REPORT NO. RS006-PM-79-31
DATE: NOVEMBER 1979 (REVISED)

UNITED STATES - FEDERAL REPUBLIC OF GERMANY COOPERATIVE STUDY OF ADVANCED GROUND VEHICLE RIDE QUALITY

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PROJECT MEMORANDUM

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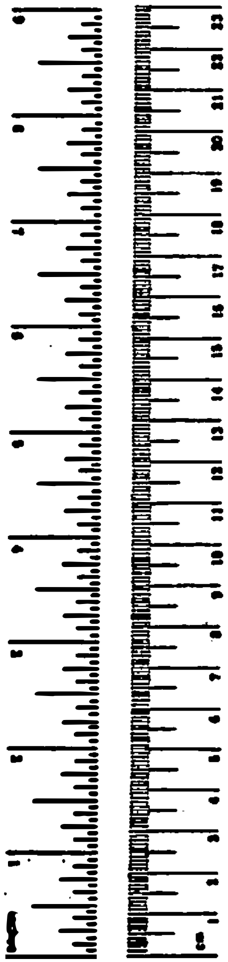
U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

METRIC CONVERSION FACTORS

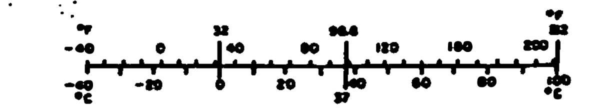
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. BACKGROUND

The experiment described in this memorandum is the second phase of an investigation of the ride-comfort and acceptability characteristics of proposed magnetically levitated, advanced high-speed, ground transportation systems. The study is sponsored jointly by the U.S. Department of Transportation and the Federal Republic of Germany's (FRG) Ministry of Research and Development. It is being carried out in the United States by the Transportation Systems Center under the Transportation Advanced Research Project sponsored by the Office of Systems Technology, with the support of the National Aeronautics and Space Administration/Langley Research Center (NASA/LRC). The FRG portion of this effort is being performed by Dornier Systems GmbH , Messerschmitt Bölkow, Blohm (MBB) GmbH, and Machinenfabrik Augsburg-Nürnberg A.G. (Man). This U.S./FRG effort is covered under a cooperative research agreement initiated in May, 1978.

In the first phase of this study, the relative comfort associated with various speed-guideway configurations for a proposed magnetically levitated vehicle (Figure 1) and for a currently operating Bundesbahn rail-coach were determined. The ride-environment of the two vehicle types was simulated using the NASA Langley Research Center's (NASA/LRC) Passenger Ride Quality Apparatus (PRQA). The simulation was based on vehicle and guideway dynamics models which depict the motion environments in terms of "bounce" or motions along the Z-axis, "sway" or motions along the X-axis, and "roll" or rotational motions about the Y-axis. Paid subjects, chosen to achieve a balance between sex & age, were exposed to brief samples of the motion environments accompanied by appropriate levels of acoustic noise. The subjects were asked to rate the comfort level of each motion sample and, in cases where the ride was perceived to be uncomfortable, were asked to identify the motions which were most disturbing.

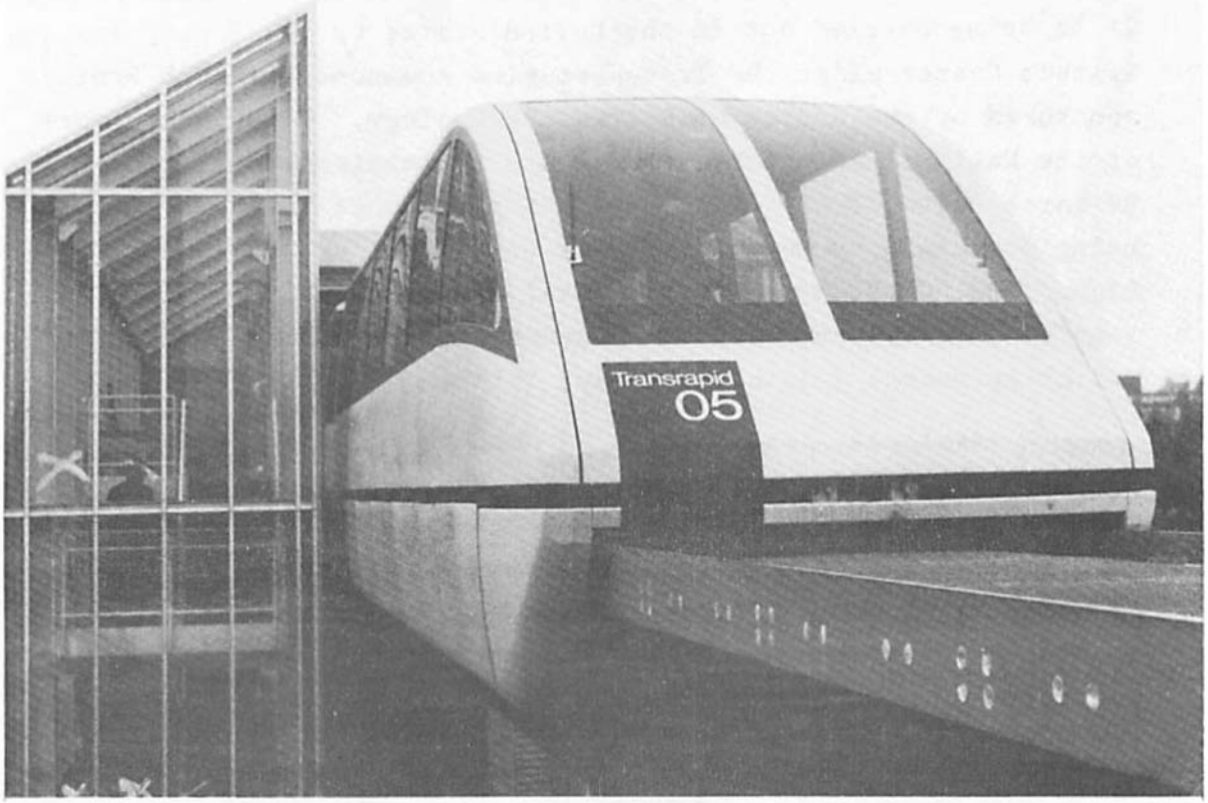

FIGURE 1. PROTOTYPE MAG-LEV VEHICLE

The results of the first phase indicated that at speeds up to 300 k/h, the magnetically levitated vehicle system would provide a ride equal to or better than the conventional rail system operating for the simulated, guideway configurations at speeds up to 160 k/h. The results also showed that the most disturbing aspect of the magnetically levitated vehicle's ride was the lateral acceleration or sway,while the most disturbing motions for the rail-coach were the vertical accelerations,or bounce.

No effort was made during the first phase to simulate actual trips. The purpose was to obtain relative subject-comfort ratings using brief (two minute) motion and noise simulations.

The major goal of the second phase was to estimate the absolute comfort levels which would be associated with actual travel on highspeed, interurban, fixed-guideway, transportation systems. To accomplish this goal, the study design incorporated many of the features to be found in such travel including realistic trip durations, simulations of the visual aspects of the countryside, control of subject expectation through descriptions of the characteristics of the vehicles simulated, and subject performance of activities analogous to those actually carried out during travel. Forty-five minute trip lengths (approximately the duration planned for the mag-lev systems) were used,and during these trips, passengers were exposed to five eight-minute trip segments which represented different speed-guideway configurations. The "trips" and the segments they were composed of were presented with synchonized moving pictures depicting the view which would be seen from surface vehicles traveling at the speeds being simulated. The color movies used to provide the subjects with a distinct feeling of forward motion, allowed them to estimate the simulated speed, enhanced the impression that a trip was being taken, and gave the subjects something to look at when they were unoccupied.

The description of the systems being simulated served to focus subject expectations. This was very important because the PRQA is configured to resemble an airliner cabin, and it was essential that the subjects judge the rides based on their experiences with other surface-systems rather than with generally smoother-riding jet aircraft. Finally, the subjects were required to perform simple reading and writing tasks similar to those ordinarily carried out during intercity travel. This served to reduce subject boredom, permitted subjects to determine effect-estimates of ride-motion interference with such tasks,and allowed the determination of the actual impact of the ride variations on reading and writing performance.

2. METHOD

2.1 DESIGN

The experimental design included three variables: type of vehicle, speed, and level of perturbation. The two vehicle types were magnetically-levitated and steel wheel-steel rail (rail coach). For each vehicle type, three variations in speed were tested. The speeds chosen for the magnetically levitated vehicle were 200, 300, and 400 k/h, and the speeds chosen for the rail coach were 125,200 and 265 k/h. The three levels of perturbation were high, low, and reduced. The perturbations used were simulations of ride irregularities caused by factors such as pier misalignment, guideway flexibility, and vehicle aerodynamics.

The three levels of perturbation could be varied for sway, bounce, and rail vibrations, but a factorial design incorporating the total number combination of all levels of the three variables would result in 162 conditions. Since the cost of running all the conditions was prohibitive, and the information many of the conditions would provide would not be useful for vehicle design (as they do not represent realistic operating conditions), no attempt was made to run them. Another reason for not using the full factorial design was that more information was needed about magnetically levitated vehicles than about rail coaches. Therefore, it was decided at a joint meeting of the U.S. and German participants, to test ten magnetically levitated and five rail coach conditions as shown in Table 1. These conditions had the greatest potential for providing information about vehicle-guideway design.

The noise level within the PRQA cabin was varied systematically in coordination with the speed, vehicle type, and guideway-induced perturbations which characterized each ride segment. The noise-input levels were derived from estimates of turbulence-produced, jet-aircraft, cabin noise provided by NASA staff. However, the major source of noise-level variation experienced by the subjects was produced by their own conversations and movements within the PRQA. Therefore, the analyses performed were based on

TABLE 1. EXPERIMENTAL RIDE CONDITIONS

	CODE	$\ddot{X}$ $\ddot{Y}$ $\ddot{\omega}$ CONDITION	$\ddot{Z}$ AXIS Z-LINEAR (rms 9)	$\ddot{Y}$ AXIS Y-LINEAR (rms 9)	$\ddot{\omega}$ - ANGULAR (rms rAd/s^2)	NOISE db.A
TRAIN	1	125 LOLOLO	0.0056	0.0059	0.0451	57
	2	265 LOLOLO	0.0072	0.0059	0.0658	63
	3	200 HIHIHI	0.0112	0.0082	0.1431	63
	4	125 USUSUS	0.0150	0.0204	0.2005	65
	5	200 LOLOLO	0.0059	0.0059	0.0594	63
MAG-LEV	6	300 LOLORD	0.0230	0.0180	0.0587	58
	7	300 LORDLO	0.0230	0.0130	0.0626	58
	8	200 HIHIRD	0.0210	0.0140	0.0582	55
	9	400 LORDRD	0.0360	0.0210	0.0795	63
	10	400 LOLORD	0.0360	0.030	0.0795	63
	11	400 LORDLO	0.0350	0.0210	0.0813	63
	12	200 HIHIHI	0.0200	0.0140	0.0709	55
	13	400 LOLOLO	0.0350	0.0300	0.0858	63
	14	300 LOLOLO	0.0200	0.0180	0.0587	58
	15	200 LOLOLO	0.0130	0.0090	0.0568	55

NOTES:
LO = LOW PERTURBATION
HI = HIGH PERTURBATION
RD = REDUCED PERTURBATION

the noise measurements made in the PRQA cabin during each segment. As these varied widely between similar ride segments, the dbA weighted noise-output levels listed were derived by averaging the noise levels recorded during the repetitions of each condition.

2.2 EQUIPMENT

Analog magnetic tapes with signals simulating the accelerations along the Y-axis (sway), along the Z-axis (bounce), and about the X-axis (roll), as well as acoustic noise were produced by MBB for the magnetically levitated vehicle. For the steel wheel-steel rail vehicle, the tapes were prepared by MAN from simulations of a prototype rail car. These tapes were used to drive the NASA/LRC Passenger Ride Quality Apparatus (PRQA). The PRQA is a motion-simulator configured to resemble a cabin section of a jet passenger aircraft. The vibration and acoustic noise levels produced in the simulator from the tapes under each of the experimental conditions are summarized in Table 1.

Under the direction of Dornier, 16 mm motion pictures of the Bavarian countryside along the Bundesbahn tracks were prepared. These films were taken from the side of a moving rail car, and were then optically processed and edited to depict the view which a passenger would see at speeds of 125, 200, 265, 300, and 400 k/h. The films were projected onto a back-projected screed adjacent to the PRQA cabin using a reflex-projection system. The screen was located so that the subjects could see the projected images through the PRQA windows, but could not see the screen edges.

2.3 SUBJECTS

Eight groups of 6 subjects totaling 48 people participated in the study. The subjects were recruited for NASA/LRC by Biometics, Inc. The subjects, chosen to achieve a balance between age and sex, were briefed and medically screened by the NASA participants prior to the experiment. The subjects were paid approximately 15 dollars for their participation.

2.4 PROCEDURE

Each of the 48 subjects was exposed to 10 of the ride conditions during the course of the experiment. The eight-minute ride conditons were presented as segments of similated trips with each group of 6 subjects receiving two 45-minute trips with a rest break in between. Each of the 45-minute trips was composed of five segments. Table 2 shows the order in which the ride segments were presented and illustrates the counterbalancing used to reduce the effects of factors such as time or order of presentation.

On each day the experiment was conducted, each subject was briefed on the operation of the simulator by NASA staff, and then they were briefed on the nature, purpose, and background of the study by TSC staff. The subjects then entered the simulator cabin, and were given instructions on the rating procedures and the performance of the reading and writing tasks. The subjects were given samples of the tasks, and their performance on these tasks was used to ascertain their comprehension of the instructions. The test began once the experimenters determined that the subjects understood the instructions. The responses for each 45-minute trip were collected using the test booklet.

During the tests, the sway, bounce, roll accelerations, cabin temperature, and level of accoustic noise for each segment of each of the simulated trips were recorded and retained for use in the subsequent analysis.

The subjects rated the ride segments in terms of perceived confort and perceived difficulty of reading and writing. They rated each condition of the three above mentioned characteristics on a scale of 1-7 with 1 representing "very comfortable" or "very easy", and 7 representing "very uncomfortable" or "very difficult."

The performance segment measures (the scales were provided in the Phase I Memorandum) included three tests: 1) an adaptation of the Carver-Darby Chunked Reading Test, 2) a word-copying test, and

TABLE 2. ORDER OF CONDITIONS

SESSION 1		SESSION 3		SESSION 5		SESSION 7	
TRIP	SEGMENT	TRIP	SEGMENT	TRIP	SEGMENT	TRIP	SEGMENT
A	1,2,3,4,5	A	15,14,13,12,11	A	11,12,13,14,15	A	5,4,3,2,1
B	10,9,8,8,6	B	10,9,8,7,6	B	6,7,8,9,10	B	6,7,8,9,10

SESSION 2		SESSION 4		SESSION 6		SESSION 8	
TRIP	SEGMENT	TRIP	SEGMENT	TRIP	SEGMENT	TRIP	SEGMENT
A	5,4,3,2,1	A	15,14,13,12,11	A	11,12,13,14,15	A	1,2,3,4,5
B	6,7,8,9,10	B	10,9,8,7,6	B	6,7,8,9,10	B	10,9,8,7,6

3) a number-copying test. In the Carver Darby test the subjects' ability to read and comprehend complex material was tested; the other two tests measured reading and writing skills. The tests used and the instructions for their use are copyrighted, but reproductions of the cover sheet and test instructions can be found in the Appendix.

3. RESULTS

Figure 2 depicts the mean-comfort ratings provided by the subjects of the simulated train rides. It should be noted that the only ride condition which has a mean-comfort score worse than neutral (C=4.0) is the one corresponding to a German rail car simulated on an AMTRAK rail at 125 k/h. The relatively poor rating may be due largely to the artificial combination of a vehicle designed for one rail system with a rail system built to entirely different standards.

To understand the implications of the mean-comfort ratings better, a binomial expansion procedure, as described in a DOT report prepared by Pepler, R.D. et al., "Development of Techniques and Data for Evaluating Ride Quality," DOT-TSC-RSPD-77-1, II (February, 1978) has been applied. Through the use of this technique , it is possible to estimate the distribution of comfort-responses which would be given by the public for a particular ride segment based on the mean-ride comfort rating the subjects gave for the segment. Table 3, reproduced from the Pepler, et al. (1977) report, was used to estimate the percent of the public which could be expected to respond to a given ride segment with a comfort response up to and including some predetermined value based on a mean-comfort response. In Figure 3, this technique was used to estimate the percent of riders which could be expected to rate the rail-car segments as neutral or better (C=4.0). For the most poorly rated segment, the German rail car on the American track, only 39 percent of potential users could be expected to rate the ride as neutral or better.

Figure 4 depicts the mean-comfort responses to the mag-lev segments. In examining this figure, it should be noted that a mean-comfort score of 3.75 indicates that 75 percent of the potential riders can be expected to rate the ride as neutral or better. Using this criteria, all of the 200 k/h segments provide acceptable rides; the 300 k/h segments, where roll and lateral motions have been reduced in amplitude, also provide acceptable

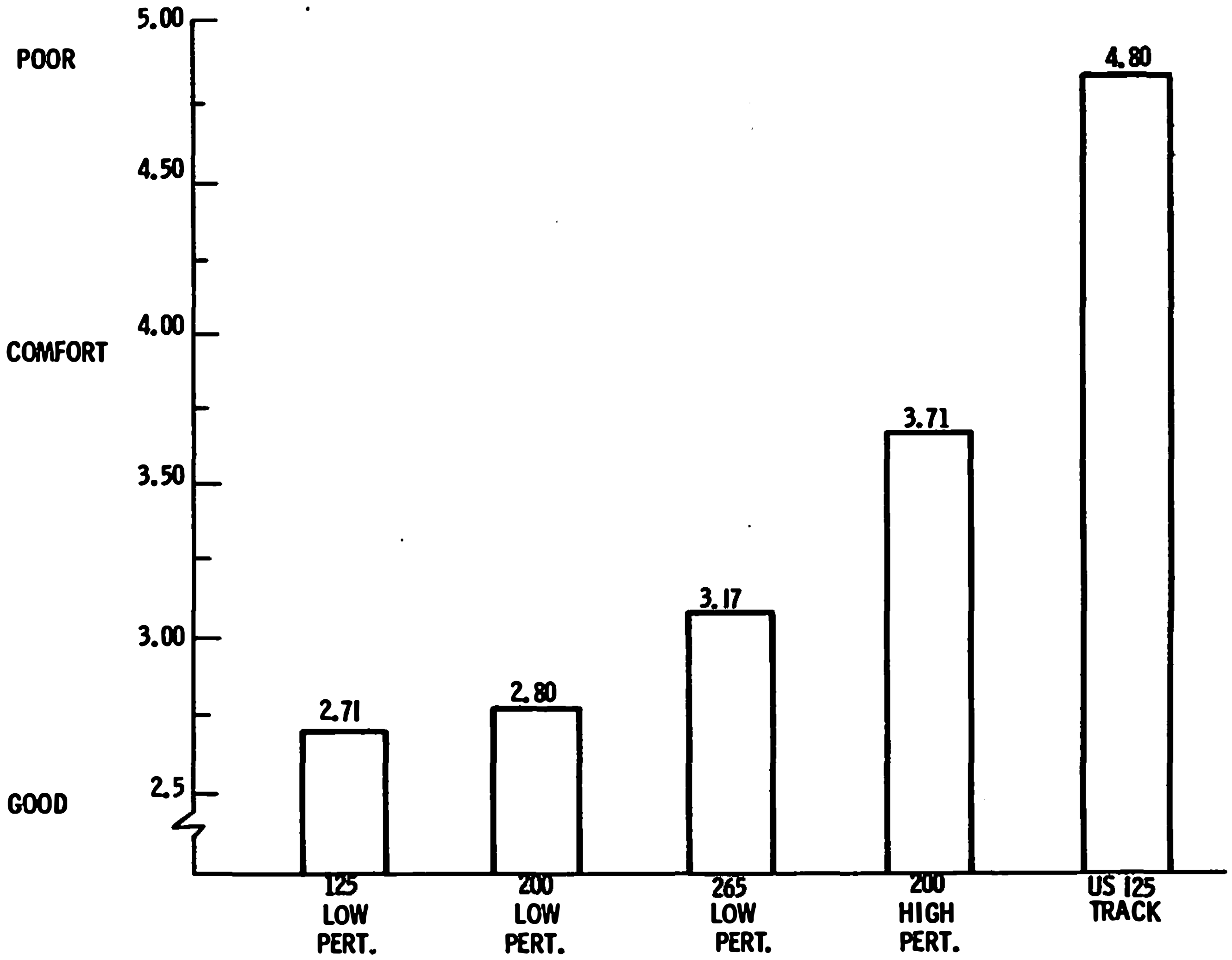

FIGURE 2. MEAN COMFORT RATINGS FOR TRAIN CONDITIONS

TABLE 3. PROBABILITY DISTRIBUTION OF PASSENGER RESPONSES AS A FUNCTION OF MEAN COMFORT VALUE

MEAN COMFORT	% ≤ 1	% ≤ 2	% ≤ 3	% ≤ 4	% ≤ 5	% ≤ 6	% ≤ 7
~~1.10~~	~~.90~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~
1.20	.82	.98	1.00	1.00	1.00	1.00	1.00
~~1.30~~	~~.74~~	~~.97~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~
1.40	.66	.94	.99	1.00	1.00	1.00	1.00
~~1.50~~	~~.59~~	~~.92~~	~~.99~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~
1.60	.53	.89	.98	1.00	1.00	1.00	1.00
~~1.70~~	~~.48~~	~~.85~~	~~.98~~	~~1.00~~	~~1.00~~	~~1.00~~	~~1.00~~
1.80	.42	.81	.97	1.00	1.00	1.00	1.00
~~1.90~~	~~.38~~	~~.78~~	~~.95~~	~~.99~~	~~1.00~~	~~1.00~~	~~1.00~~
2.00	.33	.74	.94	.99	1.00	1.00	1.00
~~2.10~~	~~.30~~	~~.70~~	~~.92~~	~~.99~~	~~1.00~~	~~1.00~~	~~1.00~~
2.20	.26	.66	.90	.98	1.00	1.00	1.00
~~2.30~~	~~.23~~	~~.61~~	~~.88~~	~~.98~~	~~1.00~~	~~1.00~~	~~1.00~~
2.40	.20	.57	.86	.97	1.00	1.00	1.00
~~2.50~~	~~.18~~	~~.53~~	~~.83~~	~~.96~~	~~1.00~~	~~1.00~~	~~1.00~~
2.60	.16	.49	.80	.95	.99	1.00	1.00
~~2.70~~	~~.14~~	~~.46~~	~~.77~~	~~.94~~	~~.99~~	~~1.00~~	~~1.00~~
2.80	.12	.42	.74	.93	.99	1.00	1.00
~~2.90~~	~~.10~~	~~.38~~	~~.71~~	~~.92~~	~~.99~~	~~1.00~~	~~1.00~~
3.00	.09	.35	.68	.90	.98	1.00	1.00
~~3.10~~	~~.08~~	~~.32~~	~~.65~~	~~.88~~	~~.98~~	~~1.00~~	~~1.00~~
3.20	.06	.29	.61	.86	.97	1.00	1.00
~~3.30~~	~~.05~~	~~.26~~	~~.58~~	~~.84~~	~~.97~~	~~1.00~~	~~1.00~~
3.40	.05	.23	.54	.82	.96	1.00	1.00
~~3.50~~	~~.04~~	~~.21~~	~~.51~~	~~.80~~	~~.95~~	~~.99~~	~~1.00~~
3.60	.03	.19	.48	.77	.94	.99	1.00
~~3.70~~	~~.03~~	~~.16~~	~~.44~~	~~.74~~	~~.93~~	~~.99~~	~~1.00~~
3.80	.02	.14	.41	.72	.92	.99	1.00
~~3.90~~	~~.02~~	~~.13~~	~~.38~~	~~.69~~	~~.91~~	~~.99~~	~~1.00~~
4.00	.02	.11	.34	.66	.89	.98	1.00
~~4.10~~	~~.01~~	~~.09~~	~~.31~~	~~.62~~	~~.87~~	~~.98~~	~~1.00~~
4.20	.01	.08	.28	.59	.86	.98	1.00
~~4.30~~	~~.01~~	~~.07~~	~~.26~~	~~.56~~	~~.84~~	~~.97~~	~~1.00~~
4.40	.01	.06	.23	.52	.81	.97	1.00
~~4.50~~	~~.01~~	~~.05~~	~~.20~~	~~.49~~	~~.79~~	~~.96~~	~~1.00~~
4.60	.00	.04	.18	.46	.77	.95	1.00
~~4.70~~	~~.00~~	~~.03~~	~~.16~~	~~.42~~	~~.74~~	~~.95~~	~~1.00~~
4.80	.00	.03	.14	.39	.71	.94	1.00
~~4.90~~	~~.00~~	~~.02~~	~~.12~~	~~.35~~	~~.68~~	~~.92~~	~~1.00~~
5.00	.00	.02	.10	.32	.65	.91	1.00
~~5.10~~	~~.00~~	~~.01~~	~~.08~~	~~.29~~	~~.62~~	~~.90~~	~~1.00~~
5.20	.00	.01	.07	.26	.58	.88	1.00
~~5.30~~	~~.00~~	~~.01~~	~~.06~~	~~.23~~	~~.54~~	~~.86~~	~~1.00~~
5.40	.00	.01	.05	.20	.51	.84	1.00
~~5.50~~	~~.00~~	~~.00~~	~~.04~~	~~.17~~	~~.47~~	~~.82~~	~~1.00~~
5.60	.00	.00	.03	.14	.43	.80	1.00
~~5.70~~	~~.00~~	~~.00~~	~~.02~~	~~.12~~	~~.39~~	~~.77~~	~~1.00~~
5.80	.00	.00	.02	.10	.34	.74	1.00
~~5.90~~	~~.00~~	~~.00~~	~~.01~~	~~.08~~	~~.30~~	~~.70~~	~~1.00~~
6.00	.00	.00	.01	.06	.26	.67	1.00
~~6.10~~	~~.00~~	~~.00~~	~~.01~~	~~.05~~	~~.22~~	~~.62~~	~~1.00~~
6.20	.00	.00	.00	.03	.19	.58	1.00
~~6.30~~	~~.00~~	~~.00~~	~~.00~~	~~.02~~	~~.15~~	~~.52~~	~~1.00~~
6.40	.00	.00	.00	.02	.11	.47	1.00
~~6.50~~	~~.00~~	~~.00~~	~~.00~~	~~.01~~	~~.08~~	~~.41~~	~~1.00~~
6.60	.00	.00	.00	.01	.06	.34	1.00
~~6.70~~	~~.00~~	~~.00~~	~~.00~~	~~.00~~	~~.03~~	~~.26~~	~~1.00~~
6.80	.00	.00	.00	.00	.02	.18	1.00
~~6.90~~	~~.00~~	~~.00~~	~~.00~~	~~.00~~	~~.00~~	~~.10~~	~~1.00~~
7.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

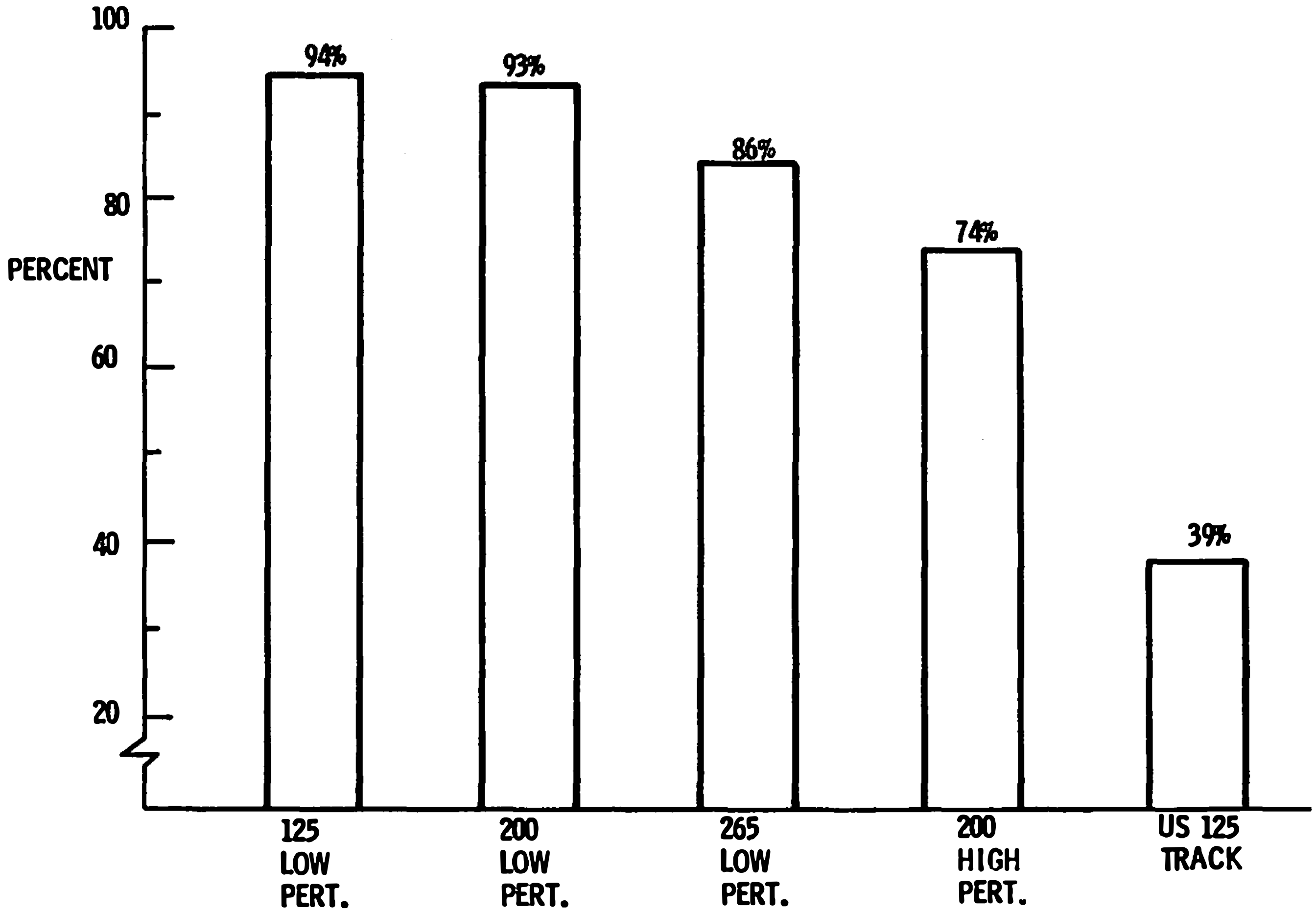

FIGURE 3. PERCENT RATING TRAIN RIDES NEUTRAL OR COMFORTABLE

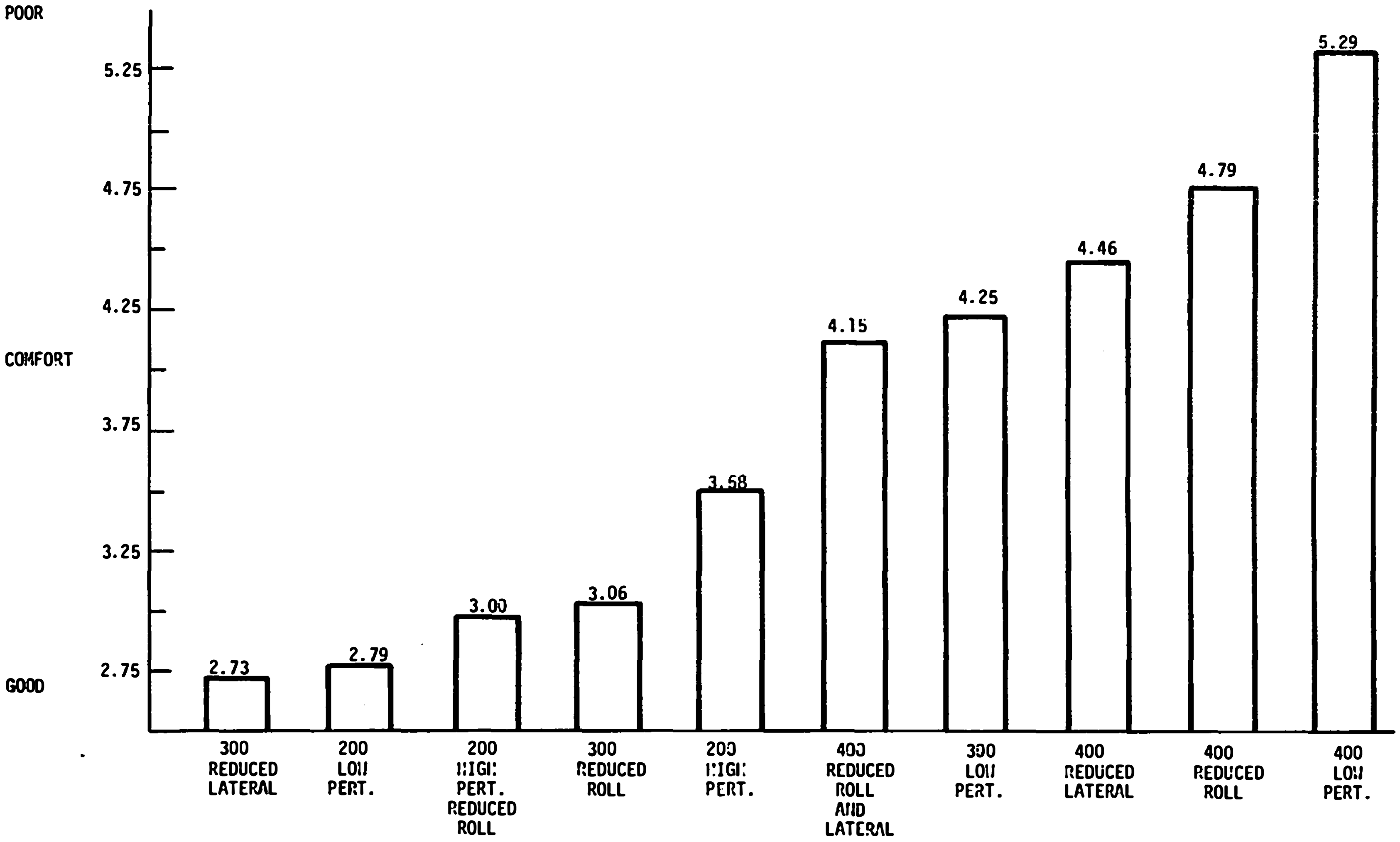

FIGURE 4. MEAN COMFORT RATINGS FOR MAG-LEV CONDITIONS

rides. The best rated mag-lev segment, 400 k/h with reduced roll and lateral motion, produced a mean-comfort response of 4.14, which indicates that 60.5 percent of the riders would rate the ride as neutral or better.

Figure 5 illustrates the effect of reducing the roll motions. In each case, the ride-comfort ratings were improved by simulating improved roll control. T-tests on the data pairs indicate that the roll reductions produced improvements that are significant, at least, at the $P<.01$ level. Figure 6 indicates the effect of reducing both lateral and roll motions. Again, significant ($P<.005$) improvements in comfort resulted. However, the improvement achieved by simulating both reduced lateral and roll motions is not as great as improvement achieved through reduction of lateral motion alone. The improvement measured by reducing roll motion and lateral motion is not statistically better than reducing just the lateral motion.

To evaluate the relative contributions of the physical variables to the subjects' comfort-responses, Pearson Product Moment Correlations were computed for the physical variable values, and between the physical variables and the comfort responses. For this statistic, the strength of the mathematical relationship is indicated by the absolute value of the statistic which can range from $r = +1.00$ (perfect positive relationship) through $r = .00$ (no relationship) to $r = -1.00$ (perfect inverse relationship), and the square of the correlation (r^2) indicates the proportion of the variance for which the relationship accounts. In the matrix depicted in Table 4,* the strongest relationship between any physical variable and comfort is with lateral motion ($r - 0.80$,

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*These correlations are based on 62 scores. There were 8 sessions of 10 conditions each in the simulator. However, there was insufficient data to perform a regression analysis on 18 of the test segments.

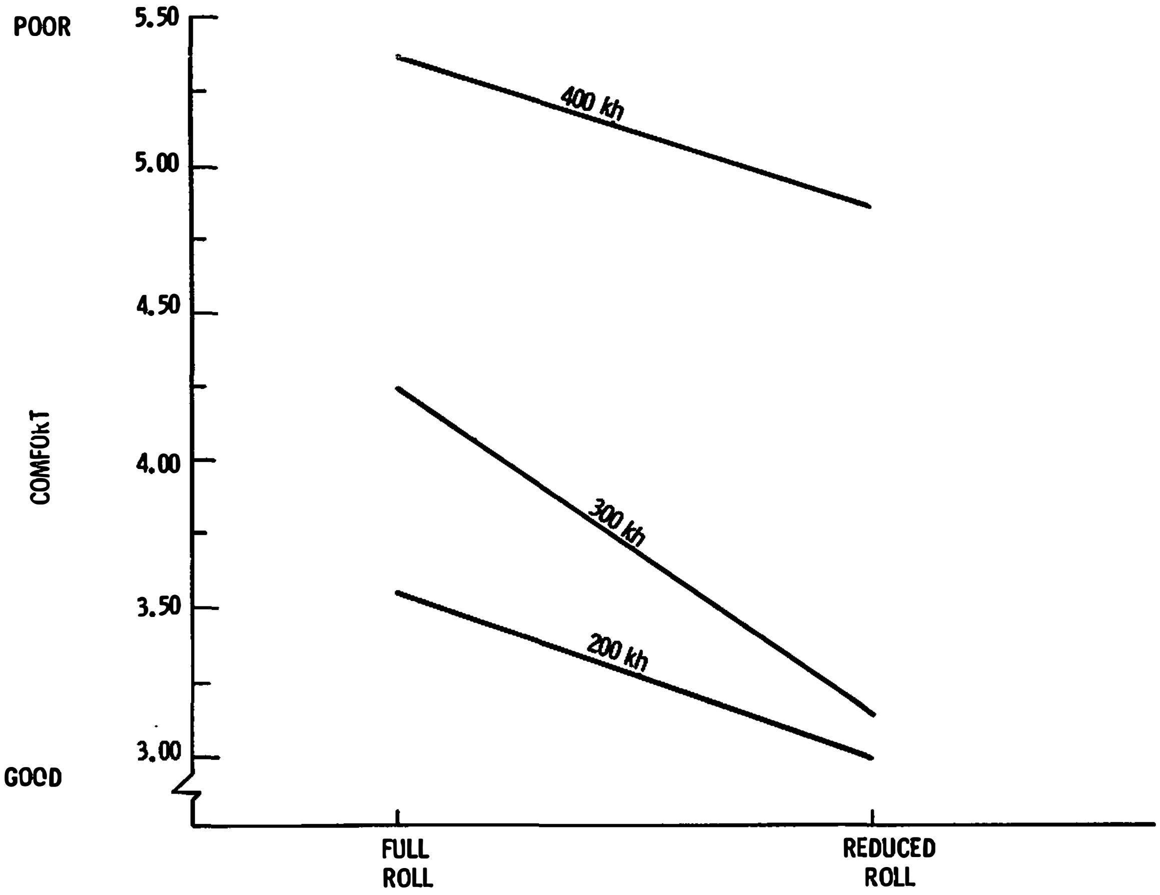

FIGURE 5. EFFECT OF REDUCED ROLL ON COMFORT FOR MAG-LEV VEHICLE

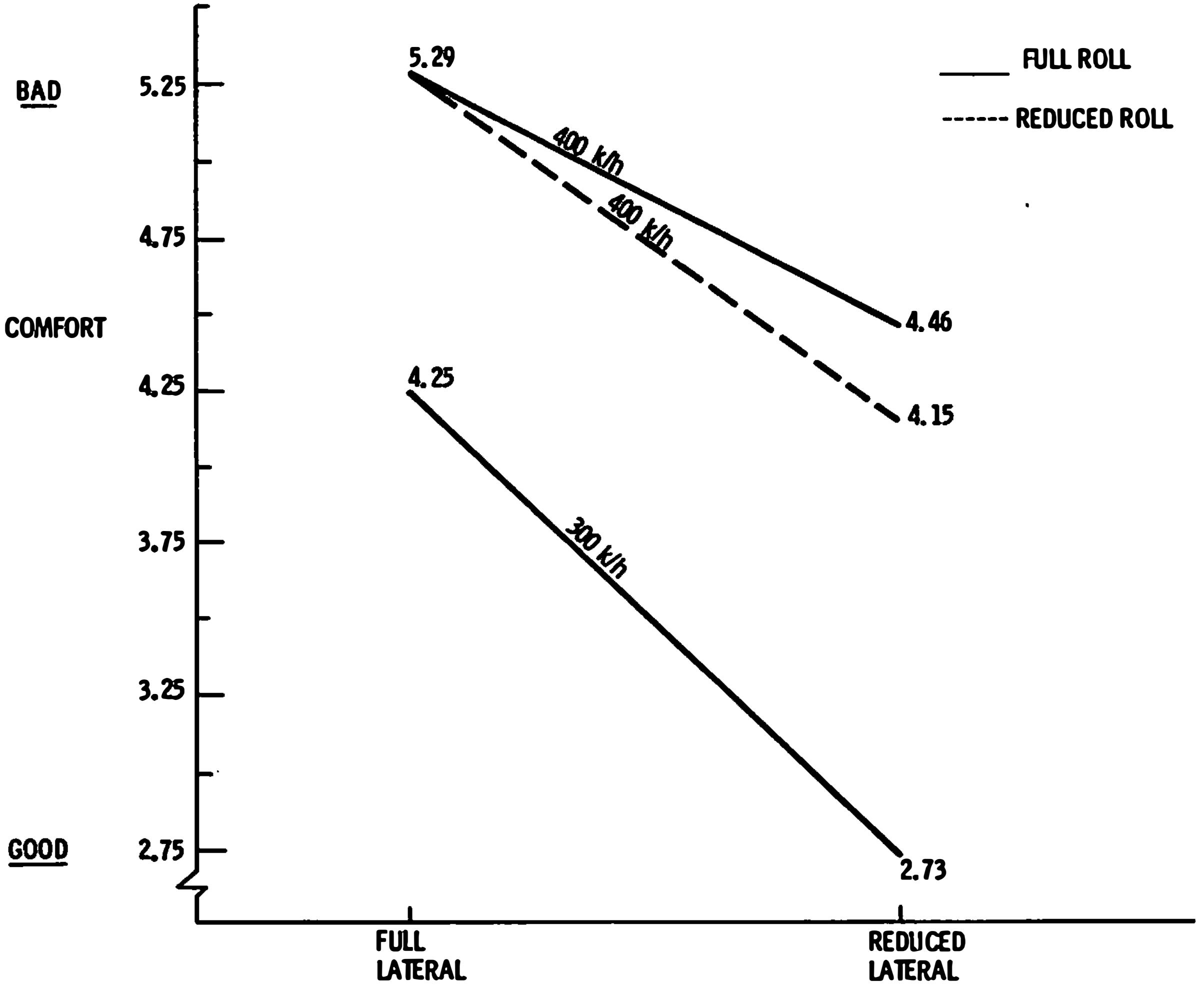

FIGURE 6. EFFECT OF REDUCED LATERAL AND ROLL ON COMFORT FOR MAG-LEV VEHICLE

TABLE 4. CORRELATIONS AMONG COMFORT RATINGS, MOTION VARIABLES, AND NOISE FOR ALL CONDITIONS

	COMFORT	NOISE	LATERAL	VERTICAL	ROLL
COMFORT	1.00				
NOISE	0.66	1.00			
LATERAL	0.80	0.48	1.00		
VERTICAL	0.65	0.39	0.86	1.00	
ROLL	0.45	0.40	0.21	0.00	1.00

N = 62

$r^2 = 0.64$), and the second highest is with noise ($r = 0.66$, $r^2 = 0.44$). While this second correlation is only slightly higher than the relationship between comfort and vertical motion, noise is less strongly correlated with the other physical variables making it more valuable as an independent predictor of comfort. This is particularly interesting as the low noise levels used in this study are generally believed to be below the threshold of discomfort.

Table 5 represents the same matrix. However, here the correlations are generated only from the mag-lev ride segments. All of the correlations are higher. This is probably due to two factors: the use of a set of simulated motion and noise variables which are highly intercorrelated themselves (a situation which is to be expected in the real world), and to a lesser extent, the use of fewer cases (62 for all segments as opposed to 48 for the mag-lev segments alone). It should be noted that a similar matrix was not computed for the rail segments alone due to the small number of available cases.

In order to determine whether the comfort ratings obtained using the PRQA simulator were likely to be similar to those expected in actual revenue service, a comfort model developed by Pepler, et al. (1977) from field tests on intercity trains, commuter buses, and various passenger aircraft was applied to the physical data recorded in the simulator. In this model, predicted comfort or $C' = 1.0 + 0.5\ddot{\omega}_R + 0.1\,[db(A)-65] + 17a_L + 17a_V$, ($\ddot{\omega}R$ = roll rate, L = sway, and V = bounce). Using the model, $\hat{C}'$ was predicted for each ride condition, and the predicted value was correlated with the actual ratings of the subjects. Table 6 depicts the correlation between "COMFORT" (C), the subject ratings, and "PRED" (C'). The correlation is quite high: $r = 0.73$, $r^2 = 0.53$. By assuming a greater sensitivity to noise than is provided in the model, the correlation can be further improved. For instance, if we postulate that a threshold of discomfort due to noise occurs as low as 60 dbA (Db60) or even 55dbA (Db55), we can increase the correlation to 0.76 or 0.78.

TABLE 5. CORRELATIONS AMONG COMFORT RATINGS, MOTION VARIABLES, AND NOISE FOR MAG-LEV CONDITIONS

	COMFORT	NOISE	LATERAL	VERTICAL	ROLL
COMFORT	1.00				
NOISE	0.76	1.00			
LATERAL	0.84	0.75	1.00		
VERTICAL	0.81	0.86	0.85	1.00	
ROLL	0.64	0.52	0.52	0.66	1.00

N = 48

TABLE 6. CORRELATIONS BETWEEN COMFORT RATINGS AND FIELD TEST DERIVED MODEL

	COMFORT	PRED.	DB60	DB55
COMFORT	1.00			
PRED.	0.73	1.00		
DB60	0.76	0.99	1.00	
DB55	0.78	0.97	0.99	1.00

N = 20

The high correlations between the predicted comfort scores and those provided by the subjects may be taken as strong substantiation that the results found with regard to the comfort ratings are realtistic.

The subjects' ratings of reading difficulty, writing difficulty, and comfort for trains and mag-lev vehicles respectively are depicted in Figures 7 and 8. In general, the subjects' rating indicate that they feel reading and writing were more seriously impaired by ride vibration and noise than was comfort.

Table 7 provides the matrix of intercorrelations between ratings of comfort, reading and writing difficulty, and physical variables that characterize the noise levels and motions for each segment. It is interesting to note that the correlation between noise level and comfort is higher than the correlation between noise level and writing difficulty ($r_{n-c} = 0.67$, $r^2 = 0.45$, vs. $r_{n-w} = 0.60$, $r^2 = 0.36$). This difference is statistically significant (has less than a 5 percent probability of being due to chance variation). Conversely, vertical and lateral motions have higher correlations with writing difficulty than does noise ($p < 0.05$). This may be interpreted as an indication that the major effect of acoustic noise is on passenger comfort, whereas, physical motion interferes with tasks requiring hand-eye coordination such as writing.

Table 8 provides the correlations between physical-ride variables and subject performance on the tasks. It should be noted that there was little or no correlation between the writing tasks (questions answered, answered correct and percent correct) and the subjects perceived difficutly in reading. It may be hypothesized that the subjects compensated for the increased difficulty they reported while performing this purely cognitive task. Conversely, the correlations between the physical variables, particularly vertical and lateral motion, and performance on the writing tasks were substantial, suggesting that total compensation for tasks requiring significant motor-skills may be very difficult or even impossible.

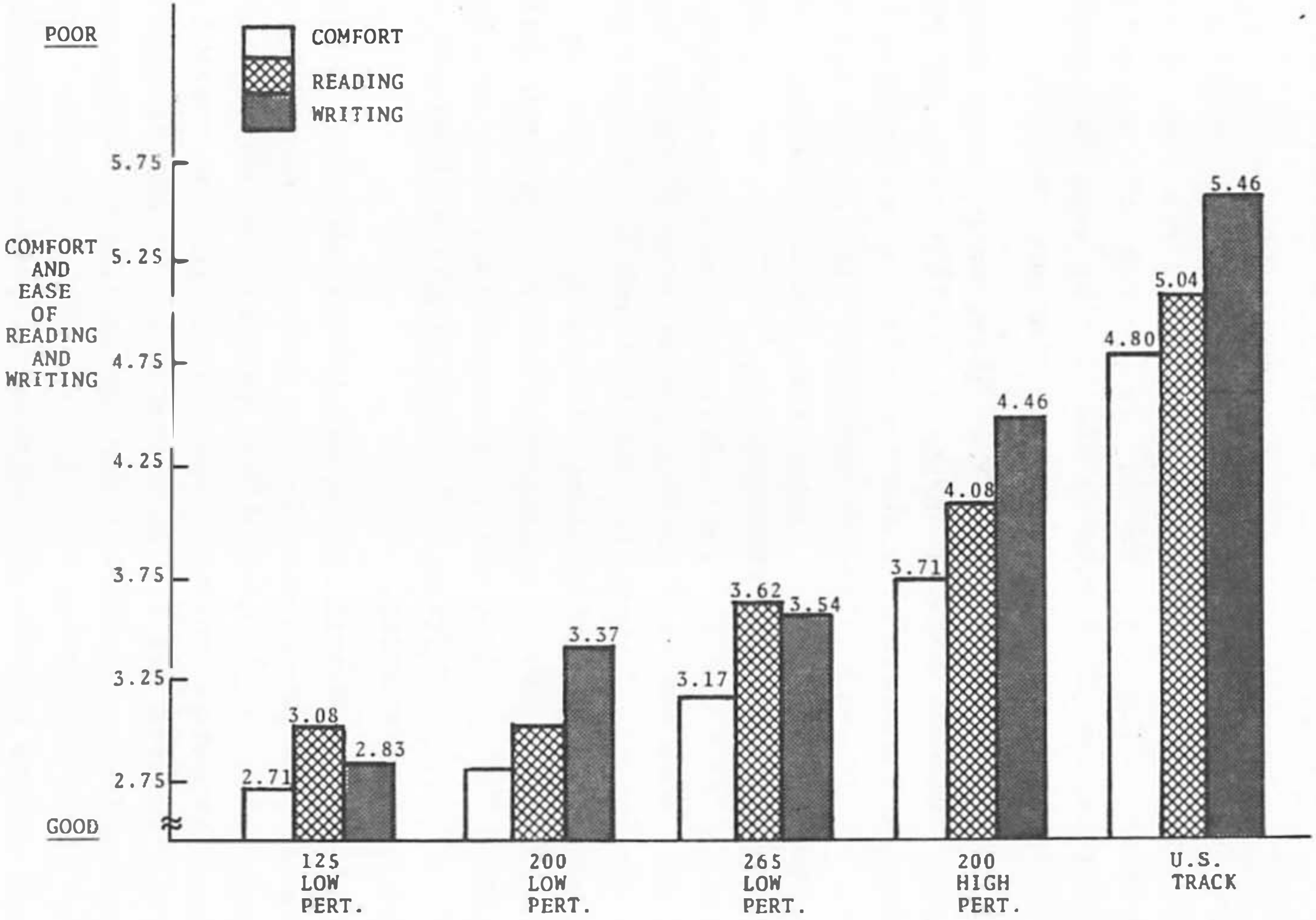

FIGURE 7. MEAN COMFORT AND EASE OF READING AND WRITING RATINGS FOR TRAIN CONDITIONS

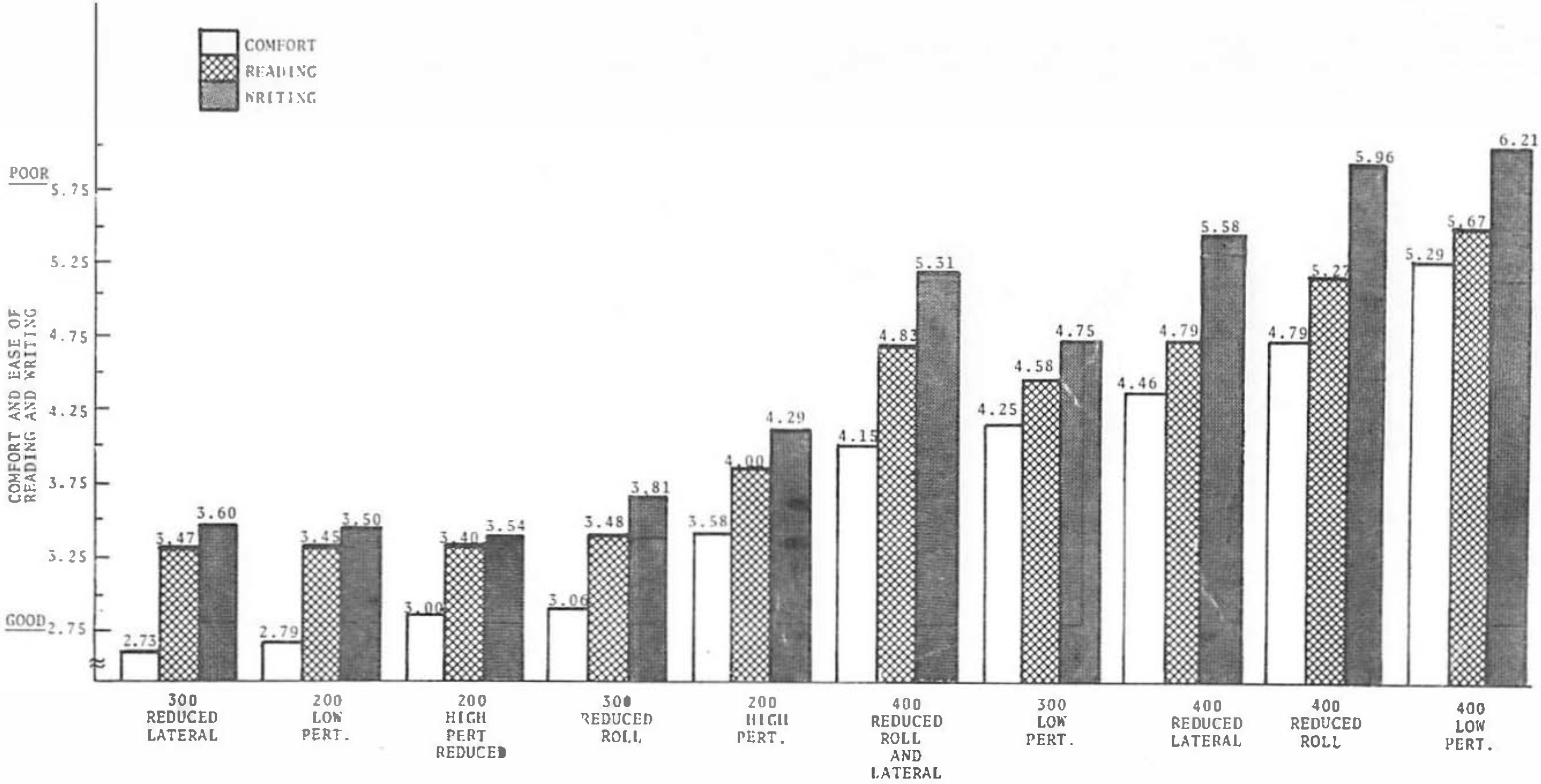

FIGURE 8. MEAN COMFORT AND EASE OF READING AND WRITING RATINGS FOR MAG-LEV CONDITIONS

TABLE 7. CORRELATIONS BETWEEN RATINGS OF COMFORT, RATINGS OF READING AND WRITING DIFFICULTY, AND NOISE AND MOTION LEVELS

CONDITION	COMFORT	READING	WRITING	NOISE	LATERAL	VERTICAL	ROLL
COMFORT	1.00						
READING	0.92	1.00					
WRITING	0.91	0.95	1.00				
NOISE	0.67	0.54	0.60	1.00			
LATERAL	0.80	0.81	0.85	0.48	1.00		
VERTICAL	0.65	0.73	0.77	0.39	0.86	1.00	
ROLL	0.45	0.41	0.41	0.37	0.21	0.00	1.00

TABLE 8. CORRELATIONS BETWEEN PERFORMANCE MEASURES AND NOISE, AND MOTION VARIABLES AND RATINGS

CONDITION	QUESTIONS ANSWERED	ANSWERS CORRECT	PERCENT CORRECT	WORDS COPIED	ERRORS	NUMBERS COPIED
NOISE	0.06	0.07	0.11	-0.25	0.41	-0.44
LATERAL	-0.06	-0.09	-0.06	-0.38	0.53	-0.57
VERTICAL	0.00	-0.02	-0.01	-0.28	0.52	-0.42
ROLL	-0.06	-0.04	-0.04	-0.14	0.18	-0.31
COMFORT	-0.14	-0.12	-0.05	-0.35	0.40	-0.57
EASE OF READING	-0.16	-0.12	-0.05	-0.35	0.42	-0.52
EASE OF WRITING	-0.12	-0.11	-0.04	-0.43	0.48	-0.52

Finally, the problem of the effect on comfort of the duration of exposure to vibration was examined. Prior work in this area has provided mixed results. The International Organization for Standardization's "Guide for the Evaluation of the Effects of Human Exposure to Whole Body Vibration" (Document 2631) indicates that the threshold of discomfort to vibration such as that experienced by the subjects in this study will decrease over periods as short as twenty minutes. However, laboratory studies have not provided data to support this hypothetical threshold decrease.

The current study, although not designed to definitively support or refute this "time-dependency hypothesis," does provide a sensitive test for periods up to 48 minutes in duration. Six of the ride conditions were presented half of the time at the beginning of a 48-minute ride, and half of the time at the end of te ride. If the time-dependency hypothesis is correct, the vibrations preceeding the trial presented at the end of the ride should reduce the discomfort threshold and cause higher discomfort ratings than would occur if the same trial were presented prior to exposure to any vibration. [Matched sample "t" tests were preformed on the subjects' comfort ratings. These are presented in Table 9. In no case was their a significant increase in discomfort attributable to exposure to vibration prior to the trail].

Table 9 shows the mean-comfort rating for each of the six conditions which occurred both first and last in the simulated ride. The values of the t-tests computed on each of the pairs is also shown. None of the t-values are statistically significant. Furthermore, in two tasks, conditions 10 and 15, the ride was rated as being more comfortable when it occurred at the end of the simulated trip. This data clearly does not support the time-dependency hypothesis.

TABLE 9. EFFECT OF DURATION ON COMFORT RATINGS

CONDITION	FIRST	LAST	t-VALUE	DEGREES OF FREEDOM
1	2.58	2.83	0.32	22
5	2.50	3.08	0.69	22
6	2.83	3.29	0.92	46
10	5.08	4.50	0.94	46
11	4.25	4.67	0.64	22
15	3.00	2.58	0.51	22

APPENDIX

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