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Repeatability Analysis of the Forces Applied to Safety Belt Anchors Using The Force Application Device

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16. Abstract
National Highway Traffic Safety Administration developed a force application device (FAD) that provides a better representation of the human form than the force application blocks presently specified in the FMVSS No. 210. NHTSA as also developed a repeatable seating procedure. The data and analysis presented in this report demonstrate that the forces applied to the seat belt anchor points by the FAD using the FMVSS No. 210 procedure is repeatable. Repeatability was determined using three different statistical methods. All but two channels were rated excellent. One channel was rated good and the other was rated acceptable. Overall, the FAD is considered to be repeatable.

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INTRODUCTION

As part of its 1995 compliance test program, a Chrysler Cirrus 4-door sedan was subjected to the requirements of Federal Motor Vehicle Safety Standard (FMVSS) No. 210, Seat Belt Anchorage Assemblies. The Office of Vehicle Safety Compliance (OVSC) performed the test. During testing, the passenger side rear outboard seat belt anchorage detached from the vehicle. The force required to detach the anchorage was less than the minimum force required by FMVSS No. 210, resulting in the agency finding that the vehicle did not comply with the safety standard.

During the resulting investigation and subsequent litigation, Chrysler argued that the test procedure outlined in the standard did not properly specify the initial position of the force application devices. Chrysler maintained that it had followed a permissible test procedure and, thus, satisfied the requirements of FMVSS No. 210. The Court of Appeals found that "NHTSA failed to provide adequate notice of what it now believes is the appropriate pelvic body block placement when testing for compliance under Standard 210." (*United States v. Chrysler Corporation*, 158 F.3d 1350, 1357 [DC Cir. 1998])

In response to the reversal, the agency developed a new force application device (FAD) and a procedure for positioning it in a seat. Although not an issue in the Chrysler litigation, the agency designed the FAD to be more representative of a human. The agency designed the new FAD and associated seating procedure to meet the following objectives:

1) To provide a repeatable test procedure so that tests satisfying the requirements of the procedure will give similar results regardless of who performs the procedure or where it is performed; and

2) To develop a FAD that provides a better representation of a person wearing a seat belt assembly.

The purpose of this report is to determine if the loads applied to the anchor points of the seat belt are repeatable when performing the FMVSS No. 210 procedure using the FAD. Furthermore, it is also intended to compare the channel measurement differences, to verify the channel change trends among the tests and to verify if any interactions between the channels and test number occur.

TEST SETUP

The agency took the following steps to avoid introducing outside variability into the test results:

1) The load cells located at the seat belt anchor points were mounted to a rigid test rig. The load cells used for these tests were from Denton ATD, Inc., model number 2881.

2) The seat was replaced with a rigid seat.

3) The seat belt webbing was replaced with high-strength webbing.

Three-axis load cells were placed at the outboard lap, inboard lap, D-ring, and the retractor (**see Figure 1**). Also, the tensile load was measured for the shoulder and lap belt hydraulic ram force, and the lap and shoulder belt webbing. Four tests were conducted in this study. In all, 16 distinct channels of information were collected for each test.

The FAD was positioned into a rigid seat according to the FAD seating procedure (**see Appendix B**). Once seated, the upper and lower parts of the FAD were each pulled with 3,000 pounds of force. After each test, the FAD was removed from the seat, reseated, and the differences in the location of the two points on the FAD were measured.

Figure 2 shows a typical output from one of the axes of the load cell (CFC 60). From this figure it can be seen that there is no exact point where the load cell force stabilizes; but there is little variation from points 3253 to 3752. This was consistent among the load cell outputs. For the purpose of comparison, only points 3253 to 3752 (500 data points) were statistically compared.

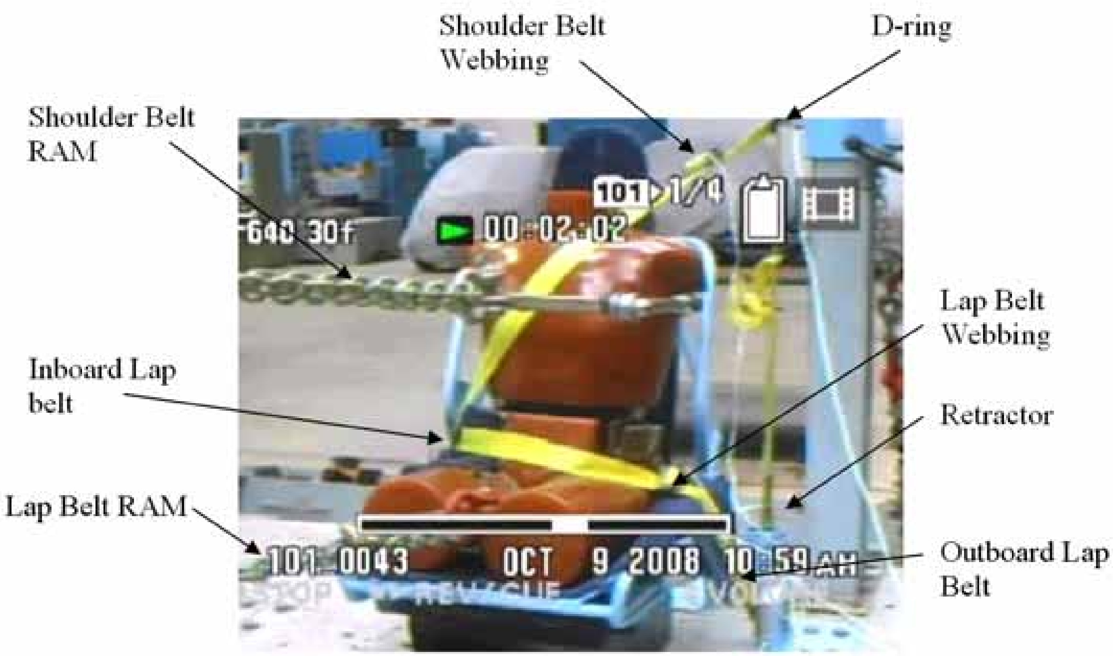

Figure 1. FAD positioned in rigid seat with the eight load cell locations

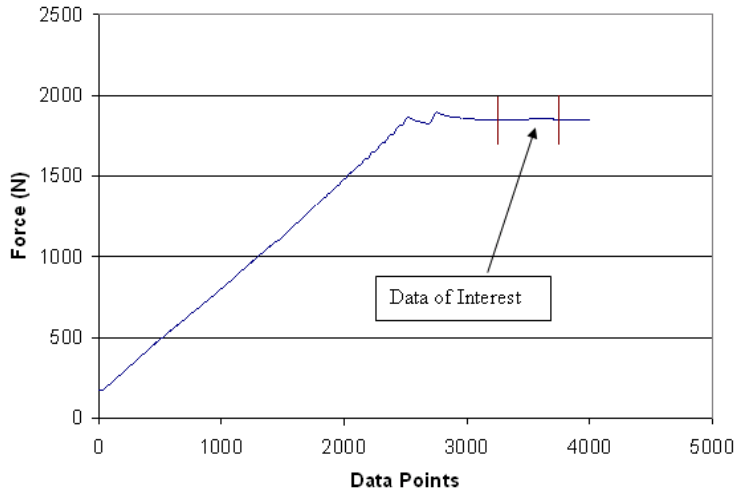

Figure 2. Typical output from one load cell channel

METHODS

Coefficient of Variation

One method of determining repeatability in test results is the use of the coefficient of variation (CV). CV is a measure of relative variability expressed as a percentage of the variable mean. CV is calculated according to the following formula:

$$CV = \frac{\sigma}{\mu} \times 100\% \qquad \text{Eq. (1)}$$

Where μ is the mean and σ is standard deviation of one variable, for instance, the force measured from one load cell. Historically, NHTSA has categorized the CV scores according to **Table 1.**[1]

Table 1: Assessment of CV scores

CV Score	Assessment
0.0% < CV ≤ 5.0%	excellent
5.0% < CV ≤ 8.0%	good
8.0% < CV ≤ 10.0%	acceptable
CV > 10%	unacceptable

The CV is useful because both the standard deviation and the mean of data should be considered. CV is a dimensionless number and is especially useful when comparing between data sets with different units, or wildly different means.

General Linear Model and Mixed Model

While CV, based on the relative variability of one variable, can be used to assess the repeatability of output from a particular channel, there are other methods that assess the repeatability of the whole system. These methods statistically model the output of the entire system over four different tests, and include the general linear model (GLM) and the mixed model.

Data with multiple measurements of the same dependent variable, such as the forces measured from one particular channel over time, is very common. Time-series data, repeated test data, as well as many experimental designs are all "repeatable measures." Similarly, repeatedly measured force data, which usually involves a smaller number of observations over time such as the four tests used in this report, is an example of repeatable measures. Multiple or repeated observations of the same subjects, for example, forces measured from the seat retractor or D-ring over time, allow statistical models to use a case as its own comparison and reference. Statistically, the observations of the dependent variable of the same subjects, for example, all four tests of a seat D-ring, are not independent but are correlated to each other, and the technique of repeated measures analysis is used to take this correlation into consideration. Two of the common models, GLM and mixed model, can be estimated using procedures in the SAS statistical software.[2] GLM and mixed model are used to describe the relationship between the dependent outcome (such as measured force) and the independent variables (such as channel and test number). For this analysis, GLM and mixed model can be used to compare the force mean values of all sixteen channels from four different tests, to determine if the force means are significantly different across channels among four tests, and particularly important for determining repeatability - to determine whether the force means are significantly different among four comparative tests that are performed at different time. The traditional value of 5 percent probability of a Type I error (false positive) is used as a threshold, or statistically significant level to determine whether to reject the null hypothesis. A p-value under 5 percent is used to determine a statistically significantly different value, or equivalently, a p-value above 5 percent indicates the results in comparison are not significantly different. For example, a p-value of 25 percent for the effect of "test number" indicates that force means are not significantly different over four tests since we would not reject the null hypothesis that there are no differences across time. In this report, the p-value would indicate whether the forces measured from four tests were repeatable and consistent.

Under the GLM, the measured force can be expressed by the following equation:

$$force = \mu + \alpha + \beta + (\alpha\beta) + \varepsilon \qquad \text{Eq. (2)}$$

Where μ is the force mean, α is test number effect, or test sequence effect on force (four tests performed at different time), β is channel effect, or group effect on force, $(\alpha\beta)$ is the interaction of test number and channel, and ε is a small random error with zero mean [2].

This statistical method provides analysts with data to do the following:

1) Determine whether the force measurements are consistent, or repeatable, over the four repeated measures performed at different time (i.e., is the test number effect within one channel significant, or not significant?);

2) Compare the channel measurement differences (i.e., the effect across channels); and

3) Verify if any interaction between the channel and test number occurs. If there is no interaction of channel with test number, the repeated force plots of various groups will be approximately parallel to each other. Otherwise, the force plots of various channels may cross or move in different directions.

Mixed model is similar to the GLM procedure, while mixed model provides more details of correlation structure types among repeated tests. The SAS mixed model estimation is used to analyze the repeated measures (the test number effect, or correlation among repeated measures, is the focus), as suggested by Equation (2).

RESULTS

Mean Values for Channel Output

Figure 3 plots the mean force values for the outboard lap belt load cell for four tests. The trend displayed in this plot is typical to that measured by the remaining load cells, except for the load cell on the retractor.

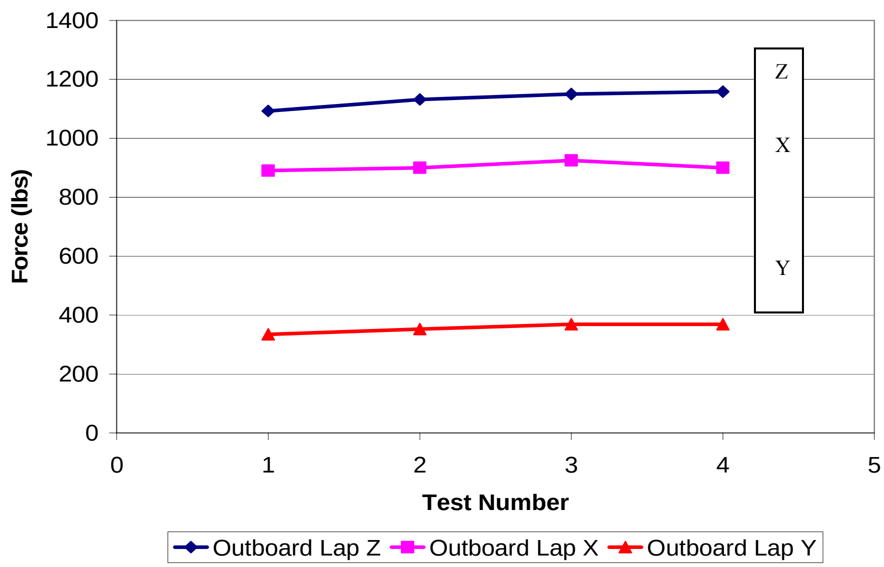

Figure 3. Mean force values for the outboard lap belt for all four tests

Figure 4 shows the mean force values for the retractor. During test 3 the mean force value in the Z-direction measured by the retractor load cell ("Retractor Z") was different from the other three tests. (The rest of the typical plots can be found in Appendix A.)

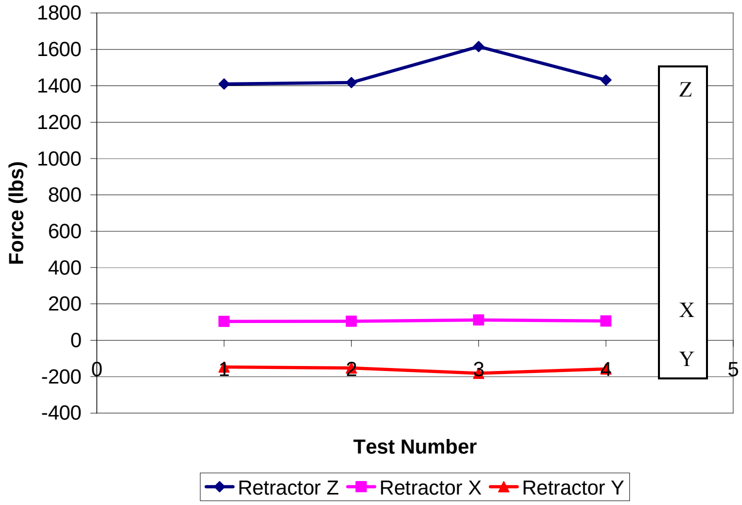

Figure 4. Mean force values for the retractor for all four tests

The next section uses different statistical analyses to determine the repeatability of the channels. It is noted that the effect of Test 3 Retractor Z force shown in Figure 4 could affect these results.

Coefficient of Variation

Table 2 shows the average of the 500 data points for each channel, the overall mean and deviation (4x500 = 2,000 data points) for the four tests and the CV for each channel. Forces with positive signs are tension forces while forces with negative signs are compression forces. The accuracy of the load cells is ± 10 lbs, which may contribute to the higher/lower CV. Using the acceptance criteria in Table 1, Retractor Y CV assessment was "Acceptable," and the CV assessment was "Good" for the Retractor Z. The CV assessments for the rest of the channels were "Excellent."

The Retractor Y maximum magnitude was less than 200 pounds and any little change in the force increased the CV percentage compared to other channels with higher readings.

The force mean of the retractor Z for test 3 is different from the other three tests, the assessment of four tests for retractor Z was "Good".

Table 2: Mean, overall deviation and CV for all data channels

Channel	Test 1 (force at Time 1) (lbs)	Test 2 (force at Time 2) (lbs)	Test 3 (force at Time 3) (lbs)	Test 4 (force at Time 4) (lbs)	Overall Mean (lbs)	Overall Deviation (lbs)	CV	Rating
Outboard Lap X	890.4	899.9	924.9	900.3	903.9	12.8	1.0%	excellent
Outboard Lap Y	334.6	352.2	368.7	368.6	356.0	14.1	4.0%	excellent
Inboard Lap Z	2222.1	2213.5	2186.4	2190.6	2203.2	15.8	0.7%	excellent
Inboard Lap X	1849.8	1836.4	1824.1	1808.8	1829.8	15.5	0.8%	excellent
Inboard Lap Y	579.4	602.9	591.5	596.9	592.6	9.0	1.5%	excellent
Outboard Lap Z	1092.9	1131.9	1150.1	1158.3	1133.3	25.2	2.0%	excellent
D-ring X	1707.9	1725.3	1741.3	1744.5	1729.8	14.8	0.8%	excellent
D-ring Y	995.7	1017.9	1061.7	1048.6	1031.0	26.1	2.5%	excellent
D-ring Z	-1938.8	-1970.2	-2195.9	-2008.0	-2028.0	99.6	4.9%	excellent
Retractor X	104.2	104.9	112.1	106.4	106.9	3.1	3.0%	excellent
Retractor Y	-147.1	-152.5	-181.7	-157.5	-159.7	13.3	8.3%	acceptable
Retractor Z	1409.3	1418.0	1615.3	1432.0	1468.7	85.1	6.0%	good
Shoulder Belt RAM	3004.0	3005.4	3005.9	2997.4	3003.2	5.0	0.2%	excellent
Lap Belt RAM	3009.2	3008.9	3008.7	3007.2	3008.5	0.8	0.0%	excellent
Lap Belt Webbing	1440.2	1472.6	1508.1	1496.4	1479.3	26.0	2.0%	excellent
Shoulder Belt Webbing	1907.5	1919.4	1937.8	1928.8	1923.4	11.6	0.6%	excellent

GLM and Mixed Model

Results from either GLM or the mixed model can be used to compare the force means and determine whether the means are significantly different across channels and over four tests using p-values. **Table 3** (from GLM procedure) and **Table 4** (mixed model) provide the calculated results.

Table 3: Key independent variables and p-values for GLM

Variable	p-value	Comments
Test	0.9830	Not statistically different
Test x Channel	0.9478	No interaction

The results of **Table 3** indicate that there are no statistically significant differences over test 1 through test 4 for the four repeated measures while all channels considered. This conclusion is verified by the p-value of test number effect of 0.98, or 98 percent--well above the significant level of 5 percent probability. These results indicate that the four tests are repeatable and consistent. Furthermore, there are no statistically significant interactions between test number and channel, and the p-value is 0.95 or 95 percent--still well above the 5 percent threshold. These results confirm that the repeated force plots of the various channels are parallel to each other and have similar trends as seen in the figures. The force mean values from the 16 channels for test 1-4 are widely spread as seen in Table 2, and GLM result also confirms the force differences of different channels with a significant p-value of less than 0.0001.

The results of **Table 4** are similar to the **Table 3** results. The four tests are repeatable and consistent over test number. Furthermore, there are no significant interactions between test number and channel.

Table 4: Key independent variables and p-value for mixed model

Variable	p-value	Comments
Test	0.9975	Not statistically different
Test x Channel	0.9523	No interaction

CONCLUSIONS

The following general conclusions can be made from this analysis:

* The test procedure using the FAD is repeatable, with 14 force channels meeting the "excellent" criteria, one channel meeting the "good" criteria (Retractor Z), and one channel meeting the "acceptable" criteria (Retractor Y).

* The retractor Y-axis has a large measurement error relative to other channels as seen by the "acceptable" coefficient of variation. However, the scale of mean value, around 200 pounds, is relatively small, thus the measurement error has a minor effect on the overall test results.

* The results of the general linear model and mixed model indicate that the forces measured from the 16 channels tend to be consistent and repeatable over time, and there are no statistically significant differences across tests.

* There are no statistically significant interaction effects between test number and channel. The repeated force plots of various channels are approximately parallel to each other and share similar trends.

* The results from the analysis of the coefficient of variation, the general linear model, and the mixed model indicate small, not statistically significant differences in the results across the tests and support the conclusion that the test is repeatable.

REFERENCES

[1] Rhule, D., Rhule, H., & Donnelly, B. (2005, June). "The Process of Evaluation and Documentation of Crash Test Dummies for Part 572 of the Code of Federal Regulation." NHTSA /DOT Report, Paper Number 05-0284, 19th Annual ESV Conference, Washington, DC.

[2] Fitzmaurice, G., & Laird, N. (2004). Applied Longitudinal Analysis. Hoboken, NJ: John Wiley & Sons.

APPENDIX A

This appendix provides the trends for all other load cells not listed in the body of the report.

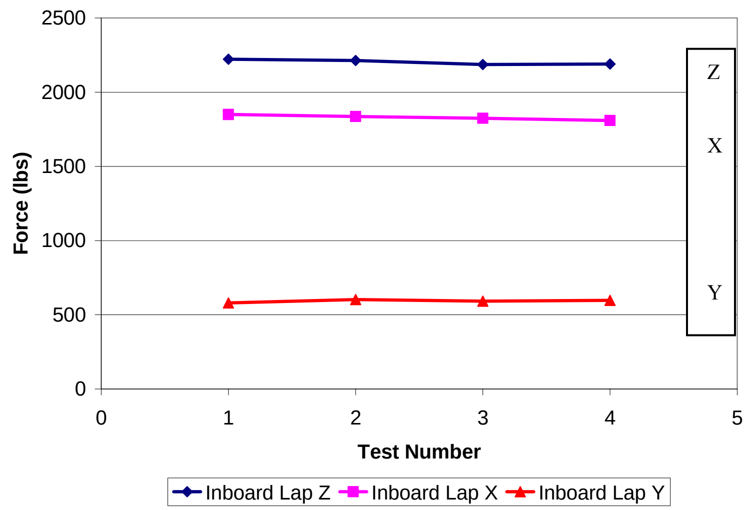

Figure A 1. Mean force values for the Inboard Lap for all four tests

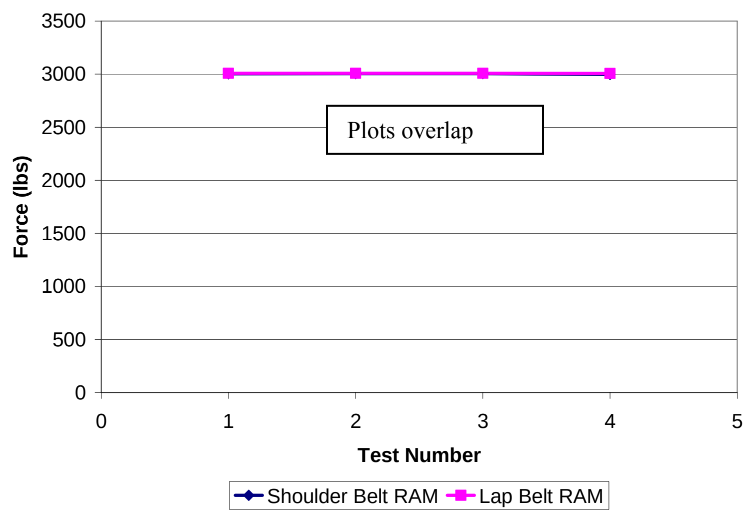

Figure A 2. Mean force values for the D-ring for all four tests

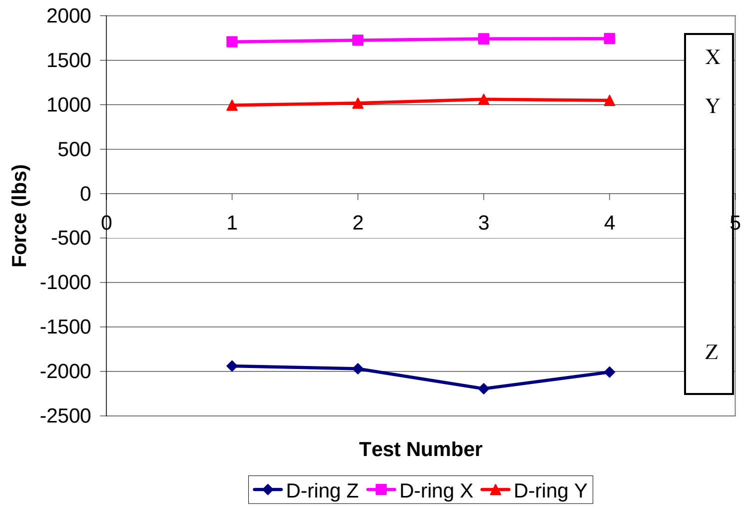

Figure A 3. Mean force values for shoulder and lap belt RAM for all four tests

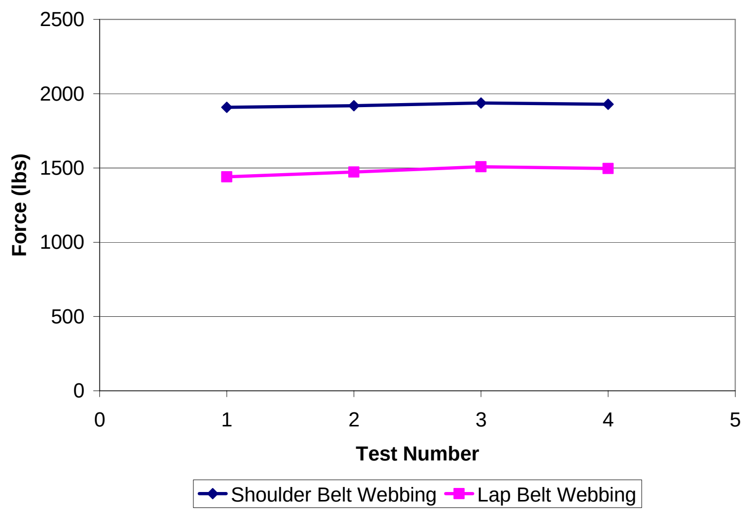

Figure A 4. Mean force values for shoulder and lap belt webbing RAM for all four tests

APPENDIX B

Seating Procedure:

(a) Place the seat in its rearmost position and, if separately adjustable in the vertical direction, at the lowest position.

(b) Adjust the seat back to the manufacturer's design seat back angle, as measured by SAE J826 (July 1995).

(c) Identify and mark the longitudinal centerline of the seat and seat back within ±10 mm for each DSP.

(d) Place the FAD1 or FAD2 on the seat such that the midsagittal plane of the FAD1 or FAD2 is vertical and coincides with the longitudinal centerline of the seat and seat back, within ±10 mm.

(e) While maintaining the alignment with the longitudinal centerline as described in (d) above, move the pelvis portion of the FAD1 or FAD2 toward the seat back, while sitting on the seat, until it is flush against the seat back.

(f) Rotate the torso of the FAD1 or FAD2 up against the seat back while holding the pelvis in place until it is flush against the seat back.

(g) Apply a horizontal force of 180±5 N to the FAD1 or FAD2 at the level of the torso pull yoke in the direction of the vehicle's longitudinal axis toward the rear of the vehicle. While performing this step, ensure that the pelvic portion of the FAD1 or FAD2 remains in contact with the seat and seat back.

(h) Buckle and position the seat belt so that the lap belt secures the pelvic portion of the FAD1 or FAD2 and the shoulder strap secures the torso portion of the FAD1 or FAD2.

(i) Remove enough slack such that the lap and shoulder belt are snug against the FAD1 or FAD2.

(j) If testing a Type 2 or Type 2A seat belt assembly, attach one actuator to the torso pull yoke and one to the pelvis eyelet. If testing a Type 1 seat belt assembly, attach the bridged pull yoke and attach the actuator to the bridged pull yoke.

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