SUMMARY

The objective of this paper was to determine the influence of fifth-wheel placement on ride quality. A six-degree-of-freedom linear model was formulated and the following analyses were performed:

1. Natural frequencies and mode shapes--(a) Natural frequencies associated with the tractor and semitrailer modes shift up in frequency as the fifth wheel is moved forward and (b) the amplitude of tractor pitching increases as the fifth wheel is moved forward.
2. Frequency response--The large resonant peaks at 2 and 4 Hz shift up in frequency and increase in magnitude as the fifth wheel is moved forward.
3. Random road response--(a) The total rms acceleration at a rigid point in the tractor representing the driver's location in both the vertical and longitudinal directions increases as the fifth wheel is moved forward and (b) the increase in rms accelerations results from increased output at frequencies in the 2- to 4-Hz range.

In addition to the analytical studies performed, an experimental investigation yielded the following conclusions: (a) The rms accelerations at the driver's location (not including the dynamics of the seat) in both the vertical and longitudinal direction increase as the fifth wheel is moved forward and (b) the analytical and experimental rms acceleration trends as a function of fifth-wheel placement agree closely.

In summary, the analytical and experimental data show that ride quality deteriorates as the fifth wheel is moved ahead of the tractor tandem's centerline. The increase in rms acceleration primarily results from the development of a resonant condition of out-of-phase tractor-semitrailer pitch in the 4-Hz region.

The comparison between the analytical and experimental results indicates good agreement when rms values are compared; however, it should be noted that the analytical model is valid only up to approximately 7 Hz. To model accurately the higher-frequency phenomena, features such as tractor-frame bending, cab-mount suspension, and wheel out of round would need to be included.

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Ride-Quality Models for Diverse Transportation Systems

LARRY G. RICHARDS, IRA D. JACOBSON, AND RICHARD D. PEPLER

This research was undertaken to develop comfort (ride-quality) models for six specific vehicles and to refine an existing composite ride-quality model. The vehicles were an automated guideway transit vehicle, a short-haul intercity rail vehicle, an urban rapid rail vehicle, a luxury-type charter bus, a compact car, and a subcompact automobile. Experiments on most vehicles were conducted in two phases: model development and model validation. In both phases, physical variables were measured for a series of ride segments, and each segment was rated for comfort level by a group of paid subjects. The important determinants of comfort for most vehicles were roll, pitch, and vertical acceleration. These variables are highly intercorrelated; all load on the same principal component of the motion-correlation matrix. Two composite ride-quality models are presented; one has four variables (roll, pitch, and vertical and longitudinal acceleration) and one has two variables (vertical acceleration and roll). The two-variable comfort model is sufficient for most uses.

For many years, transportation specialists have recognized the need to develop a quantitative tool for evaluating the ride quality of existing and proposed vehicles. Such a tool would permit them to compare the relative merits of two competing systems, to write vehicle specifications, and to initiate cost-effective design changes. Currently, designers and planners of transportation systems must rely on the use of comparative (as good as) criteria, subjective rating methods, and guidelines for human tolerance to vibration (such as International Standard 2631:1978), none of which reliably assesses nor predicts passenger comfort or the acceptability of a ride. Recent work (1,2) has provided the basis for better criteria.

Initially, the study of ride quality was undertaken as a laboratory exercise, primarily to determine the influence of vibration (almost exclusively in the vertical direction) on subjective judgments of motion and comfort. More recent laboratory work (3-5) that uses simulation facilities at the Langley Research Center seeks to determine how various components of motion and noise combine to influence subjects' judgments of comfort.

Field studies of passenger comfort have been conducted by Jacobson and Richards (6-9) and Kuhlthau and Jacobson (10). In the United Kingdom, Clarke and Oborne (11) have studied passenger reaction to public service vehicles, particularly to cross-channel Hovercraft, helicopters, and trains. Manenica and Corlett (12) assessed rider reaction to a Hovercraft and a local bus service. In Japan, panels of experts have been employed to evaluate specific industrial and agricultural vehicles (13).

Richards and Jacobson (6,8) surveyed airline passengers about their reactions to the flight environment and their perceptions of factors that influenced their level of comfort. On one questionnaire, passengers ranked various comfort-level factors; seat factors were seen to be most important, followed by noise, temperature, and motion. On a second questionnaire, passengers indicated the degree of discomfort they associated with each of a set of environmental factors. Ratings of noise, vibration, motion, and seat variables were significantly associated with passenger comfort.

Jacobson and Richards (7,9) obtained continuous recordings of the motion characteristics of aircraft while test subjects simultaneously rated their levels of comfort at intervals throughout the flights. The highest simple correlations with rated comfort resulted from root-mean-square (rms) values for vertical and transverse acceleration and roll rate. Principal-component analyses of the intercorrelation matrices for the motion variables yielded a major first component marked by transverse and vertical acceleration, roll, and pitch in all cases. This component is the physical correlate of rated comfort for the air mode.

Expanded comfort models for aircraft have taken account of the effects of noise (14) and seat factors (15), as well as temperature and pressure. A complete air model will involve all relevant environmental variables, seating and space variables, and maneuver factors. An initial formulation of such a model has been presented in two previous papers (15,16). Jacobson, Kuhlthau, and Richards (2) showed how quantitative models of this sort could be used as a tool by system designers to evaluate or predict passenger satisfaction with the ride environment of a vehicle. Their method has been proposed as a general approach to ride-quality evaluation (17).

The ride quality of ground-based vehicles has also been assessed. However, most previous studies of ground vehicles have been limited to linear accelerations. Investigators have been discouraged by the lack of correspondence between rated comfort and vertical and lateral acceleration (18), but angular rates may be important to ride quality for ground vehicles. As Higgenbotham noted at the 1977 Transportation Research Board meeting, great variations can occur among comfort ratings for three different rail cars although no differences in lateral and vertical acceleration were apparent. Comfort levels may have been determined by the angular rates, but they had not been measured.

Several field experiments were conducted to determine the effects of the environment of ground-based vehicles (city buses and intercity trains) on passenger comfort (19,20). As with the aircraft, the physical characteristics of the environment and the passengers' comfort ratings in that environment were assessed simultaneously for ride segments throughout a trip. Roll rate was strongly related to judged comfort for buses, as were noise and roll rate for trains. Richards, Jacobson, Barber, and Pepler (20) also developed a ride-quality model for buses on curved roadways that included both the mean and rms transverse acceleration. It is thus necessary to use different comfort models for different terrains and road configurations. If curves occur infrequently on a given ride, they can probably be safely ignored. However, if more than a certain percentage of the trip is on curved roads, an adjusted model would have to be used.

Passengers are clearly influenced by the dominant input on each type of vehicle. For ground-based vehicles, roll rate was generally the dominant motion, and passenger comfort judgments were strongly related to it; in the air mode, the linear accelerations, vertical and transverse, were most important. However, the correlation matrices and their principal components indicate that similarities exist in the motion characteristics of these vehicles and suggest that unified comfort models are feasible, given more extensive data (21). General models are needed to specify standards for exposure to environmental inputs and to specify criteria for the design of new vehicles or for the assessment of existing ones. Such composite models were formulated by Richards, Jacobson, Barber, and Pepler (19) for (a) ground-based vehicles and (b) vehicles having characteristics of both ground and air modes.

The major goal of the present research was to assess the ride environments of six additional vehicles. The particular vehicles have different characteristics and were selected for different reasons: Some represent state-of-the-art developments in their field; others are simply refinements of already examined vehicles; and some are new and relatively untried concepts. The second goal of this research was to examine a group of relevant contemporary vehicles to see whether they yield the kinds of results expected from the previous models. The purpose is not so much to do new modeling as to see whether these vehicles present any surprise in terms of older models. If no surprising results are found, this provides greater confidence in the previous work and its generality.

METHOD

Overview of the Research

This research program was designed to assess the ride quality of six specific vehicles, to develop comfort models for each, and to refine a composite ride-quality model in light of these data. The particular vehicles were

Table 1. Data base.

	Experimental Phase		Validation Phase	
Vehicle	Segments	Subjects	Segments	Subjects
Luxury bus			17	30
Group A	41	28		
Group B	40	33		
Compact car	16	24[a]	16	15[b]
Subcompact car	16	24[a]	16	15[b]
Metroliner rail car			17	31
Group A	11	21		
Group B	12	27		
PATCO rail vehicle			16	22
Group A	17	25		
Group B	16	30		
AGT vehicle	8	65		

Note: There was no distinction between runs for the AGT vehicle; there were 12 test runs with up to six subjects on a run.
[a]Eight groups of three each.
[b]Five groups of three each.

1. A small automated guideway transit (AGT) vehicle, operating at Morgantown, West Virginia;
2. A short-haul intercity rail vehicle, the Metroliner, operating from Washington, D.C., through New York City to Boston;
3. An urban rapid rail vehicle used by the Port Authority Transit Corporation (PATCO) system;
4. A luxury-type charter bus designed for tour use chartered from a firm near Darien, Connecticut;
5. A compact automobile, the 1978 Ford Fairmont, a four-door sedan with automatic transmission; and
6. A subcompact automobile, the 1978 Volkswagen Rabbit, a two-door model with automatic transmission.

To develop models for these vehicles, experiments on most vehicles were conducted in two phases: model development and model validation. In both phases, data were collected during actual test rides. Physical variables were measured for a series of ride segments, each of which was also rated for comfort level by a group of paid subjects. Subjects were chosen to represent different levels of age, sex, and prior experience with the transportation mode under study.

For some vehicles, 20-30 persons could ride at the same time, so that adequate sample sizes could be obtained in one or two trips. Other vehicles permitted the running of only 8 or so individuals at a time. Special test conditions prevailed for the automobile studies. Only 3 subjects could participate at one time, and 1 of these was the driver. The experimenter and equipment were also in the car during each test run. The driver rated each segment by pressing one of seven buttons on a response console to enter his or her comfort response directly onto the magnetic tape along with the motion recording for the ride segment. Table 1 summarizes the data base for this report.

Ride comfort and acceptability are significantly influenced by the external inputs to the vehicle (for example, surface conditions, track type, and vehicle speed). To ensure that the models are based on adequate samples of the vehicle's ride environment, a wide range of these variables was included in the research design. Routes were carefully selected and tested in advance of actual data collection. For some vehicles, a high degree of control over external vehicle inputs was not possible, because scheduled services over existing routes had to be used. However, trip segments were chosen to provide typical ranges of vehicle motions. Whenever possible, segments were identified by landmarks and were spatially distinct. The experimenter alerted the subjects as the vehicle approached, entered, and left the test segment. At the end of each segment, the subjects rated the comfort of the ride. The start and end of each segment were marked on the motion-recorder tape. Noise, temperature, relative humidity, and vehicle speed were measured and recorded during each segment.

Environmental Measurements

The Portable Environmental Measuring System (PEMS II), developed by the University of Virginia, was used to obtain analog recordings of motion in six degrees of freedom: accelerations along the three linear directions and angular rates about the three rotational axes. All measurements were taken on the floor of the vehicle. Various alternative representations of the data could be extracted from the analog traces, including means, rms's, power spectral densities, frequency-band content, International Standard weighted scores, etc. In past work, the rms values of the dimensions of motion were found to correlate more strongly with human reactions to the motion than did any of the alternative measures. The environmental characteristics used in this study and their units of measure are shown below.

Environmental Characteristic	Symbol	Value
Longitudinal acceleration	a_L	rms about the mean (g)
Transverse acceleration	a_T	rms about the mean (g)
Vertical acceleration	a_V	rms about the mean (g)
Roll rate	ω_R	rms about the mean (°s)
Pitch rate	ω_P	rms about the mean (°s)
Yaw rate	ω_Y	rms about the mean (°/s)
Noise	dB(A)	Single value [dB(A)]
Temperature	T	Single reading(°C)

Subjective Response Forms

Passengers' ratings of ride comfort are the primary dependent measures used for model development and validation. Comfort level for each segment of a trip was rated on a seven-point scale on which 1 = very comfortable, 4 = neutral, and 7 = very uncomfortable. Passengers were told to rate according to what they perceived as comfortable or uncomfortable.

General Modeling Logic

The basic modeling task is to relate the physical (environmental) measurements to the mean comfort levels experienced by the passengers during the segments. For each physical input, its linear regression on rated comfort is obtained. Multiple regression, both stepwise and simultaneous, is also done with the physical variables as predictors and rated comfort, or mean rated comfort, as the criterion. Principal component analyses of the intercorrelation matrices for the physical variables are used to detect multicolinearity.

RESULTS

Models for Individual Vehicles

Summary statistics for the six motion variables are presented in Tables 2 and 3. Although noise and temperature were measured, they were not included in the analyses because of lack of variability. Each table includes the bus and train data from a previous report (19), as well as the results for each vehicle in the present study. The statistics, computed on the rms values for each variable,

Table 2. Summary statistics for roll rate, pitch rate, and yaw rate for all vehicles.

Vehicle	Roll Rate						Pitch Rate						Yaw Rate					
	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	2.40	0.80	0.33	1.10	4.60	3.50	2.10	0.50	0.24	1.20	3.40	2.20	2.10	0.60	0.29	1.10	3.50	2.40
Luxury bus	1.92	0.29	0.15	1.05	2.76	1.71	1.76	0.23	0.13	1.14	2.31	1.17	2.50	0.96	0.38	1.10	5.45	4.35
Group A	1.93	0.28	0.15	1.28	2.43	1.15	1.75	0.23	0.13	1.26	2.31	1.05	2.56	0.98	0.38	1.27	5.10	3.83
Group B	1.92	0.31	0.16	1.05	2.76	1.71	1.76	0.24	0.14	1.14	2.16	1.02	2.45	0.94	0.38	1.10	5.45	4.35
Validation	0.98	0.19	0.19	0.70	1.28	0.58	0.83	0.05	0.06	0.77	0.96	0.19	1.51	0.08	0.05	1.41	1.65	0.24
Compact car																		
Phase 1	2.08	0.73	0.35	1.34	3.64	2.30	2.08	0.71	0.34	1.31	3.58	2.27	2.58	1.30	0.50	1.05	5.74	4.69
Phase 2	2.13	0.77	0.36	1.15	3.80	2.65	2.10	0.72	0.34	1.08	3.70	2.62	2.56	1.25	0.49	1.04	5.58	4.54
Subcompact car																		
Phase 1	2.41	0.89	0.37	1.38	5.27	3.89	3.01	1.16	0.39	1.33	5.58	4.25	2.43	1.29	0.53	0.89	5.93	5.04
Phase 2	2.30	0.92	0.40	1.23	5.10	3.87	2.85	1.18	0.41	1.33	5.64	4.31	2.58	1.44	0.56	0.99	5.62	4.63
Train (previous)	1.40	0.30	0.21	0.90	2.60	1.70	0.95	0.10	0.11	0.76	1.10	0.34	1.30	0.30	0.23	0.80	2.70	1.90
Metroliner rail	1.72	0.45	0.26	1.37	3.19	1.82	1.62	0.76	0.47	1.22	4.58	3.33	1.68	0.34	0.20	1.31	2.58	1.27
Group A	1.56	0.15	0.10	1.37	1.81	0.44	1.37	0.09	0.07	1.22	1.51	0.29	1.59	0.24	0.15	1.31	1.92	0.61
Group B	1.87	0.58	0.31	1.38	3.19	1.81	1.85	1.01	0.55	1.32	4.58	3.26	1.76	0.40	0.23	1.33	2.58	1.25
Validation	1.28	0.21	0.16	0.77	1.63	0.86	1.01	0.16	0.16	0.66	1.31	0.65	1.13	0.29	0.26	0.77	1.80	1.03
PATCO rapid rail	1.61	0.68	0.42	0.94	3.79	2.85	1.34	0.89	0.66	0.65	4.83	4.18	1.56	0.79	0.51	0.73	3.59	2.86
AGT vehicle	1.60	0.29	0.18	0.89	2.47	1.58	1.66	0.32	0.19	1.02	2.96	1.94	3.46	1.38	0.40	1.73	5.63	3.90

Table 3. Summary statistics for longitudinal, transverse, and vertical acceleration for all vehicles.

Vehicle	Longitudinal Acceleration						Transverse Acceleration						Vertical Acceleration					
	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	0.044	0.015	0.34	0.017	0.073	0.056	0.075	0.028	0.37	0.031	0.134	0.103	0.082	0.027	0.33	0.036	0.152	0.116
Luxury bus	0.035	0.014	0.40	0.012	0.077	0.065	0.070	0.028	0.40	0.021	0.142	0.121	0.067	0.017	0.25	0.037	0.112	0.075
Group A	0.036	0.014	0.39	0.013	0.070	0.057	0.071	0.027	0.38	0.026	0.142	0.116	0.066	0.018	0.27	0.037	0.112	0.075
Group B	0.035	0.014	0.40	0.012	0.077	0.065	0.068	0.028	0.41	0.021	0.134	0.113	0.069	0.017	0.25	0.039	0.105	0.066
Validation	0.008	0.001	0.13	0.006	0.010	0.004	0.009	0.001	0.11	0.007	0.012	0.005	0.033	0.006	0.18	0.028	0.048	0.020
Compact car																		
Phase 1	0.040	0.020	0.50	0.015	0.092	0.077	0.050	0.030	0.60	0.020	0.123	0.103	0.050	0.020	0.40	0.033	0.105	0.072
Phase 2	0.040	0.015	0.34	0.013	0.080	0.067	0.060	0.030	0.50	0.020	0.148	0.128	0.060	0.020	0.33	0.033	0.106	0.073
Subcompact car																		
Phase 1	0.040	0.020	0.50	0.014	0.090	0.076	0.050	0.030	0.60	0.021	0.134	0.113	0.070	0.020	0.29	0.036	0.112	0.076
Phase 2	0.040	0.020	0.50	0.017	0.097	0.080	0.060	0.040	0.67	0.019	0.158	0.139	0.070	0.020	0.29	0.044	0.122	0.078
Train (previous)	0.012	0.004	0.33	0.007	0.022	0.015	0.029	0.010	0.34	0.009	0.064	0.055	0.030	0.007	0.23	0.018	0.046	0.028
Metroliner rail	0.021	0.008	0.38	0.011	0.038	0.027	0.022	0.009	0.41	0.012	0.049	0.037	0.035	0.011	0.31	0.024	0.076	0.052
Group A	0.022	0.008	0.36	0.011	0.033	0.022	0.019	0.006	0.32	0.012	0.028	0.016	0.032	0.005	0.16	0.024	0.041	0.017
Group B	0.021	0.008	0.38	0.012	0.038	0.026	0.025	0.010	0.40	0.012	0.049	0.037	0.038	0.014	0.37	0.028	0.076	0.048
Validation	0.020	0.007	0.35	0.008	0.030	0.022	0.020	0.009	0.45	0.015	0.050	0.035	0.040	0.005	0.13	0.030	0.050	0.020
PATCO rapid rail	0.040	0.020	0.50	0.009	0.100	0.091	0.020	0.004	0.20	0.016	0.035	0.019	0.030	0.005	0.17	0.019	0.043	0.024
AGT vehicle	0.030	0.010	0.33	0.010	0.050	0.040	0.040	0.020	0.50	0.020	0.070	0.050	0.040	0.010	0.25	0.030	0.050	0.020

include the mean ($\bar{X}$), standard deviation (SD), coefficient of variability (CV), minimum value (MIN), maximum value (MAX), and range. Table 4 presents similar statistics for the mean comfort ratings.

The luxury bus results show substantially lower means and variability for roll and pitch rates than did the conventional bus. However, yaw had slightly higher means and standard deviations for the luxury bus. All linear accelerations were greater for the conventional bus. In particular, the luxury bus displayed less vertical acceleration. Mean comfort judgments were better for the luxury bus than for the conventional bus, except for the validation phase. The luxury bus validation study involved peculiar circumstances and severely restricted ranges for all motion variables. An unusual situation led to poor mean comfort ratings in the presence of extremely good motion characteristics.

The two automobiles showed similar patterns of results for the measured linear accelerations. Roll and pitch rates were more extreme and more variable for the subcompact than for the compact car. The phase 1 data showed that riders were more comfortable in the compact car than in the subcompact, but this difference was not apparent for the phase 2 data.

The Metroliner data from this study differed in several respects from the previous train results. The present data contain more extreme levels of roll, pitch, and longitudinal and vertical acceleration than the earlier data but less noise.

Table 4. Summary statistics for mean comfort ratings for all vehicles.

Vehicle	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	3.40	1.10	0.32	2.20	6.30	4.10
Luxury bus	2.56	0.55	0.21	1.48	3.85	2.37
Group A	2.57	0.47	0.18	1.78	3.46	1.68
Group B	2.54	0.63	0.25	1.48	3.85	2.37
Validation	3.48	0.72	0.21	2.47	4.87	2.40
Compact car						
Phase 1	2.99	0.98	0.33	1.33	5.67	4.34
Phase 2	3.16	1.08	0.34	1.00	5.67	4.67
Subcompact car						
Phase 1	3.27	1.08	0.33	1.33	6.33	5.00
Phase 2	3.17	1.20	0.38	1.33	6.33	5.00
Train (previous)	2.90	0.80	0.28	1.70	4.80	3.10
Metroliner rail	2.45	0.62	0.25	1.70	3.77	2.07
Group A	2.15	0.39	0.18	1.71	3.05	1.34
Group B	2.73	0.68	0.25	1.70	3.77	2.07
Validation	2.92	0.48	0.16	2.13	3.81	1.68
PATCO rapid rail	2.36	0.36	0.15	1.76	3.63	1.87
AGT vehicle	2.66	0.74	0.28	1.33	5.67	4.34

Table 5. Correlations of motion variables with comfort for all vehicles.

				Acceleration		
Vehicle	Roll	Pitch	Yaw	Longi-tudinal	Trans-verse	Verti-cal
Regular bus	0.76[a]	0.22	0.05	0.48	0.28	0.57[a]
Validation	0.69[a]	0.76[a]	0.31	0.11	0.53[a]	0.74[a]
Luxury bus	0.53[a]	0.63[a]	-0.02	0.04	0.03	0.70[a]
Group A	0.61[a]	0.55[a]	-0.01	0.13	-0.02	0.61[a]
Group B	0.49[a]	0.70[a]	-0.04	-0.02	0.06	0.80[a]
Validation	-0.08	0.31	-0.25	0.43	0.47	0.22
Compact car						
Phase 1	0.46[a]	0.44[a]	0.14	0.13	0.18	0.46[a]
Phase 2	0.48[a]	0.48[a]	0.22	0.12	0.27	0.57[a]
Subcompact car						
Phase 1	0.49[a]	0.51[a]	0.03	0.52[a]	0.02	0.58[a]
Phase 2	0.47[a]	0.55[a]	-0.03	0.51[a]	-0.12	0.38[a]
Train (previous)	0.44[a]	0.31	0.20	0.43[a]	0.34	0.08
Metroliner rail	0.57[a]	0.44[a]	0.42[a]	0.08	0.37	0.65[a]
Group A	0.81[b]	0.34	0.47[b]	-0.01	0.63[b]	0.20
Group B	0.46[b]	0.37	0.32	0.18	0.14	0.68[b]
Validation	0.37	0.14	0.36	0.11	0.49[a]	0.62[a]
PATCO rapid rail	-0.01	-0.03	0.09	-0.12	0.41[b]	0.06
AGT vehicle	0.22	0.26	0.35	0.50[a]	0.39	0.47[b]

[a]Significant at $\alpha \leq 0.001$.
[b]Significant at $\alpha \leq 0.05$ (small sample sizes).

Table 6. Best model of ride quality for each vehicle.

Vehicle	"Best" Model	R
Luxury bus	$C' = 0.33 + 19.33\, a_V + 0.53\omega_p$	0.76
Compact car	$C' = 1.66 + 0.36\omega_R + 10.53a_V$	0.47
Subcompact car	$C' = 0.30 + 28.98a_V + 21.96a_L$	0.66
Metroliner rail car	$C' = 1.14 + 37.33a_V$	0.65
PATCO rapid rail	-[a]	
AGT vehicle	$C' = 0.39 + 42a_V + 24a_L$	0.56

[a]There was no good model based on motion variables.

However, the two groups of experimental subjects differed in the motion characteristics of their test segments: Extreme motion values were evident only for group B. In the validation phase, the linear accelerations were comparable to the experimental data sets. However, angular rates were less for the phase 2 data than for the phase 1 data.

The range of comfort ratings for the PATCO vehicle tests was extremely limited; most passengers found their rides comfortable or very comfortable. Limited ranges of mean comfort values are also apparent for group A of the luxury bus test and for all groups in the Metroliner study.

Table 5 summarizes the correlations of all the motion variables with comfort for all the vehicles in this and the previous study. All the rows represent independent tests of ride quality models except the top rows for luxury bus and Metroliner rail, which represent combined information from two groups each and are therefore not independent of the rows for their respective groups A and B. Roll shows significant correlations with comfort in 11 of the 15 independent data sets, vertical acceleration in 12 of the 15, and pitch in 9 of 15. There were only two vehicle tests for which these variables showed no correlation with comfort, and both data sets were problematic. For the luxury bus validation data and the PATCO vehicle data, no ride-quality model worked well.

For most of the individual vehicles, the same motion variables emerged as important determinants of comfort: roll, pitch, and vertical acceleration. They are highly intercorrelated and, in principal-components analyses, all load on the same component. Thus, composite models of ride quality will reflect this component either by including one of the variables that load strongly on it or by incorporating a linear combination of all of them.

Table 6 contains the "best" multiple regression model for each of the vehicles studied. Each model is the result of both the modeling and the validation processes. The multiple correlation (R) obtained by each model is also shown. Tables 5 and 6 also reveal the selective influence of other motion parameters. Longitudinal acceleration is important in the subcompact car and for the Morgantown AGT vehicle. In the first case, longitudinal acceleration is correlated with roll, pitch, and vertical acceleration. Transverse acceleration also correlates with comfort for several vehicles. Its contribution may depend on the number of curves in the track or roadway encountered during the test run. In a previous study of ride quality for buses on a curved roadway, transverse acceleration was the only motion component in the model (20).

Composite Models

The data from the present experiment were also used to develop composite models. The data from the several vehicles were merged together into a single analysis. Since different subjects were involved in tests for the different vehicles and since the several vehicles have different frequency spectra, the equations shown here will be lower bounds on the relations that might be obtained. All six motion variables were used, but the data from PATCO and the luxury bus validation study were not included. Thus, the composite data set consisted of the luxury bus experimental data, the Morgantown AGT and Metroliner data, and all the automobile data. The phase 1 and phase 2 distinctions were ignored for this analysis. This resulted in a total of 563 usable ride segments. The regression model that best fits these data is

$$C' = 0.20\omega_r + 0.14\omega_p + 10.15a_V + 7.71a_L + 1.36 \quad (1)$$

This model has a multiple correlation of 0.54. For roll, pitch, and vertical acceleration alone, the respective correlations with comfort are 0.49, 0.50, and 0.46; models that involve either vertical acceleration and roll or vertical acceleration and pitch result in an R of 0.52. Thus the four-variable model does not improve much on a two-variable model. Furthermore, roll, pitch, and vertical acceleration all load highly on a single principal component of the motion intercorrelation matrix. However, roll and pitch are sufficiently independent of vertical acceleration to add predictability when they are included in the model.

The influence of longitudinal acceleration is a result of the automobile data. The car data represent a large part of the composite data set (350 of the 563 observations) and thus strongly influence the overall model. When the total data are partitioned into those for cars and those for other vehicles, the best equation for cars includes roll and vertical and longitudinal accelerations, whereas that for the other vehicles involves only roll and vertical acceleration. Thus, the influence of longitudinal acceleration is peculiar to a certain vehicle, just as the influences of transverse acceleration result from particular operating conditions (curved roadway). Whereas Equation 1 is statistically optimal for the composite data set, Equation 2 is more representative of ground-based vehicles in general:

$$C' = 0.41\omega_R + 11.84a_V + 1.43 \quad (2)$$

It is recommended as a general model. The fit of Equations 1 and 2 to comfort data for each of the vehicles in this study is shown below. Clearly, the two-variable equation is adequate in most cases and preferable in some.

	Correlation	
Vehicle	Equation 1	Equation 2
Luxury bus		
Experimental	0.68	0.72
Validation	0.23	0.09
PATCO rapid rail	-0.05	0.00
AGT vehicle	0.50	0.37
Metroliner	0.33	0.43
Compact car	0.47	0.49
Subcompact car	0.59	0.54

DISCUSSION

These results reaffirm the importance of the angular rates as determinants of comfort for ground-based vehicles. Although earlier composite models appear to be generally appropriate for the data presented here, two refined composite models were presented. Except for two anomalous data sets, there were no real surprises in the new data; the right variables were important to comfort when they displayed enough variability. Models involving roll, pitch, and vertical acceleration were found in most cases. Occasionally an additional variable also proved important (longitudinal or transverse acceleration).

The previous train model had involved a noise component. However, in this study noise was not a significant determinant of comfort in the Metroliner rail-car data; it simply did not show the high mean levels and wide variability encountered in the earlier study. Both noise and temperature would be important to comfort under the right circumstances. In this study, however, both had values that fell in the comfortable range on all vehicles and showed little variation within any test run. It appears that the extreme noise variation found in the first train study is not representative of the usual environment in trains or of most other vehicles. However, it may be characteristic of certain train routes.

The two anomalous data sets (the PATCO vehicle and the luxury bus validation data) may both reflect the role of attitudes, or passenger preconditioning, on reactions to the vehicle environment. Subjects in the luxury bus replication study were extremely negative about the whole experience: It was a cold, rainy day; and the test run was delayed. For the PATCO subjects, on the other hand, everything went very smoothly and on schedule. The respondents were very favorably disposed toward PATCO in general and very cooperative with the experiment in particular. Their overall positive attitudes are reflected in their ratings of the test segments. They rated everything as comfortable.

While the six degrees of freedom of motion may be independent in theory, they are correlated in practice. For the vehicles discussed above, a high degree of multicolinearity exists among the motion inputs, particularly roll, pitch, and vertical acceleration. These vehicles have characteristic patterns of motion variation; there is a cross coupling of several degrees of freedom of motion. It is conceivable that future vehicles will have different patterns of covariation of the motion inputs. Studies are needed to explore what happens to human reactions when the existent cross correlations are broken down or altered. Such studies may be done on six-degree-of-freedom motion simulators.

Two goals of past ride-quality research have been (a) the development of a ride-quality meter and (b) the establishment of standards or criteria for human exposure to whole-body vibration. The approach described here may accomplish both of these goals. The main problem with past work on both goals has been the failure to assess vibration in all six degrees of freedom simultaneously. Traditional ride-quality meters are not good enough because they incorporate only linear accelerations. Their failures are almost certainly due to the fact that they ignore the contributions of the angular rates to ride quality. Similarly, people often report being uncomfortable in environments that existing standards (International Standard 2631:1978) deem acceptable. However, since those standards also cover only the linear accelerations, the rider's discomfort may well be due to the rotational degrees of freedom. An adequate set of standards and a successful ride-quality meter will have to incorporate equations such as those reported here.

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Maximum Deceleration and Jerk Levels That Allow Retention of Unrestrained, Seated Transit Passengers

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Three experiments performed to determine the maximum deceleration and associated rate of change of deceleration (jerk) that will allow the majority of potential users of automated guideway transportation systems to remain securely in their seats are described. In each experiment subjects representative of three anthropometric classes underwent various levels of deceleration and jerk. These experiments were performed in an instrumented vehicle controlled by an automated braking system. Seat sensors, movies, and subject ratings were employed to determine the deceleration at which subjects began to move off the seat pan. Subjects were decelerated while seated normally, sideways, and forward facing but tilted backward (facing forward with the seat pan tilted back 3, 9, or 12°). Subjects underwent jerk levels of 0.25, 0.75, and 1.25 *g*/s while seated normally only. Jerk was found not to affect maximum deceleration levels. Modifications of features common to transit seating were found to increase retention. The maximum deceleration allowing retention was determined for both forward- and side-facing seated passengers. These results are discussed and presented in tabular and graphic form.

A major design goal of transit systems, particularly of automated guideway transit (AGT) systems, is high passenger flow rate. One technique employed to accomplish this goal is to minimize the headway between vehicles moving in the same direction along the guideway. However, a sufficient stopping distance between vehicles must be maintained for the safety of the passengers. The more closely one vehicle follows another, the more quickly it must