FDC 7107

NORTHEAST CORRIDOR CANT DEFICIENCY TESTS FOR THE EVALUATION OF PASSENGER COMFORT IN CURVES

November 29 and 30, 1978

Report Number 1 - SUMMARY

Northeast Corridor Project
Federal Railroad Administration
U. S. Department of Transportation

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CONTENTS

Test documentation included in Report Number 2 - Supporting Documentation: Northeast Corridor Cant Deficiency Tests for the Evaluation of Passenger Comfort in Curves, November 29 and 30, 1978

1. Introduction and Conclusions

1.1 Background

Maximum allowable train operating speed in curves is presently set by the following formula contained in Section 213.57 of the FRA Office of Safety, Track Safety Standards:

$$V\ max = \sqrt{\frac{E_a+3}{0.0007d}}$$

where:

V_{max} = Maximum allowable operating speed (mph)

E_a = Actual superelevation of the outside rail (inches)

d = Degree of curvature (degree).

The constant number 3 appearing in the numerator of the equation is the maximum allowable vehicle cant deficiency or unbalance in the curve in inches. The three inches of vehicle unbalance gives an allowable speed increase in curves equivalent to that of 3 inches of additional superelevation. When the vehicle unbalance is zero, the vehicle operates through the curve at balance speed with no steady state lateral acceleration to the left or right. At positive levels of vehicle unbalance there is a lateral force exerted on the passengers toward the outside of the curve. This lateral force is proportional to the level of vehicle unbalance and depends on the type of vehicle suspension system. Modern vehicle suspension systems are improved over those in existence when the 3" vehicle unbalance limit was established.

Operating modern passenger trains in curves at vehicle unbalances higher than 3 inches (up to 6 inches with conventional suspension systems) is common in other countries. Curve speed increases for each additional inch of vehicle unbalance range from 5 to 6 percent which result in significant triptime reduction, particularly in areas of very curvy track alignment.

Because of this potential for trip time improvement by operating modern conventional passenger cars at more than 3" of vehicle unbalance, the train tests described in this report were performed.

1.2 Purpose

Two days of train tests were performed to subjectively evaluate the overall ride comfort and measure actual lateral acceleration on the passenger in typical curves on the Northeast Corridor at vehicle unbalances in excess of 3 inches. The major objectives of tests were:

- Perform the tests with Amfleet equipment on selected typical curves in the Northeast Corridor on wood and concrete tie track.
- Obtain a numerical subjective comfort rating from riders in the train in each curve tested.
- In each curve, measure actual lateral acceleration on the passenger with accelerometers.
- Compare measured lateral accelerations, as a function of vehicle unbalance, with calculated values of lateral acceleration.

- Statistically correlate passenger subjective comfort ratings with selected physical ride characteristics which might influence the comfort rating such as vehicle unbalance, time spent in curve, jerk in spiral transition and location in train.

The overall purpose of the tests was to evaluate comfort related parameters and not to measure vehicle overturning or safety related factors. Overturning calculations were made for the tests performed, however, and safety was not calculated to be critical.

1.3 Description of Tests

The train tests were successfully carried out in four curves located approximately 7 miles west of Kingston, Rhode Island on November 29, 1978 and in three curves located approximately 7 miles east of New London, Connecticut on November 30, 1978. Authorization to run the tests was given by the FRA Office of Safety in their letter dated November 22, 1978 from Mr. Robert H. Wright to Mr. R. F. Lawson of Amtrak. The train consisted of one F40PH locomotive and four Amfleet cars. Fourteen persons rated the ride on the first day of testing and ten persons on the second day.

Each passenger who evaluated comfort was given a rating sheet which contained a space for a numerical rating and comments for each test curve. The numerical rating was based on a scale from 1-10, five being marginally acceptable and 10 being best.

A portable data collection system was used to collect train speed, location in the curve, and vertical and lateral acceleration in the second and fourth (last) cars in the train.

A total of 13 separate tests were performed which involved running through four curves in each test on November 29 and three curves on November 30.

1.4 Results and Conclusions

A summary of the test results is shown in Tables 1 and 2. Following is a summary of the analysis of the test data:

- At 6" of vehicle unbalance the average comfort rating was between 6 and 7. (A comfort rating of five was marginally acceptable and 10 best.)

- The average lateral acceleration, vehicle vibration, and ride quality index (from mathematical model) were all approximately 10-60 percent worse in the rear of the last car of the train as compared with the middle of the second car in the train.

- The measured lateral force on the passenger in Amfleet cars was found to increase approximately linearlly with vehicle unbalance, at 0.020g per inch of unbalance. This is close to values which have been calculated analytically.

- A stepwise linear regression analysis was performed to evaluate the correlation between the subjective comfort ratings and selected physical ride characteristics. Based on data from the two days of testing (limited statistical data) the statistical analysis showed that comfort in curves can be most closely approximated by the following equation:

$$y = 9.74 - 28.84\, X_1 - 0.49\, X_2$$

for: $0.015 \leq X_1 \leq 0.10$

$0.3 \leq X_2 \leq 2.75$

where: y = comfort rating, 0-10 (10 best, 5 marginally acceptable)

X_1 = maximum jerk in curve (higher of entering or exiting spiral, minimum one second duration), g/second

X_2 = (time in body of curve) X (average lateral acceleration in curve), seconds and g

This equation was developed using the average comfort rating of all passengers in each test curve. The coefficient of correlation (r) was 0.87 and r^2 was 0.76.

Several general conclusions can be drawn from the tests performed.

- For the curves tested, vehicle unbalance in the 3" to 6" range provides an acceptable level of passenger comfort.

- Jerk levels were generally acceptable (except where track was misaligned). However, there are other curves in the NEC which have shorter spirals and therefore higher jerk levels. Unbalance levels should be set selectively in each curve on the NEC.

- No events in the tests indicated any safety problem associated with operating trains at up to 6" vehicle unbalance.

- Further tests with tilt body and conventional vehicles will be run to check safety at speeds associated with vehicle unbalance in excess of 3". These will include instrumented wheels.

TABLE 1: TEST RESULTS

Tests Performed November 29, 1978

Test ID	Curve #	Speed (mph)	Vehicle Unbalance E_u (inch)	Average Jerk Entering Curve (g/sec.)	Average Lateral Acceleration in Curve (g)	Average Jerk Exiting Curve (g/sec)	Peak Jerk in Entering or Exiting Curve (g/sec)	Number of Persons Rating	Average Comfort Rating (0 -10)
01	24	79	1.0	NA	NA	NA	NA	14	7.3
	28	50	2.9	NA	NA	NA	NA	14	6.8
	46	45	0.7	NA	NA	NA	NA	14	7.5
02	61	89	5.1	.029	.124	.037	.048	14	7.5
	62	92	5.1	.032	.117	.036	.056	14	7.0
	63	88	6.4	.043	.114	.040	.069	14	5.9
	64	92	5.8	.028	.103	.028	.049	14	7.2
03	61	80	3.0	.016	.077	.021	.030	14	8.4
	62	81	3.1	.019	.080	.022	.038	14	8.2
	63	80	4.3	.029	.084	.026	.051	14	7.0
	64	81	3.2	.017	.070	.017	.031	14	8.5
04	61	89	5.1	.030	.127	.038	.053	10	7.5
	62	93	5.3	.036	.130	.041	.064	10	7.3
	63	85	5.6	.037	.100	.034	.059	10	7.4
	64	92	5.8	.031	.117	.032	.051	10	8.5
05	61	84	3.9	.022	.100	.028	.037	9	7.7
	62	84	3.6	.025	.100	.028	.053	10	7.7
	63	85	5.7	.039	.107	.036	.065	10	6.6
	64	85	4.1	.022	.090	.023	.036	9	8.1
06	61	88	4.8	.029	.127	.038	.053	8	7.3
	62	93	5.3	.035	.127	.040	.070	8	7.1
	63	91	7.3	.059	.150	.054	.086	8	5.5
	64	91	5.6	.034	.127	.034	.050	8	7.9

Notes:

- NA - Not available. Recording device malfunction.
- All numbers based on the output of the accelerometer in the middle of car number two (No. 21114).
- The peak jerk is the maximum jerk in either the entering or exiting spiral. It has a minimum one second duration.

TABLE 2: TEST RESULTS

Tests performed November 30, 1978

Test ID	Curve #	Speed (mph)	Vehicle Unbalance E_u (inch)	Average Jerk Entering Curve (g/sec.)	Average Lateral Acceleration in Curve (g)	Average Jerk Exiting Curve (g/sec)	Peak Jerk in Entering or Exiting Curve (g/sec)	Number of Persons Rating	Average Comfort Rating (0 -10)
08	61	93	6.1	.033	.134	.042	.064	6	8.0
	62	92	5.1	.034	.124	.038	.067	6	8.0
	63	92	7.6	.057	.144	.052	.096	6	6.8
	64	93	6.1	.034	.124	.034	.055	6	7.8
09	86	69	1.3	.015	.037	.017	.051	6	9.4
	85	69	4.6/2.5	.021	.084	.040	.040	6	8.6
	84	69	3.1	.018	.070	.018	.020	6	9.2
10	86	64	0.6	.007	.020	.008	.007	6	9.6
	85	62	2.6/1.3	.010	.073	.046	.030	6	8.7
	84	64	1.9	.009	.040	.009	.013	6	9.4
11	86	76	2.3	.022	.050	.026	.022	6	9.2
	85	76	6.8/4.0	.033	.134	.053	.056	6	7.8
	84	76	4.9	.030	.110	.030	.026	6	8.7
12	86	69	1.3	.023	.057	.027	.014	6	9.3
	85	71	5.2/2.9	.026	.127	.052	.040	6	8.1
	84	69	3.1	.023	.090	.023	.020	6	8.9
13	86	71	1.6	.022	.053	.025	.013	6	9.2
	85	73	5.8/3.3	.038	.154	.047	.047	6	7.3
	84	77	5.1	.039	.140	.039	.037	6	8.1
14	86	73	1.9	.027	.063	.031	.017	5	9.5
	85	76	6.8/4.0	.040	.157	.069	.051	5	7.4
	84	80	6.0	.042	.144	.042	.043	5	8.5

Notes:

- NA - Not available. Recording device malfunction.
- All numbers based on the output of the accelerometer in the middle of car number two (No. 21114).
- The peak jerk is the maximum jerk in either the entering or exiting spiral. It has a minimum one second duration.
- Curve 85 is compound.

2. Description of Test Train, Track, and Instrumentation

2.1 Test Train

The test train consist included the following cars:

Locomotive: one EMD F40PH No. 207

Trailing Cars:

Car #1: long distance Amfleet coach with newly trued wheels - No. 21865

Car #2: long distance Amfleet coach - No. 21114

Car #3: Amcafe - No. 20034

Car #4: Amcoach - No. 21872. (last car in train)

2.2 Track

<u>Test Site Locations</u>

The tests were carried out at two primary (B and C) and one secondary (A) location as described below:

Test Section	Track Number	Curve Number	Milepost* TS	Milepost* ST	Physical Location
A (Secondary)	1	24 (WB)	194.4	193.7	Hebronville Interlocking (MA)
	1	28 (WB)	188.9	188.8	Lawn Interlocking (RI)
	1	46 (WB)	181.9	181.7	East of East Cranston Interlocking (RI)
B (Primary)	1	61 (WB)	154.3	154.9	4 miles south of Kingston (RI)
	1	62 (WB)	153.6	153.1	4.5 miles south of Kingston (RI)
	1	63 (WB)	152.5	151.9	5.5 miles south of Kingston (RI)
	1	64 (WB)	151.0	150.8	7 miles south of Kingston (RI)
C (Primary)	2	86 (EB)	129.0	129.3	Palmers Cove East Interlocking (RI)
	2	85 (EB)	129.3	129.7	0.5 miles east of Palmers Cove East Interlocking (RI)
	2	84 (EB)	129.9	130.1	1 mile east of Palmers Cove East Interlocking (RI)

* Boston South Station is at Milepost 228.8

Track geometry and condition

Test Section A was selected to allow the train riders to familiarize themselves with the 1-10 comfort rating system (described later). The 3 simple curves in this test section are wood tie track which had not recently been surfaced or lined prior to the test. The class of track was not known. The curve geometry is shown in Table 3.

Test Section B contained four simple curves on newly installed concrete tie track. The class of track and curve geometry is shown in Table 3.

Test Section C contained two simple and one compound curve (CV 85) on recently rehabilitated wood tie track. The class of track and curve geometry for each curve is shown in Table 3.

2.3 Instrumentation

Ensco Inc. was retained to provide a portable data collection system to collect vehicle acceleration, speed and position data. The data collection system was a modification of the FRA Portable Ride Quality Package, and consisted of two magnetic tape recorders, two signal conditioning and coding units, four accelerometer packages, a radar speed measuring device, and an automatic location detector. The accelerometers were mounted on the floor in the middle and rear of the second and fourth (last) cars in the train.

Six channel brush chart recorders were used to display real time data during the test. The signals displayed were lateral and vertical accelerations and speed and automatic locating device (ALD). The ALD

<u>TABLE 3: CURVE GEOMETRY AND CLASS OF TRACK</u>

Test Section	Curve Number	Track Number	Length of Spiral entering (ft.)	Length of Curve (ft.)	Length of Spiral exiting (ft.)	Degree of Curvature	Average Superelevation in Curve (in.)	Class of Track by Standard: Maximum Deviation of Mid ordinate - 62' chord	Class of Track by Standard: Variation in X-level in 31' on Spirals	Class of Track by Standard: Difference in X-level, less than 62' apart on curve between spirals
A (1)	24	1	372	2900	403	1°-26.25'	5 1/4	NA*	NA	NA
	28	1	124	300	124	4°-00'	4 1/8	NA	NA	NA
	46	1	279	450	326	4°-33'	5 3/4	NA	NA	NA
B (2)	61	1	558	1010	434	2°-00'	6	6	5	6
	62	1	496	1766	434	1°-33.75'	4 1/8	6	5	6
	63	1	341	2461	372	2°-15'	5 3/4	5	5	6
	64	1	503	496	496	2°-00'	6	6	5	6
C (2)	86	2	248	1043	217	1°-26.25'	3 1/2	5	5	6
	85	2	372	527/124/899 (Compound)	309	3°03.75', 2°-00'	5 5/8, 4 1/8	5	5	6
	84	2	403	726	403	2°-30'	5 1/4	5	6	6

* Not available

<u>Notes</u>:

(1) Length of spirals from DCP stringline notes taken in August 1977.
Length of curve and superelevation taken from track charts dated July 1978.

(2) All data taken from DCP field notes dated November 22, 1978.

signals were generated by metal targets placed at specific curve geometry points in each curve of Test Sections B and C. The curve geometry points were tangent-to-spiral (TS), spiral-to-curve (SC), curve-to-spiral (CS), and spiral-to-tangent (ST).

3. Description of Tests

Train tests were performed on November 29, 1978 and November 30, 1978. On the first day of testing, the train departed Boston South Station at approximately 9:30 AM and proceeded directly to Test Section C (CV 24, 28, 46). People on the train included the engineer (Don Lacey - Engine Foreman of Boston Division) and additional members of the train crew; Amtrak, FRA, DCP, and Bechtel personnel who participated in running the tests; and 14 people* (mostly engineers) who were riding the train to provide a subjective rating of comfort in each curve traversed.

Each of the 14 persons evaluating ride comfort was given a rating sheet in which he or she rated the comfort level in each curve from 1 to 10; a 5 rating being marginally acceptable and a 10 rating being best. Space was provided for comments. No attempt was made to define the precise ride sensations that should have been evaluated.

Six tests were run on November 29, 1978 as outlined in sequence below.

Test #	Test Section
01	A
02	B
03	B
04	B
05	B
06	B

All tests were run operating westbound on Track 1.

* Four of these people were only on the train for the first three of the six tests on November 29.

Table 4 in the next section of this report describes the train speed in each curve, E_u (vehicle unbalance), and the test results.

On November 30, 1978, the second day of testing, people on the train included the engineer (Don Lacey) and additional members of the train crew; Amtrak, FRA, DCP and Bechtel personnel who participated in running the test; and 6 people (mostly engineers) who were rating ride comfort in curves. The same rating system was used as described previously.

Seven tests were run on November 30, 1978 as outlined in sequence below:

Test #	Test Section
07 (aborted)	A
08	B
09	C
10	C
11	C
12	C
13	C
14	C

Table 5 in the next section of this report describes the speed in each curve, E_u, and the test results.

During both days of testing, conditions not normally experienced riding a train were: lack of the normal number of passengers riding the train, higher than average noise levels because the doors between cars were held open for instrumentation cables, and short test runs.

Approval to Perform Tests

Approval to operate at speeds where E_u exceeded 3" was given by the FRA Office of Safety in their letter dated November 22, 1978 from Mr. Robert H. Wright to Mr. R. F. Lawson of Amtrak. The letter permits speeds in curves per the following formula: $V = \sqrt{\frac{E_a+6}{.0007d}}$ with application as defined in Section 213.57 of the FRA Track Safety Standards. Within the curve, E_a is the average superelevation and d is the average degree of curvature, measured in inches and degrees respectively. Permissable deviations in d and E_a from the average or designated value are provided in Sections 213.55 and 213.63 of the FRA Track Safety Standards.

For points within the curve where d and E_a are both exactly equal to their average or designated values, the second term in the numerator represents the actual unbalanced superelevation for the speed defined in the formula. For points within the curve where E_a and d deviate from the designated values, the second term in the numerator may be greater or less than the actual unbalanced superelevation. Thus an unbalanced superelevation greater than 6 inches is permitted by the formula, provided that the deviations in d and E_a do not exceed maximum permissable deviations in Sections 213.55 and 213.63 of the Track Safety Standards.

Based on average values for d and E_a, the speeds permitted by the formula above in curves 63 and 64 in Test Section B are 86.4 mph and 92.6 mph respectively. Attaining and holding train speed precisely at these speeds to achieve 6" unbalance in both curves presented some difficulty.

Review of the actual values for E_a and d in the two curves shows that the differences in E_a and d are significantly less than the permissible deviations per Sections 213.55 and 213.63 as shown below:

Factor	Curve 63	Curve 64	Difference	Permissible deviation per Sections 213.55 and 213.63 for Class 5 Track
d (inches of mid offset from 62 foot chord)	2.25" (2.25^o)	2" (2.0^o)	+ 1/4"	1 1/4"
E_a (outer rail elevation over inner rail elevation)	5 3/4"	6"	1/4"	± 1"

Thus, a speed of 92.6 mph is permitted in curve 63 at points in the curve where deviations in d and E_a are such that d and E_a are equal to the designated values for curve 64. Significant additional deviations are permissible, as shown above.

On this basis, the maximum target speed in curve 63 was increased to a level equal to the maximum target speed in curve 64. This speed provided a maximum unbalanced superelevation achieved in all tests of 7.6 inches in curve 63 in the initial test run on November 30.

4. Test Results

4.1 General

The results of the tests on November 29 and 30 are shown in Tables 4 and 5 respectively.

Figure 1 is a plot of the average comfort rating in each test curve versus the vehicle unbalance in the curve. Figure 2 is a plot of measured lateral acceleration in the middle of car two versus vehicle unbalance in the curve.

A description of the numbers appearing in Tables 4 and 5, which were computed for each curve in each test, follows. First, the vehicle unbalance (E_u) was computed based on the actual train speed, degree of curvature, and average superelevation. Peak and average jerk were computed for the entering and exiting spirals. The average jerk is the average lateral acceleration in the body of the curve divided by the total time spent in the spiral and determined by the ALD's.* The peak jerk is the maximum jerk in the exiting or entering spiral that occurs for a minimum of one second. The peak jerk averages about 50 percent greater than the average jerk and reaches to as much as 75 percent higher in some spirals. Reasons for this include superelevation run into the tangent, maximum superelevation not achieved at the SC or CS point, misalignment of the spiral, and car body response.

The average lateral acceleration in Tables 4 and 5 is the steady state or RMS value. This value did not vary significantly within the body of the curves because the superelevation and degree of curvature remained relatively constant. The average comfort rating, which was explained previously, is also shown on the tables.

The W_Z rating shown in the tables is a measure of ride quality. The rating system was originally developed in 1941 in Germany and updated in 1968. It has a five point scale where 2 is a very good ride and 5 a "dangerous" one, 3 being the upper limit for passenger cars. Unfortunately, due to the limited data, the rating could only be computed for each test run which included 3 or 4 curves.

* Approximately 50 percent of the curves on the NEC have spiral lengths which would cause a higher jerk rate than was experienced in the test curves.

In the tests performed, the best W_z rating was 1.99* in test 12. Overall, this was the lowest unbalance test run:

Curve	E_u
86	1.3
85	5.2/2.9
84	3.1

The worst W_z rating was 2.20* in test 8. This was the highest unbalance test run:

Curve	E_u
61	6.1
62	5.1
63	7.6
64	6.1

Even at this high unbalance level, the 3.0 limit was not reached. In fact 2.20 is only marginally greater than the 1.99 rating.

The ISO number in the table is a measure of vehicle vibration. The ISO is the number of hours that a passenger could reasonably be subjected to the measured vibrations within a 24 hour period. As with the W_z rating, only one number could be computed for each test.

The best ISO rating was 15.3* in test 3, described below:

CV	E_u
61	3.0
62	3.1
63	4.3
64	3.2

The worst ISO rating was 6.1* in test 11, described below:

CV	E_u
86	2.3
85	6.8/4.0
84	4.9

* Middle of car number two (21114).

The worst rating for all tests was on the wood tie track, the test with next to the highest unbalance. The best rating was on the concrete tie track, the test with the lowest unbalance. The ISO was better on the highest unbalance test on concrete ties (10.3 in test 8) than the lowest unbalance on wood ties (9.9 in test 10).

From Figure 1 it can be seen that there is good correlation between the measured lateral acceleration in the train (middle of car number two) and the vehicle unbalance. The relationship is approximately 0.020g per inch of unbalance. The relationship is nearly linear over the range of 0 to 6 inches unbalance.

Accelerometers were positioned in the middle and rear of the second and last cars in the train. All calculations and manipulation of recorded data presented in this report were based on the readings from the accelerometer in the middle of the second car. However, there were some significant differences in the readings from the other accelerometers, as summarized below:

	Average Measurements Normalized		
Accelerometer	RMS Lateral Acceleration	W_z	ISO
1 (middle car 2)	1.0	1.0	1.0
2 (rear car 2)	1.2-1.3	1.00-1.05	0.6 -0.7
3 (middle car 4)	0.95-1.2	1.02-1.07	0.75-1.0
4 (rear car 4)	1.3-1.5	1.06-1.15	0.3 -0.4

It can be seen that the middle of car two provides the best passenger comfort, followed closely by the middle of car four. The rear of car two is significantly worse in lateral acceleration and vibration (ISO),

TABLE 4: TEST RESULTS

Test performed November 29, 1978

Test ID	Curve #	Speed (mph)	Vehicle Unbalance E_u (inch)	Average Jerk Entering Curve (g/sec)	Average Lateral Acceleration in Curve (g)	Average Jerk Exiting Curve (g/sec)	Peak Jerk in Entering or Exiting Curve (g/sec)	Comfort Rating W_z	Vibration Index ISO	Number of Persons Rating	Average Comfort Rating (0-10)
01	24	79	1.0	NA	NA	NA	NA	NA	NA	14	7.3
	28	50	2.9	NA	NA	NA	NA	NA	NA	14	6.8
	46	45	0.7	NA	NA	NA	NA	NA	NA	14	7.5
02	61	89	5.1	.029	.124	.037	.048	2.7	12.7	14	7.5
	62	92	5.1	.032	.117	.036	.056			14	7.0
	63	88	6.4	.043	.114	.040	.069			14	5.9
	64	92	5.8	.028	.103	.028	.049			14	7.2
03	61	80	3.0	.016	.077	.021	.030	2.13	15.3	14	8.4
	62	81	3.1	.019	.080	.022	.038			14	8.2
	63	80	4.3	.029	.084	.026	.051			14	7.0
	64	81	3.2	.017	.070	.017	.031			14	8.5
04	61	89	5.1	.030	.127	.038	.053	2.16	13.3	10	7.5
	62	93	5.3	.036	.130	.041	.064			10	7.3
	63	85	5.6	.037	.100	.034	.059			10	7.4
	64	92	5.8	.031	.117	.032	.051			10	8.5
05	61	84	3.9	.022	.100	.028	.037	2.15	14.0	9	7.7
	62	84	3.6	.025	.100	.028	.053			10	7.7
	63	85	5.7	.039	.107	.036	.065			10	6.6
	64	85	4.1	.022	.090	.023	.036			9	8.1
06	61	88	4.8	.029	.127	.038	.053	2.17	12.4	8	7.3
	62	93	5.3	.035	.127	.040	.070			8	7.1
	63	91	7.3	.059	.150	.054	.086			8	5.5
	64	91	5.6	.034	.127	.034	.050			8	7.9

Notes:
- NA - Not available. Recording device malfunction.
- All numbers based on the output of the accelerometer in the middle of car number two (No. 21114).
- The peak jerk is the maximum jerk in either the entering or exiting spiral. It has a minimum one second duration.
- W_z is a measure of ride quality. 0 is the best value, 2 is very good, and 3 is the upper limit for passenger cars.
- ISO is a measure of vibration. 24 is the best value and 0 the worst.

TABLE 5: TEST RESULTS

Tests performed November 30, 1978

Test ID	Curve #	Speed (mph)	Vehicle Unbalance E_u (inch)	Average Jerk Entering Curve (g/sec)	Average Lateral Acceleration in curve (g)	Average Jerk Exiting Curve (g/sec)	Peak Jerk in Entering or Exiting Curve (g/sec)	Comfort Rating W_z	Vibration Index ISO	Number of Persons Rating	Average Comfort Rating (0-10)
08	61	93	6.1	.033	.134	.042	.064	2.2	10.3	6	8.0
	62	92	5.1	.034	.124	.038	.067			6	8.0
	63	92	7.6	.057	.144	.052	.096			6	6.8
	64	93	6.1	.034	.124	.034	.055			6	7.8
09	86	69	1.3	.015	.037	.017	.051	2.08	8.2	6	9.4
	85	69	4.6/2.5	.021	.084	.040	.040			6	6.6
	84	69	3.1	.018	.070	.018	.020			6	9.2
10	86	64	0.6	.007	.020	.008	.007	2.04	9.9	6	9.6
	85	62	2.6/1.3	.010	.073	.046	.030			6	8.7
	84	64	1.9	.009	.040	.009	.013			6	9.4
11	86	76	2.3	.022	.050	.026	.022	2.14	6.1	6	9.2
	85	76	6.8/4.0	.033	.134	.053	.056			6	7.8
	84	76	4.9	.030	.110	.030	.026			6	8.7
12	86	69	1.3	.023	.057	.027	.014	1.99	14.4	6	9.3
	85	71	5.2/2.9	.026	.127	.052	.040			6	8.1
	84	69	3.1	.023	.090	.023	.020			6	8.9
13	86	71	1.6	.022	.053	.025	.013	2.12	7.4	6	9.2
	85	73	5.8/3.3	.038	.154	.047	.047			6	7.3
	84	77	5.1	.039	.140	.039	.037			6	8.1
14	86	73	1.9	.027	.063	.031	.017	2.17	6.8	5	9.5
	85	76	6.8/4.0	.040	.157	.069	.051			5	7.4
	84	80	6.0	.042	.144	.042	.043			5	8.5

Notes:

- o NA - Not available. Recording device malfunction.
- o All numbers based on the output of the accelerometer in the middle of car number two (No. 21114).
- o The peak jerk is the maximum jerk in either the entering or exiting spiral. It has a minimum one second duration.
- o W_z is a measure of ride quality. 0 is the best value, 2 is very good, and 3 is the upper limit for passenger cars.
- o ISO is a measure of vibration. 24 is the best value and 0 the worst.
- o Curve 85 is compound.

FIGURE 1: AVERAGE COMFORT RATINGS

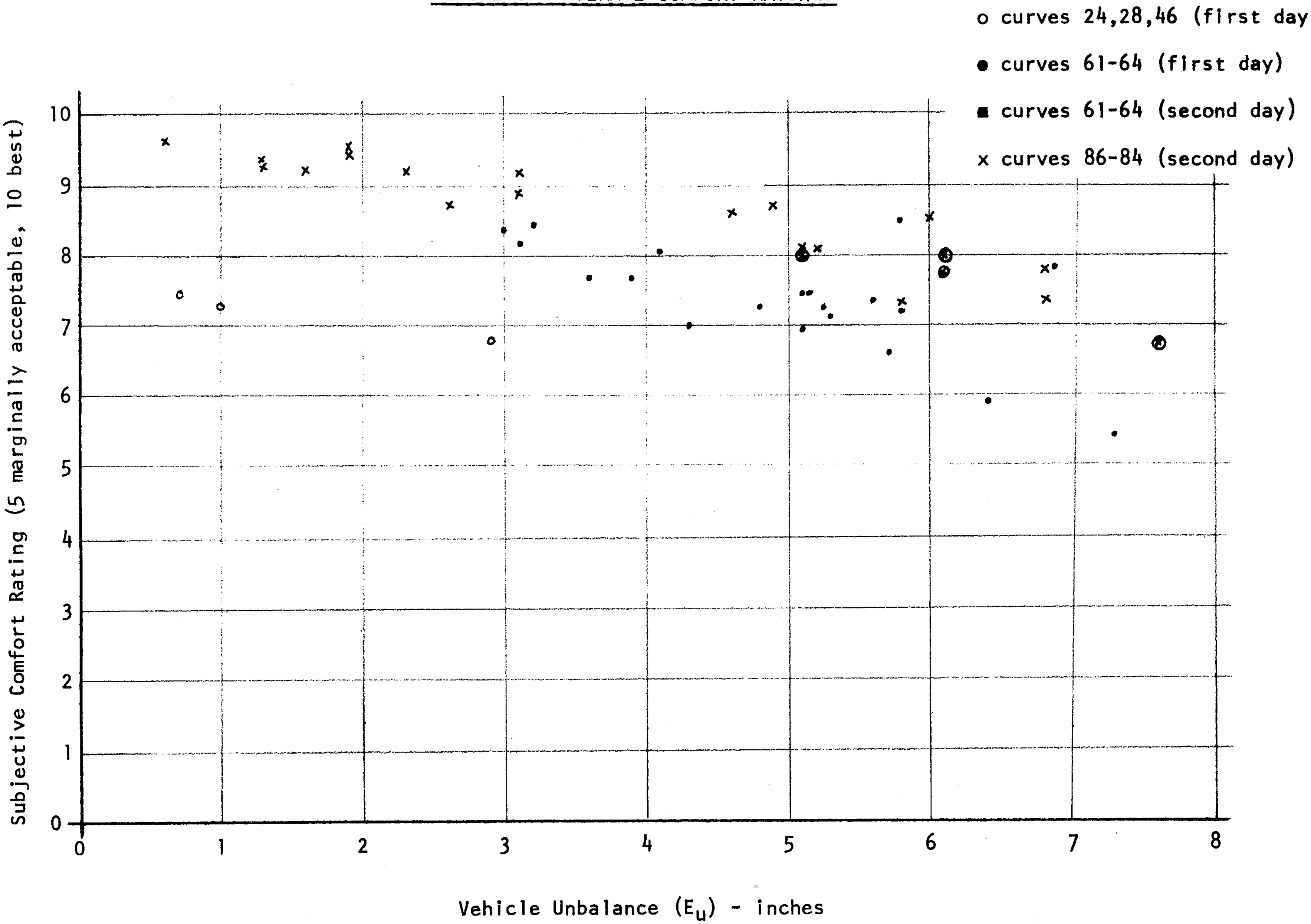
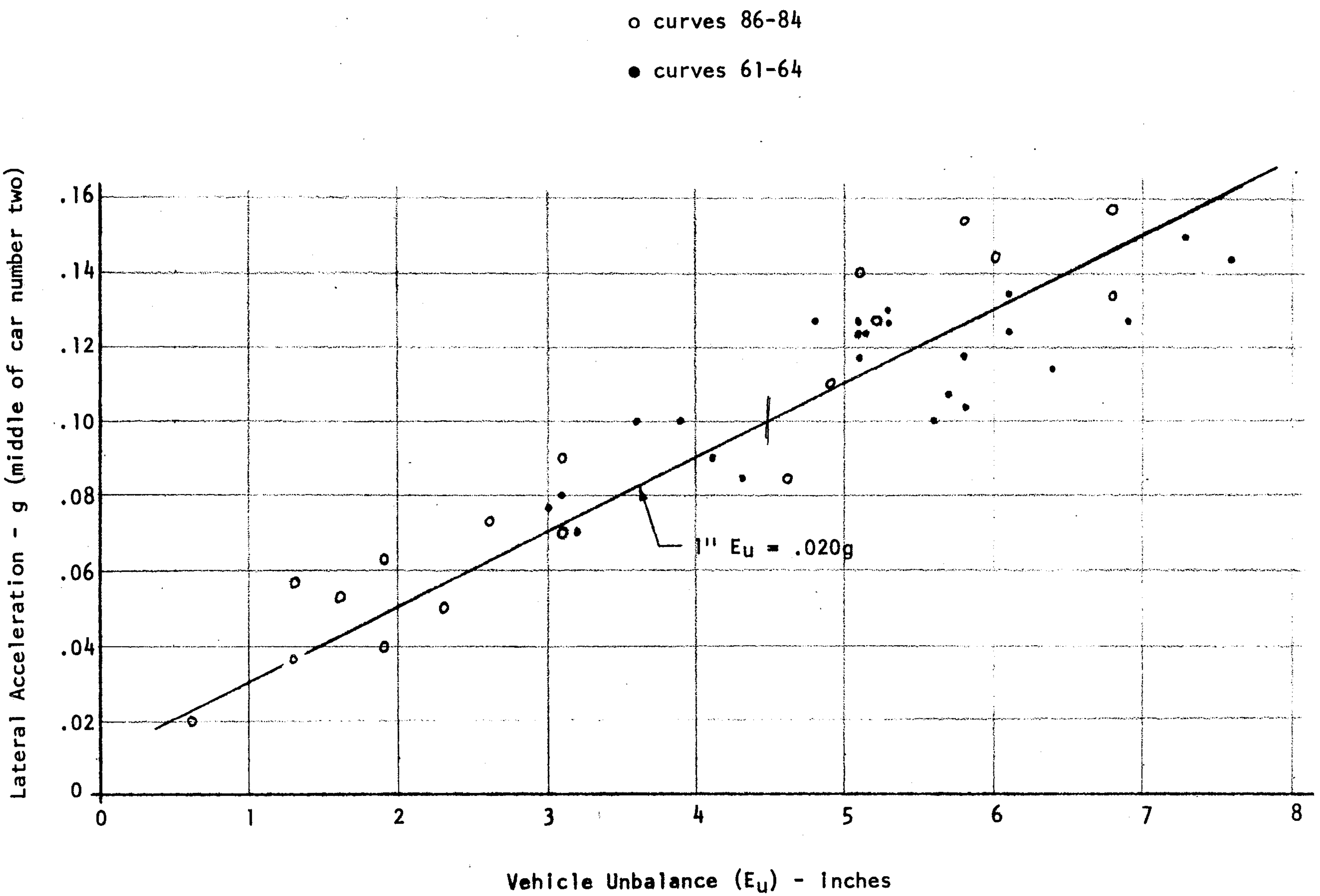


FIGURE 2: VEHICLE UNBALANCE VERSUS MEASURED LATERAL ACCELERATION



but surprisingly not in overall ride comfort (W_Z). The rear of car four is significantly worse by all measures. Unfortunately, the subjective comfort ratings do not really substantiate these results, undoubtedly because of the small sample size (only one or two people rode in the rear of car four).

4.2 Statistical Analysis

388 subjective passenger comfort ratings were recorded by the train riders during the two days of testing. Using this data, a statistical regression was performed to determine the correlation between the passenger comfort ratings (dependent variable) and the following independent variables in curves:

- o average lateral acceleration on passenger
- o time spent in curve
- o average jerk in entering and exiting spirals
- o peak jerk in entering or exiting spiral (minimum one second duration)
- o location in train

The stepwise multiple linear regression analysis revealed that there was good correlation between the passenger comfort ratings and three independent variables. Based on the statistical study, the following equation best predicts the actual comfort ratings:

$$y = 9.74 - 28.84\,X_1 - 0.49\,X_2$$

for: $0.015 \leq X_1 \leq 0.10$

$0.3 \leq X_2 \leq 2.75$

where:

y = comfort rating, 0-10 (10 best, 5 marginally acceptable)

X_1 = maximum jerk in curve (higher of entering or exiting spiral, minimum one second duration), g/second

X_2 = (time in body of curve) X (average lateral acceleration in curve), seconds and g.

This equation is based on data from the tests performed on both days. It was derived using the average comfort rating for all passengers in each curve. On this basis, the r and r^2 values are 0.87 and 0.76 respectively. When each individual comfort rating was used in the regression analysis, very nearly the identical equation resulted, however, the r and r^2 dropped to 0.55 and 0.31 respectively.

Of the variables tested, it was found that the goodness of fit was little effected when maximum rather than average jerk in the spiral was used. The variable location in train could not really be handled properly in the regression study because for it to be meaningful, a ride measure reflecting physical ride characteristics would have to have been established for each train location. This was not possible, and, furthermore, the sample size was too limited.

In addition to the equation described above, six other equations were computed as shown in Table 6. Case 1 in the table is the equation above. Case 2 is identical to Case 1, but is based solely on the first day's testing. Case 3 is identical to Case 1, but is based solely on the second day's testing. The goodness of fit for Cases 2 and 3 are very close to that for Case 1.

Cases 4, 5, and 6 are identical to Cases 1, 2, and 3 respectively, except all comfort rating were used instead of the average comfort rating in each curve. The r and r^2 values are much worse for these cases as would be expected.

Case 7 was an attempt to predict the passengers' ability to precisely predict the change in comfort from one test curve to the next. This was done by normalizing the comfort ratings for the tests on November 29 only. The resulting equation had an r^2 value of 0.37, compared with 0.18 without normalization.

Based on the small data sample, the statistical analysis showed quite conclusively that there is good statistical correlation between the subjective comfort ratings and the average lateral acceleration, jerk in spiral, and time in curve. Additional tests will undoubtedly provide data which could be used to refine the best fit equation described in this section, perhaps taking additional variables such as the comfort rating index (W_z) and vibration index (ISO) into account.

TABLE 6: RESULTS OF STEPWISE LINEAR REGRESSION ANALYSIS

Case	Description	r^2y	ry	rx_1y	rx_2y	c_o	c_1	c_2
1	Average Rating All Tests	0.76	0.87	-0.84	-0.79	9.74	-28.84	-0.49
2	Average Rating Tests 2-6 (1st day)	0.79	0.89	-0.86	-0.83	8.01	-30.20	-0.44
3	Average Rating Tests 8-14 (2nd day)	0.72	0.85	-0.85	-0.68	9.69	-28.84	-0.12
4	Actual Rating All Tests	0.31	0.55	-0.53	-0.50	9.83	-29.13	-0.50
5	Actual Rating Tests 2-8 (Curves 61-64)	0.18	0.42	-0.39	-0.41	9.05	-17.60	-0.56
6	Actual Rating Tests 9-14 (Curves 86-84)	0.37	0.61	-0.53	-0.52	10.40	-23.74	-1.76
7	Normalized Rating Tests 2-6 (1st day)	0.37	0.61	-0.60	-0.56	9.65	-36.04	-0.37