, a rating change of more than one category appears unlikely. Thus, the repeatability of modern vehicle performance in a frontal offset crash test is sufficient for making evaluations of the crash protection provided by different designs. It is anticipated that increasing manufacturer attention to designing for offset crash protection will further increase the predictability of structural performance, making offset crash test results even more repeatable.

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