A SURVEY OF LONGITUDINAL ACCELERATION COMFORT STUDIES IN GROUND TRANSPORTATION VEHICLES

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16. Abstract

Experimental studies of objective and subjective passenger response to various fore-and-aft, or longitudinal, vehicle acceleration transients are reviewed. It is found that the wide variability in type of study and form of results does not allow conclusive statements to be made regarding passenger acceptability of any specific acceleration - jerk profile in a given transportation system.

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EXECUTIVE SUMMARY

INTRODUCTION AND PROBLEM STATEMENT

This report surveys available experimental results on passenger comfort due to changes in a vehicle's longitudinal direction. The purpose of the study was to assess the state-of-the-art in passenger tolerances to longitudinal acceleration and jerk loads. These effects bear on the design of vehicle propulsion and braking systems, as well as central headway, speed, and scheduling controls, for automated, high-capacity vehicle networks.

RESULTS AND CONCLUSION

The literature survey uncovered a total of eleven studies dealing with passenger comfort due to longitudinal motion. Of these, six were "subjective" studies, in which selected passengers were exposed to various motion changes and asked to record their feelings about the motion on a questionnaire. The remaining five studies attempted to objectively measure some comfort-related parameters, such as loss of balance or severity of brake application. It is found that the wide variability in type of study and form of results does not allow conclusive statements to be made regarding passenger acceptability of any specific acceleration-jerk profile in a given transportation system. The survey did indicate, however, that for public mass transportation, steady non-emergency accelerations in the range 0.11 g to 0.15 g fall in the "acceptable" range for most studies, and could be larger. It is unlikely that values of jerk larger than 0.30 g/s would be acceptable for most public transportation.

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INTRODUCTION

Passenger comfort in public ground transportation is determined by the changes in motion felt in all directions, as well as by other environmental effects. This report, however, treats only comfort due to motion changes in a vehicle's longitudinal direction, that is, in its direction of travel or fore-and-aft direction. In automated or semi-automated vehicle network, fast starts and stops will be necessary in order to merge vehicles into high speed traffic at close headways. However, the limiting factor in operating a vehicle network at high capacity, high velocity, and short trip times may in fact be passenger intolerance of the high longitudinal acceleration and jerk loads required. If passengers are unrestrained in the vehicle, the standees, aged, infirm and children will be the critical passengers to consider. Passenger tolerances to longitudinal acceleration and jerk loads will thus affect not only the design of the vehicle propulsion and braking system, but also the central headway, speed, and scheduling controls for the entire network. To assess the state-of-the-art in this area, the work that follows surveys available experimental studies of longitudinal comfort.

PART I

ACCELERATION AND DECELERATION LEVELS IN CURRENT USE

An excellent review of experimental longitudinal comfort studies prior to 1970 can be found in the work by Gebhard [1]*. He points out that conventional subways and commuter trains are designed to accelerate at about 3.0 mph/s (4.830 kph/s) or .138 g. Long cross-country passenger trains accelerate less than half this fast. Table 1 provides some acceleration data for a variety of passenger vehicles. It should be observed that none of the acceleration values for the public ground systems, in which passengers may be standing, exceeds 0.16 g. On the other hand, if a passenger is properly seated (car or airplane) or prepared (motorcycle), the acceleration levels can be as high as 1/2 g or larger.

Deceleration levels specified for various transportation vehicles depend upon whether the braking is normal, called service braking, or emergency. For electric rapid transit cars in the U.S., Reference [5] indicates normal braking of 0.12 g to 0.14 g and emergency braking from 0.14 g to 0.30 g. An automobile can decelerate at rates larger than 0.6 g [6]. Table 2 lists normal and emergency deceleration capability for the first three vehicle systems of Table 1.

Objective Comfort Measurements

Most of the known attempts to assess passenger comfort have used a "questionnaire," or subjective approach. In these studies, which will be reviewed in the next section, selected subjects were placed in vehicles or laboratory devices, exposed to various motion changes, and asked to record their feelings about the motion on a questionnaire. In this section, we review those few studies available in which some objective measurement of comfort-related parameters was attempted. Objective studies have the advantage that results are less easily open to misinterpretation than are results of subjective studies.

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*Numbers in brackets refer to references at the end.

TABLE 1.

ACCELERATION LEVELS FOR VARIOUS PASSENGER VEHICLES

Vehicle	Approximate mph/s	Maximum kph/s	Acceleration g	Reference
Morgantown PRT System (Morgantown, West Virginia)	3.0	4.8	.137	2
AIRTRANS (Dallas-Fort Worth Airport)	2.5	4.1	.116*	3
BART (San Francisco)	3.3	5.3	.152*	4
Motor Cars				
VW 1500	4.5	7.2	.205	1
Ford Fairlane	7.9	12.7	.360	1
Pontiac Grand Prix	10.0	16.1	.456	1
Motorcycle				
Norton 750	13.0	20.9	.593	1
Commercial Jet				
Aircraft Takeoff	11.0	17.7	.501	1

*These vehicle systems have a number of acceleration and jerk specifications, depending on the operating condition. The values listed are the maximums.

TABLE 2.

DECELERATION LEVELS FOR THREE VEHICLE SYSTEMS

Vehicle	Max. Normal Dec			Max. Emergency Dec			Reference
	mph/s	kph/s	g	mph/s	kph/s	g	
Morgantown	3.0	4.8	.137	7.2	11.5	0.330	2
AIRTRANS	2.5	4.1	.116	6.1	9.8	0.280	3
BART	3.3	5.3	.152	3.3	5.3	0.152	4

It has been suspected that automobile drivers impose upon themselves consistently higher longitudinal accelerations than found in public ground transportation. To investigate this possibility Mortimer [7] and his associates planted a recording accelerometer in the trunk of a car in the motor pool at the University of Michigan. Drivers who used the car were aware that an experiment was in progress, but not what type of experiment it was. Originally, the car was equipped with conventional hydraulic brakes, and 28 people drove it for 4254 miles. Then power assist was added to the brakes and 16 people drove the car for an additional 2001 miles. Figure 1 gives the distribution of peak decelerations for a total of 8934 brake applications. It can be seen that decelerations exceeded 0.15 g for 35% of the brake applications. Recall from Table 2 that this deceleration level was the maximum normal deceleration of the three automated vehicle systems surveyed. On the other hand, Figure 1 shows that only for 2.5% of the brake applications did drivers exceed 0.3 g, which is the maximum emergency deceleration for the vehicle systems in Table 2. Mortimer gives no indication of the type of driving conditions experienced by these drivers, but it is likely that a substantial amount of city driving was involved. Moreover, it is not clear whether the accelerometer data was processed to remove the effects of grade changes.

In a different study by Torres [8], longitudinal accelerations experienced by drivers under freeway conditions were measured. A standard 1967 Plymouth sedan was instrumented to measure fore-and-aft acceleration and velocity. Acceleration data was "de-trended" to remove the effects of grade changes. The most useful data was collected using six drivers, each on a different day making eight runs in one direction (east bound) and eight in the opposite direction (west bound) over a two-mile section of the eight-lane Ventura Freeway in southern California. The drivers were instructed to drive as they normally do, which led to an appreciable amount of lane changing and passing. Runs were made during the morning peak traffic period with the heavy traffic in the eastbound direction. Figure 2 presents two "de-trended" acceleration histograms for one driver, each obtained by averaging over three runs. Torres presents these histograms as being typical for all drivers. Apparently, all accelerations larger than 4 ft/s^2 (.124 g) were lumped together at the "tails" of these histograms. Observe that both the mean accelerations and durations of accel-

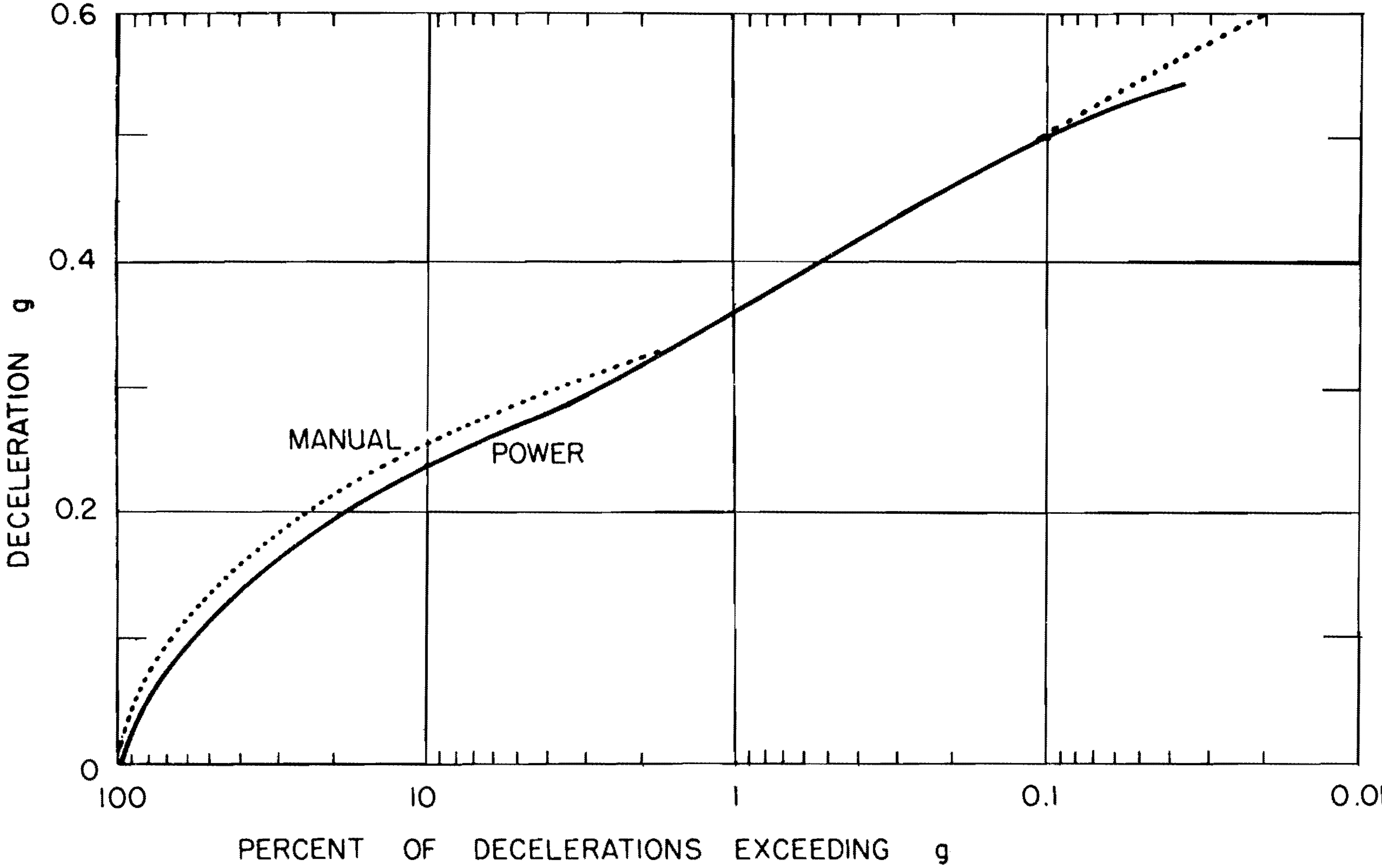

Figure 1. Frequency Distribution of Braking Decelerations (After Mortimer [7]).

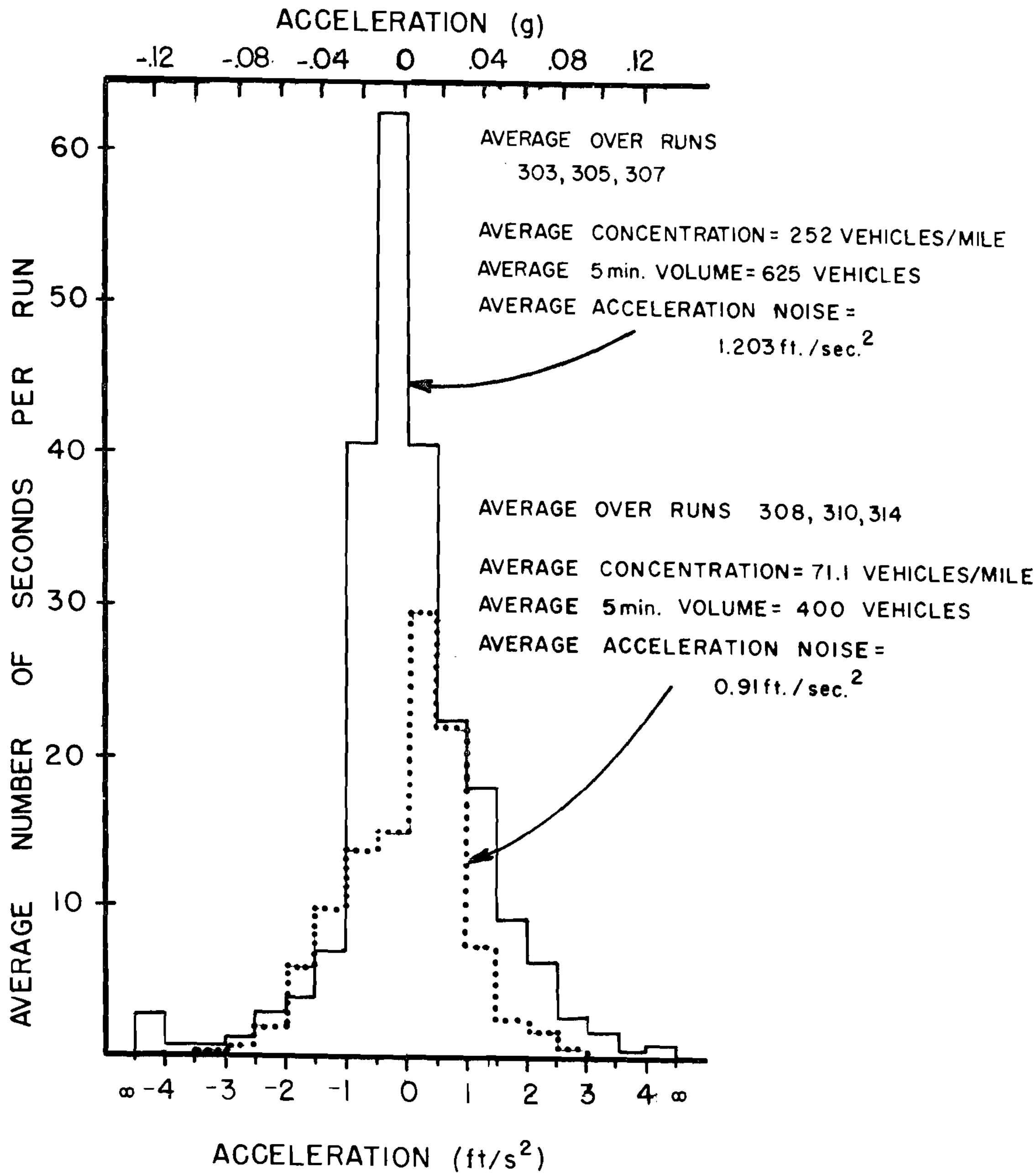

Figure 2. Acceleration Histograms (After Torres [8]).

eration change dramatically with vehicle concentration. Unfortunately, mean accelerations across the driver set for various traffic conditions were apparently biased by calibration errors. However, the standard deviations of the detrended acceleration data appear valid and were found to be related to traffic volume, as shown in Figure 3. Torres calls this standard deviation "acceleration noise" and considers it a measure of driver effort or stress. As the geometry of the highway or prevailing traffic conditions change, the driver is forced to adapt dynamically. Unfortunately, road-vehicle interactions and wind buffeting, rather than driver effects, may account for the "acceleration" noise at higher speeds. These effects may also account for some of the large dispersion of data in Figure 3. No attempt was made to separate these effects from driver effects. As expected, higher speeds occur at lower volumes, such that wind-buffeting and road-vehicle interaction effects would be most severe at the lower volumes. If, as Torres suggests, "acceleration noise" is a measure of driver stress, one might support from these results a suspicion that such stress increases with traffic volume. On the other hand, the relationship between stress and acceleration noise has not been conclusively established and remains a subjective assumption.

A different type of measurement was done by Hirschfeld [9] in the 1930's to determine the effects of motion on loss of balance of standing passengers. This investigation merits special consideration for several reasons: (1) standing passengers may in fact be the critical elements in governing longitudinal motion characteristics in public ground transportation; (2) the study uncovered evidence that different acceleration - jerk profiles produce different results, such that single-number specifications for these quantities may be incomplete. In what follows, we trace Gebhard's [1] summary of Hirshfeld's [9] results.

The experimental laboratory arrangement consisted of a small car riding on a smooth track such that the car could accelerate from rest at any value up to 12 ft/s^2 (.373 g) with jerk at any value up to 50 ft/s^3 (1.553 g/s). The measured quantity for a standing passenger facing forward in the car was "loss of balance," which was electrically recorded when the standee either grabbed a handrail for support or moved either foot from the prescribed position: left heel eight inches (20.3 cm) in front of and ten inches (25.4 cm)

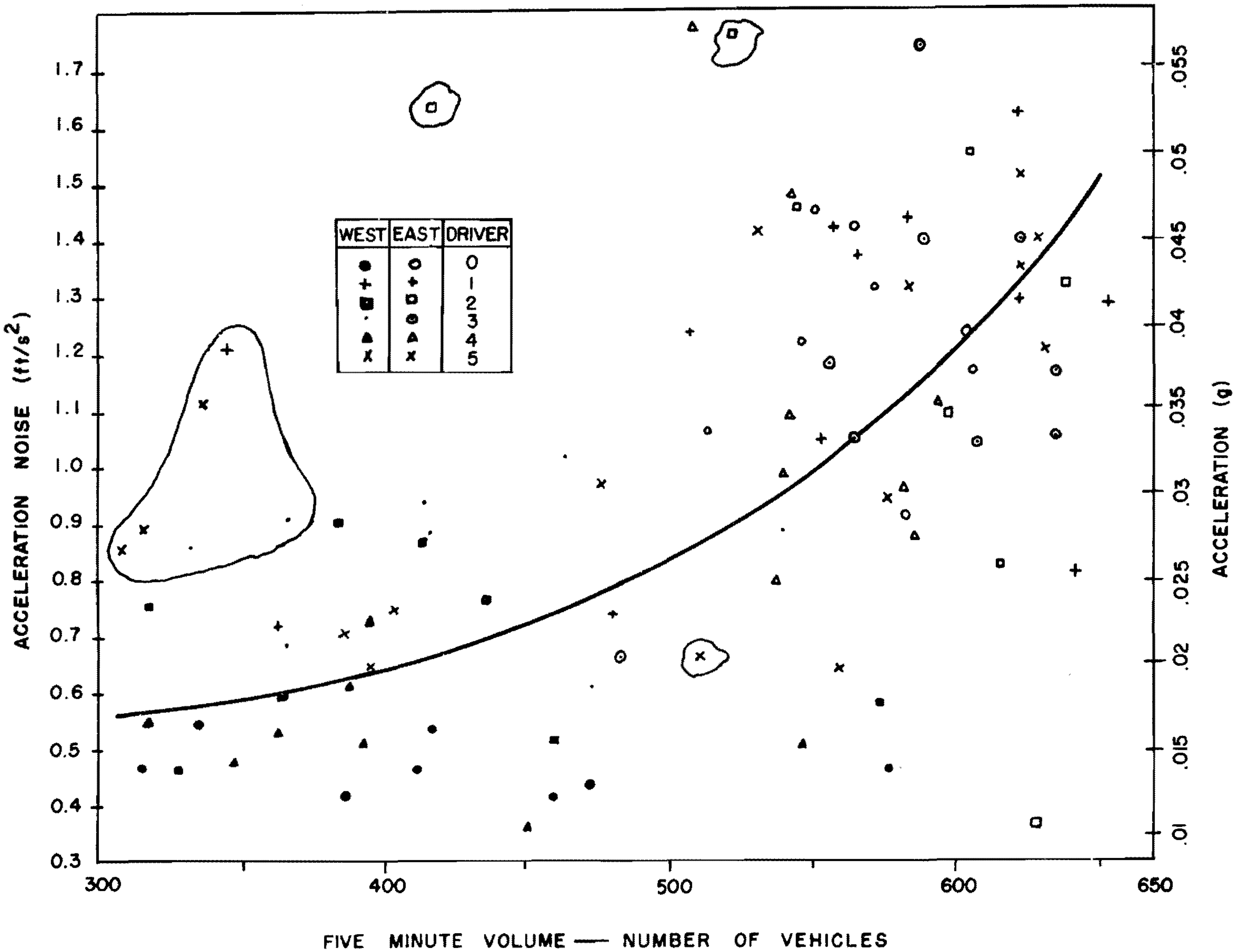

Figure 3. Acceleration Noise vs. Volume (After Torres [8])

to the left of the right heel, with electrical contacts at the left toe and right heel.

A total of 110 subjects of both sexes of various ages (11 to 78 years), heights (4'4" to 6'4"), weights (87 to 235 pounds), and backgrounds were tested under a variety of starting conditions. The most significant of these conditions were as follows:

A. Acceleration $\hat{a}$ was increased linearly from zero at constant jerk $\hat{j}$, such that $\hat{a} = \hat{j}t$ where t is time. Values of $\hat{j}$ ranged from less than 1 to 10 ft/s^3 (less than .031 g/s to 0.311 g/s) and t ranged up to 7 secs.

B. Acceleration was increased from 0 very rapidly to a specified constant value. This was accomplished by suddenly releasing the brake from a car having a specified pre-release force. This force yielded jerk values of 10 ft/s^3 (.311 g/s) or greater over a period of 1 second or less. Values for the final constant acceleration phase ranged from 1.0 to 3.5 ft/s^2 (.031 to .109 g).

C. Jerk was increased linearly from 0 such that $\hat{j} = k_1 t$. Thus, acceleration increased parabolically from 0 according to $\hat{a} = 0.5\, k_1 t^2$. Values of k_1 ranged from 0.2 to 1.0 ft/s^4 (.0062 to .031 g/s^2) and t ranged up to 7 seconds.

D. A short initial "warning" period of constant low acceleration for 3 seconds was followed by a parabolic increase in $\hat{a}$ as in Method C. The initial value of $\hat{a}$, ranging from 1 to 2 ft/s^2 (.031 to .062 g), was established by linearly increasing the acceleration from 0 at values of $\hat{j}$ from 2 to 7 ft/s^2 (.062 to .219 g/s).

Table 3 lists the number of subjects and tests run, together with the positions of the subjects, for each of the four methods. A major difficulty with the data reported by Hirshfeld is that the results for subjects are pooled, and the data is given as the percentage of tests in which all riders maintained balance to a given level of acceleration. Moreover, no attempt was made to use the same subjects for all of the test conditions, or for that matter, for all the various values for $\hat{j}$ or k_1 in any one testing condition. Different subjects and different numbers of subjects were used in the various tests.

TABLE 3.

CONDITIONS USED FOR LOSS-OF-BALANCE TESTS

(AFTER HIRSHFELD [9] AND GEBHARD [1])

	Subject's Position	Starting Method	Number Of Subjects	Number Of Tests
1.	Facing Forward, Unsupported	A	79	489
2.	Facing Forward, Unsupported	B	25	236
3.	Facing Forward, Unsupported	C	44	133
4.	Facing Forward, Unsupported	D	15	81
5.	Facing Forward, Unsupported	A	23	98
6.	Facing Sideways, Unsupported	A	22	74
7.	Facing Forward, Holding Over-Head Strap	A	26	123
8.	Facing Forward, Holding Vertical Stanchion	A	27	87
9.	Facing Forward, Males on Low and High Heels	A	6	37
10.	Facing Forward, Females On Low and High Heels	A	3	9

Hirshfeld reports that a given subject was extremely variable in ability to retain balance, although this variability is not quantified. Variability between subjects was also large, but this variability was not related to any subject characteristics such as sex, age, or height.

Results for several values of $\hat{j}$ are given in Table 4 for Method A with unsupported subjects facing forward, Condition 1, Table 3. The only case for which the number N of tests is mentioned is for $\hat{j} = 4.5$ ft/s^3 (.140 g/s), for which N = 58. As may be seen from the table for values of $\hat{a}$ between 3 and 7 ft/s^2 (.094 and .217 g), higher balance retention is obtained for the larger jerk values. Hirshfeld suggests that this may be due to a subject's tendency to quickly sense and strongly adjust to high jerk values, carrying through the adjusting posture to high values of $\hat{a}$. Low jerk values, on the other hand, are more casually accepted such that the subject does not have a strong compensating posture when high values of $\hat{a}$ are reached. However, Hirshfeld's data suggests that the limit for this effect is approximately 7 ft/s^3 (.217 g/s). This conclusion tends to be supported by data from Method B, Condition 2, Table 3, in which $\hat{j}$ was at least 10 ft/s^3 (.311 g/s). No subject was able to maintain balance for $\hat{a} = 3.5$ ft/s^2 (.109 g) under Method B, whereas in Method A, 50% of all subjects maintained balance to $\hat{a} = 5$ ft/s^2 (.155 g) or larger when $\hat{j}$ was less than 7 ft/s^3 (.217 g/s). Hirshfeld reports that for all tests with forward facing standees in Method A, the average acceleration obtained before loss of balance was 5.3 ft/s^2 (.165 g).

Method C tested the possibility that "slower starts," with jerk increasing linearly, would allow progressive adjustment by the subject, such that ultimately higher values of $\hat{a}$ could be reached without losing balance. Results are given in Table 5 for unsupported standees facing forward, Condition 3, Table 3, for several values of k_1 in the formula $\hat{j} = k_1 t$. As for Method A, the data shows that "faster starts" (higher values of k_1, in this case), do not lead to more loss of balance. However, it can be seen by comparing data in Tables 4 and 5, that no advantage is gained by using the slower start of Method C. In fact, since minimizing the time to reach a desired acceleration a_d is likely to be important in automated transportation systems, Method A would be superior for those cases of constant jerk $\hat{j}$ in which $\hat{j}^2/a_d > k_1/2$. For $a_d = 3.0$ ft/s^2 (.093 g), 80 to 90 percent of the tests showed balance retention for the highest values of $k_1 = 1.0$ ft/s^4 (.031 g/s) in Method C and $\hat{j} = 6.5$ ft/s^3 (.202 g/s)

TABLE 4.

STARTING METHOD A:
PERCENT OF TESTS IN WHICH BALANCE WAS
RETAINED, UNSUPPORTED FORWARD-FACING STANDEES
(AFTER HIRSHFELD [9] AND GEBHARD [1])

Avg. Acceleration Attained		Jerk					
ft/sec^2	g	ft/s^3	g/s	ft/s^3	g/s	ft/s^3	g/s
1	.031	99%		97%		99%	
2	.062	95		93		93	
3	.093	87		81		85	
4	.124	67		70		80	
5	.155	42		55		70	
6	.186	12		30		60	
7	.217	4		18		20	
8	.248	1		7		-	

TABLE 5.

STARTING METHOD C:

PERCENT OF TESTS IN WHICH BALANCE WAS RETAINED,

UNSUPPORTED FORWARD-FACING STANDEES

(AFTER HIRSHFELD [9] AND GEBHARD [1])

Avg. Acceleration Attained		k_1, Rate of Change of Jerk				
		ft/s^4 g/s^2	ft/s^4 g/s^2	ft/s^4 g/s^2	ft/s^4 g/s^2	ft/s^4 g/s^2
ft/s^2	g	0.2 .0062	0.4 .0124	0.6 .0186	0.8 .0248	1.0 .0311
1	.031	98%	100%	100%	100%	100%
2	.062	92	100	100	100	99
3	.093	71	75	90	98	86
4	.124	48	42	55	56	75
5	.155	41	15	32	31	47
6	.186	16	8	9	13	15
7	.217	1	3	5	-	3

in Method A. The inequality above is satisfied for this comparison, and the corresponding times are 0.46 seconds for Method A and 2.45 seconds for Method C.

With Method D, Hirshfeld attempted to assess whether a short "warning acceleration" would lead to better balance retention. However, the results were no better than the more severe starting tests of Method A. On the average, balance was lost for $\hat{a} = 5.4$ ft/s^2 (.168 g) at t = 7.0 seconds. In Method A, only 2.5 seconds were required for this average acceleration.

Results for the remaining test conditions 5 through 10 in Table 3 are available only in the form of average accelerations attained before loss of balance, and this data is given in Table 6. These results should be compared with the average $\hat{a} = 5.3$ ft/s^2 (.165 g) obtained for Method A with forward facing standees, Condition 1 in Table 3. As might be expected, facing sideways unsupported, holding on overhead strap, and holding a vertical stanchion give increasingly better results compared with the unsupported-forward condition. Moreover, it might be possible to interpret the "facing backward, unsupported" condition as equivalent to deceleration for forward facing, unsupported standees. Under such an interpretation, the average from Table 6 of 4.2 ft/s^2 (.130 g) indicates that deceleration would be more critical than acceleration.

The problem addressed by Hirshfeld was also investigated by Browning [10] in more recent work. Browning was interested in passenger tolerance to motion of pedestrian conveyors moving at line speeds in the range 9.11 to 14.58 ft/s (10 to 16 kph). The upsetting effect of accelerations was studied by filming subjects standing on a trolley accelerated in a known fashion. The trolley ran on pneumatic wheels and was guided along a single floor-mounted rail. Power was provided by a battery electric towing trailer with provision to automatically control acceleration. The main testing stage "involved between 150 and 300 adult subjects drawn from all parts of the Royal Aircraft Establishment, together with a similar number of people from families of employees and a number of special subjects, i.e., groups of children and disabled people." All subjects carried what was thought to be realistic amounts of luggage. Data from these experiments were recorded in three ways: (a) edited films showing many people taking part in the experiments; (b) an analysis of these films made by the author or by a panel of experts; and (c) an analysis of the written responses made by the passengers immediately after taking part in the experiments. Browning however, is suspicious of the subject opinions, and the bulk of the

TABLE 6.

STARTING METHOD A:

AVERAGE ACCELERATION OBTAINED BEFORE LOSS OF BALANCE

(AFTER HIRSHFELD [9] AND GEBHARD [1])

Condition	Average Acceleration Attained	
	ft/s^2	g
Facing backward, unsupported	4.2	0.13
Facing sideways, unsupported	6.1	0.19
Facing forward, holding overhead strap	7.4	0.23
Facing forward, holding vertical stanchion	8.7	0.27
Facing forward, unsupported		
Males, high heels	4.8	0.15
Males, low heels	5.3	0.16
Females, high heels	5.3	0.16
Females, low heels	3.2	0.10

conclusions are based on Method B. Summarizing earlier work, but providing no details, he reports that small amplitude fore-and-aft vibration of the floor is effectively damped out by the legs of a standing person. Apparently, the natural frequency of the balancing reaction is approximately 1 hz, and fore-and-aft vibration of large amplitudes (several cm) near this frequency makes balancing difficult unless the subject walks.

The upsetting effect of acceleration, Browning reports, depends not only upon the level of acceleration, but also on the jerk, a conclusion also reached by Hirshfeld. However, Browning's acceleration time profile, shown in the inset of Figure 4, resulted in a constant steady velocity at the end of the profile transient, whereas Hirshfeld's did not. A profile such as that shown in the inset of Figure 4 has been called a "three-phase" start by Thurlow [11], and for the case at hand, the constant decelerating jerk at the end of the profile was made equal to the accelerating jerk at the beginning. Browning assumes that the upsetting effect is applicable to the complete profile. Figure 4 shows in solid lines the combinations of acceleration and "rise time," defined in the inset, judged by the panel to cause "slight relative movement" for passengers and recommended by the panel as tentative "acceptance curves." In dotted lines are shown corresponding curves of jerk versus rise time derived from the solid line data. Observe that the jerk can be as high as .325 g/s for fit adults, provided the acceleration is no larger than .065 g. Now consider Hirshfeld's implication that the first phase of the starting transient is responsible for upsetting effects, rather than the complete transient. Under this assumption, compare data in Figure 4. The three encircled points, calculated from the second row of Table 4, represent the only acceleration - rise time values from Table 4 that lie between the two acceleration curves in Figure 4. Accordingly, if this assumption were valid, Browning's "slight relative motion" corresponds to 93-95% balance retention in Hirshfeld's study. On the other hand, the comparison is not strictly accurate, and caution must be employed in drawing such conclusions.

Finally, for a given line speed, acceleration patterns that cause the same upsetting effect are not equally attractive because they do not all require the same acceleration length. Browning reports that the choice of values for the three-phase start of Figure 4 to yield minimum lengths is virtually independent of the line speed in the range 10-16 kph, and are given as follows:

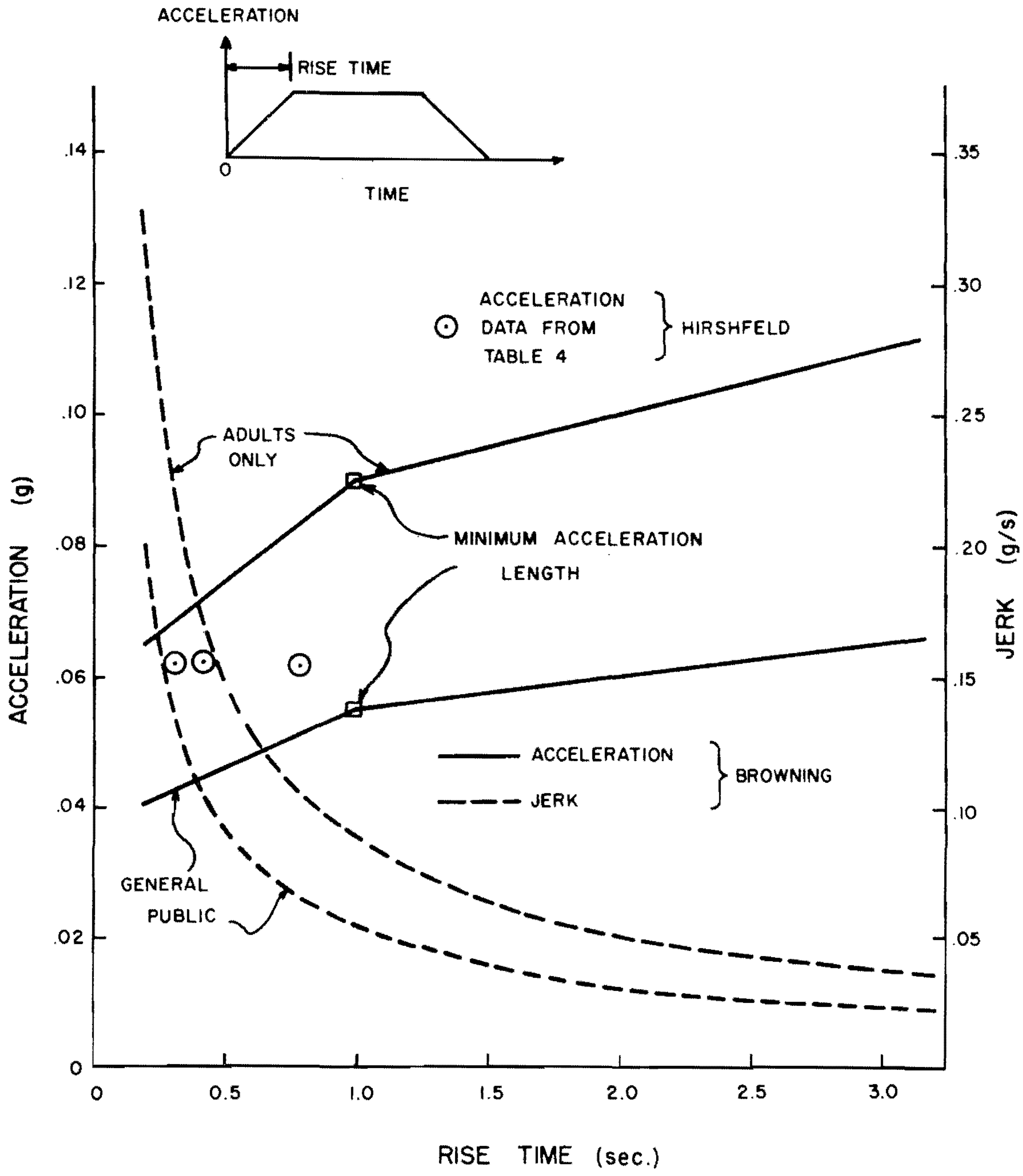

Figure 4. Tentative Acceptance Curves for the Acceleration of a Floor (After Browning [10])

	General Public	Fit Adults
Moderate Relative Movement	.070 g in ½ to 1 s (.070 to .350 g/s)	.115 g in ½ to 1 s (.115 to .230 g/s)
Slight Relative Movement	.055 g in 1 s (.055 g/s)	.090 g in 1 s (.090 g/s)
Virtually No Relative Movement	.040 g in 1 to 2 s (.020 to .040 g/s)	.065 g in 1 to 2 s (.033 to .065 g/s)

Small boxes mark the points in Figure 4 that correspond to minimum acceleration lengths for "slight relative movements." Given a minimum acceleration length, observe that for "moderate relative movement" the jerk values can be twice as high as acceleration values, whereas for "slight relative movement," these values are equal.

Subjective Comfort Measurements

By far, the most common type of experimental study with subjects consists of relating physical measurements of acceleration and jerk to passenger opinions marked on a questionnaire. In most cases, a salient part of the procedure called for subjects to mark a scale using from 3 to 7 gradations with subjective titles assigned to each gradation, such as "just noticeable," "quite pronounced, but not at all uncomfortable," and "rather uncomfortable." In reviewing these studies, two categories of difficulties arise. The first is due to fundamental questions regarding validity of this approach for assessing passenger comfort. The second arises because of the wide variation among investigators in methods, subject populations, questionnaire designs, experimental vehicles, and nature of measured data. On the other hand, some of the same questions arise for objective studies. We address these difficulties in order.

Gebhard [1] has suggested that one difficulty with questionnaire responses on acceptability is that these judgements do not necessarily reveal what a subject will actually accept in a transportation system. In fact, this problem may be a special case of the classical conflict between Freudian and Skinnerian psychologies: What a subject says he feels may not indicate how he behaves, or may be induced to behave, in any situation. To this writer's knowledge, it has not been tested, let alone established, that a rider's judgement of acceptability in a short experimental ride is adequate to define tolerance or acceptability in daily commuting. It is more likely that this issue should be treated as a trade-off between a number of variables, as for example, between travel time, convenience and comfort. More simply put as an elementary example, given two transportation systems operating between two points, one "uncomfortable" but "fast" and the second "comfortable" but "slow," what are the percentages of people of various backgrounds that actually use (not say they will use) one system over the other. As Gebhard states [1], "Riders overwhelmingly accept the automobile for travel to the center city, while damning the many annoyances due to traffic and parking." A subject who regularly exceeds ¼ g in his private automobile may check 1/8 g as the upper limit of comfort on a questionnaire. What is needed, it appears, is assessment of behavior itself (i.e. ridership), rather than feelings about acceptability.

The second category of difficulties is not unrelated to the first. Hanes [12] has defined the problem as the difficulty in determining exactly who did what and how. Fundamentally, the responses made by a subject on a questionnaire are likely to depend upon what he thinks is expected of him. Hence, variability among results of different tests could be dependent upon instructions subjects are given, number of gradations used for sealed judgements, and wording of descriptions associated with the scale. For example, consider two questionnaires each having five places for responses numbered 1, 2, ...5. Suppose for the first questionnaire, the descriptions were (in order 1 to 5) "imperceptible," "just perceptible," "fairly perceptible," "perceptible," and "very perceptible." For the second, let the descriptions be "not noticeable," "noticeable," "strong," "slightly uncomfortable," and "very uncomfortable." There exists the possibility that a bias exists for the second questionnaire over the first at the suggestion that discomfort may be encountered during the test. Moreover, there is no accurate method to relate the responses on one questionnaire to those of the other.

Finally, the type of subject population used has an enormous effect on the type of responses obtained. It is reasonable to expect a thorough study to report responses with respect to various subject population variables, such as age, sex, ridership history, and occupation (including transportation expertise). The parenthetical variable is included because in several instances

[6, 13, 14] complete tests have been done with the only subjects being those with occupational affiliation with transportation. The bias introduced by such a procedure has been analyzed in a recent study [15] and will be reviewed later. Although all of the studies reported below exhibit some of these theoretical limitations, it is nevertheless instructive to review the data.

Wilson [6] conducted tests on braking of automobiles using as subjects eight department heads or their assistants from General Motors Proving Grounds. Table 7 gives the average ratings in three categories of these eight for various average decelerations. Wilson does not report how the average ratings were compiled, but the average deceleration values were calculated from the distances required to stop from 70 mph (112.7 kph), and thus are likely below the maximum decelerations experienced during the stop. Also shown for comparison are two other deceleration values. It is interesting to compare the first value in Table 7, labeled "comfortable" and "preferred" with Mortimer's data in Figure 1. From this figure we see that Mortimer's drivers equaled or exceeded 0.266 g for less than 10% of the brake applications, pointing up a substantial descrepancy between the objective and subjective measurements, particularly those that use subjects having expertise in the area being investigated.

In a later study, Loach [13]conducted exploratory tests on a two-car electric train and an electric trolley bus. The subjects used were the 12 members of the Track Committee of the Railway Executive of British Railways. For both vehicles, the subjects sat on longitudinally oriented seats, or stood. No details are given as to the type of acceleration or deceleration profile used, except that the driver "endeavored to accelerate or decelerate at a constant rate." The average judgements of the subjects are given in Table 8 for seated subjects in the electric train. Apparently, the subjects were in fact experiencing lateral acceleration and deceleration because of the seating arrangement, which may account for the relatively low acceleration values reported. Loach reports that in one or two tests with the subjects standing in unspecified orientation, evaluations showed that .10 g was the approximate limit that could be attained without discomfort and that .123 g was somewhat uncomfortable. Results of deceleration tests with the trolley bus are "pooled," containing evaluations of both sitting and standing subjects, and are given in Table 9. No explanation is

TABLE 7.

EVALUATION OF 70 MPH STOPS IN AUTOMOBILES
AT GM PROVING GROUND
(AFTER WILSON [6])

	Evaluation+ or Condition*	Average Deceleration (g)
+1.	Comfortable to Passenger, Preferred by Driver.	0.266
+2.	Undesirable, but not alarming to Passenger; Driver would rather not use.	0.343
*3.	Design Deceleration for Pennsylvania Turnpike	0.401
+4.	Severe and Uncomfortable to Passengers, Slides Objects off Seats. Driver Classes as an Emergency Stop.	0.432
*5.	Maximum Stop, Car Stays in a 12-Foot Lane with-out skidding. Brakes in Best Condition.	0.606

TABLE 8.

EVALUATION OF ELECTRIC TRAIN MOTIONS

(AFTER LOACH [13])

Evaluation	Acceleration or Deceleration (g)
Just Noticeable	.046
Noticeable	.059-.068
Pronounced but not Objectionable	.091
Quite Pronounced but not at all Uncomfortable	.105-.114
Strong and Slightly Uncomfortable	.127
Rather Uncomfortable	.155

TABLE 9.

EVALUATION OF TROLLEY BUS MOTIONS

(AFTER LOACH [13])

Evaluation	Deceleration (g)
Pronounced and Barely Comfortable, especially when there had been a rapid increase in the deceleration to that value	.182
Somewhat Uncomfortable	.228
Uncomfortable	.273

given by Loach for the lack of lower acceleration levels in the trolley bus test, for the changes in subjective evaluation titles between the train and bus tests, or for the apparent discrepancies in the results of the two tests. Moreover, although jerk was not measured, Loach states that a given deceleration was more easily withstood when lower values of jerk were used.

A more thorough series of studies have been conducted by various investigators connected with the Japanese National Railways (JNR) [14, 16, 17, 18, 19]. The first three of these are related, and Gebhard [1] has summarized the descriptions used for a five-category rating scale, given in Table 10. The 1960 report by Matsudaira [14] covered a preliminary test using 20 engineers connected with the JNR, whereas his 1962 report [16] apparently covers the same tests as those described in more detail by Matsui [17], in which approximately 40 college students were used. Accordingly, the slight variability in wording between the second and third columns of Table 10 could be due to anomalies in translation from Japanese to English. On the other hand, the substantial differences in descriptors in the first column from those of the other two could not likely be attributed solely to translation problems and it is evident that the meanings are very different for some of the categories. In the first study, using the 20 JNR engineers or subjects, Matsudaira [14] found that starting accelerations up to 0.15 g fell in Ride Index 3 (Table 10) or below for seated passengers, although evidently seats were oriented both laterally and longitudinally. In deceleration tests, judgements of seated and standing passengers were pooled, and most subjects rated decelerations between 0.16 and 0.18 g under Ride Index 4.

For the second series of tests reported by both Matsudaira [16] and Matsui [17], we follow the latter because of the detail available. Approximately 40 volunteer male students from two universities were used as subjects. Attempts were made to assess independently the effects of constant deceleration, called R tests for "retardation," and constant jerk, called J tests. The deceleration profile used was similar to the three-phase profile used by Browning for acceleration in Figure 4, except that only the constant acceleration level in the second phase and the jerk level in the final phase were controlled and held constant. The initial jerk phase was not controlled. All tests were conducted with an

TABLE 10.

DESCRIPTORS USED FOR JUDGEMENTS ABOUT
ACCELERATION AND DECELERATION IN JNR TESTS
(AFTER GEBHARD [1])

Ride Index	Investigator		
	Matsudaira [14] Acceleration and Deceleration	Matsudaira [16] Deceleration	Matsui [17] Deceleration
1	Insensible	Insensible	Not Noticeable
2	Just Sensible	Just Sensible	Just Noticeable
3	Sensible, but not Uncomfortable	Noticeable	Remarkable
4	Somewhat uneasy	Slightly Uncomfortable	A bit Uncomfortable
5	A little Uncomfortable	Very Uncomfortable	Quite Uncomfortable

initial speed of 70 kph in a special passenger car of a two-car train. An audible signal was given during the second phase of constant deceleration so that raters could concentrate their attention on either the constant value of deceleration or the constant value of J in the third phase, according to which category of test, specified beforehand, was being conducted. Raters were told to close their eyes before the first phase and open them 30 seconds after the car had stopped. Standing raters could use overhead hand straps and faced sideways with feet 30 cm apart. The form used for the evaluation actually provided for a contiuum of evaluations in which the ride index number in Table 10 marked only the upper boundaries of the categories described. That is, for example, a rater could check anywhere between 2 and 3 on the scale to fall in Ride Index 3. Results were presented of ride index averages for various postures plotted versus either accbleration for R tests or log of jerk for J tests. Altogether, 169 tests were made, producing 7000 ratings. During R tests, the final jerk value was held constant and five values of deceleration, randomly chosen, were used. For jerk tests, four values of jerk were used, each with two different levels of constant deceleration. Under a fixed condition of rater's posture in each of the R and J test series, the same combination of constant deceleration and constant jerk appeared at least three times. Matsui presents the most useful condensation of all this data to be that shown in Table 11. He considers Ride Index 3 as the limit for normal service braking and Ride Index 4 as the limit for emergency braking. Each of the tabular values represents either the acceleration (jerk) for the Mean Ride Index shown, or the acceleration (jerk) for the mean index plus one standard deviation (S.D.) in Index. Observe that for side facing, sitting passengers, all acceleration values for both ride indices are considerably higher than Loach's values in Table 8 under the headings "Quite Pronounced but not at all Uncomfortable" and "Strong and Slightly Uncomfortable." Moreover, quick computation shows that the side-facing, standing passengers apparently tolerated higher accelerations and jerks in Ride Index 3 than those recommended by Browning for fit adults in Figure 4, although Browning's subjects were likely facing forward without overhead straps. On the other hand, Hirshfeld's average attained accelerations of 0.19 and 0.23 g for side-facing standees and front-facing standees using straps, respectively, in Table 6, correlates well with

TABLE 11.

DECELERATION AND JERK EVALUATIONS
(AFTER MATSUI [17])

	Sitting Front-faced	Sitting Rear-faced	Sitting Side-faced	Standing Side-faced
R-Tests Deceleration (g)				
Ride Index 3				
Mean = 3	.19	.19	.16	.15
Mean + S.D. = 3	.14	.13	.13	.11
Ride Index 4				
Mean = 4	.3	.3	.2	.2
Mean + S.D. = 4	.22	.19	.18	.17
J-Tests Jerk (g/s)				
Ride Index 3				
Mean = 3	1.2	1.7	0.5	2.0
Mean + S.S. = 3	0.3	0.3	0.12	0.12
Ride Index 4				
Mean = 4	10.0	10.0	10.0	10.0
Mean + S.D. = 4	1-2	3-4	1-2	2-3

Ride Index 3: "Remarkable"

Ride Index 4: "A Bit Uncomfortable"

Matsui's mean of 0.2 g under Ride Index 4 for side-facing standees. Finally, for front-facing, seated passengers, the value of 0.14 g under Ride Index 3 was equalled or exceeded by Mortimer's [7] drivers 40-50% of the time (Figure 1).

In perhaps the most detailed subjective study, reported briefly by Matsudaira [18], and later in more detail by Urabe and Noruma [19], three categories were used to obtain passenger evaluations: (1)"Sensation," with four levels: "No feeling," "Indistinct feeling," "Distinct feeling," and "Strong feeling"; (2) "Mood," with a continuum scale ranging from, 0 labeled "Comfortable" to, 5, labeled "Uncomfortable." The continuum was scored in five levels by scoring "0" for all marks between 0 and 1, "1" for all marks between 1 and 2, etc.; (3) "Judgement," with two levels labeled "Permissible comfort" and "Not Permissible discomfort." The subjects consisted mainly of approximately 50 college students [18], supplemented with "some" JNR employees [19], number unspecified. The investigators conducted deceleration tests, starting at approximately 70 kph and using a three-phase deceleration profile, in which the first and third phases had constant jerk controlled at different values. The study was apparently designed to obtain passenger ratings in each of the categories above for various combinations of posture, initial jerk-phase value, constant deceleration value, and final jerk-phase value. It is unclear, however, what different acceleration and jerk values actually were used. Evidently, the critical parameters were found to be deceleration and final jerk values. Tables 12 and 13 give the main results, and it should be noted that all seated passengers faced sideways, thus experiencing lateral deceleration. Table 12 presents data on the "Sensation" category, and gives percentages of subjects who had "Strong feelings" for the deceleration and final jerk values indicated. Table 13 gives data in the "Judgement" category, for "Not Permissible discomfort." Observe that at the lower end of the rater population deceleration and jerk values judged "Not Permissibly Uncomfortable" are lower than those "strongly felt." The opposite holds at the high end of the rater population. It can be seen that tolerance to deceleration and jerk values are greater in a crowded, seated position and least when standing facing backward. Moreover, subjects who feel decelerations strongly do not necessarily rate them as unacceptably uncomfortable.

The most recent study available, by Cussik and Mooring [15], was conducted

TABLE 12.

CONSTANT DECELERATION AND FINAL JERK VALUES
MARKED "STRONG FEELING" BY THE INDICATED PERCENTAGES OF RATERS [19]

Percent of Raters	Deceleration (g)										Jerk (g/s)									
	0	5	10	20	30	40	50	60	80	100	0	5	10	20	30	40	50	60	80	100
ncrowded Sitting ideways	.122	.125	.127	.133	.139	.147	.156	.164	.181	.204	.074	.077	.082	.091	.099	.108	.119	.130	.158	.187
rowded Sitting ideways	.136	.139	.142	.147	.156	.164	.170	.178	.195	.218	.085	.088	.093	.102	.113	.125	.136	.150	.181	.224
tanding Facing orward	.113	.116	.119	.127	.133	.142	.150	.158	.175	.198	.054	.057	.062	.071	.079	.088	.099	.113	.142	.184
tanding Facing ackward	.085	.088	.091	.096	.102	.108	.113	.122	.139	.158	.057	.059	.062	.071	.076	.085	.093	.105	.125	.153

TABLE 13.

CONSTANT DECELERATION AND FINAL JERK VALUES

MARKED "NOT PERMISSIBLY UNCOMFORTABLE" BY THE INDICATED PERCENTAGES OF RATERS [19]

Percent of Raters	Deceleration (g)										Jerk (g/s)									
	0	5	10	20	30	40	50	60	80	100	0	5	10	20	30	40	50	60	80	100
Uncrowded Sitting Sideways	-	.085	.105	.130	.150	.164	.175	.187	.207	.221	-	.068	.091	.122	.147	.451	.184	-	-	-
Crowded Sitting Sideways	-	.096	.119	.142	.161	.175	.187	.198	.215	.226	-	.074	.091	.113	.127	.139	.147	-	-	-
Standing Facing Forward	-	.079	.096	.119	.130	.142	.153	.158	.173	.184	-	.074	.091	.113	.127	.139	.150	-	-	-
Standing Facing Backward	-	.071	.076	.091	.102	.110	.116	.122	.133	.139	-	.027	.040	.059	.028	.091	.102	.113	.136	-

as part of a program for the development of new urban transportation systems. Four prototype "Personal Rapid Transit (PRT) Systems" developed by different companies were tested in conjunction with an exhibition called "TRANSPO '72" at Dulles International Airport, Washington, D. C. Apparently, all subjects were seated but the seating arrangements varied among the vehicles. The investigation employed 94 "normal" subjects drawn from the staff of the Johns Hopkins University, Applied Physics lab, none of whom was engaged in transportation-related work. Detailed statistics on each subject were collected and care was taken to insure statistical representation of the general population in each rating group. In addition, 12 transportation specialists, called "experts," were used as subjects. All were male engineers or technicians ranging in age from 25 to 50 years old. Cussik and Mooring [15] report that although detailed physical measurements and subjective responses were recorded and remain available, only limited and inconclusive data analysis was done. In fact, the authors list references to 42 magnetic data tapes on ride quality alone. Only a sample of the subjective reactions was chosen for correlation with measured acceleration and jerk, and only for two of the vehicles did the sample deal with longitudinal acceleration and jerk. Vehicle I had 12 side-facing seats, such that subjects experienced longitudinal accelerations as lateral accelerations. Vehicle II had six side-facing seats, three forward-facing seats, and three backward-facing seats, but the data presented is averaged over all passengers. Moreover, in the limited data available, given in Table 14, it is unclear whether the "mean judgement" included the "experts" as well as the "normals." The evaluation scale used was as follows: 0 (not detectable), 1 (barely noticeable), 2 (clearly noticeable), 3 (strong), and 4 (violent). It is unclear whether the starts and stops in Table 14 were of the three-phase type discussed earlier, and no information is given as to what points in the starting and stopping transients correspond to the acceleration and jerk values listed. The values given were "manually scaled from the acceleration records, care being taken to exclude extremely sharp peaks (those that peaked in less than about 0.1 record)." Cussik and Mooring note that the judgement for Vehicle I on stopping appears high when compared with the other data, but no explanation is given.

In addition to the limited comfort data, Cussik and Mooring present a com-

TABLE 14.

RIDE COMFORT SUMMARY FOR TWO PRT VEHICLES
(AFTER CUSSIK AND MOORING [15])

Vehicle and Condition	Longitudinal Acceleration or Deceleration (g)	Longitudinal Jerk (g/sec)	Mean Judgement
I Start	0.17	0.25	Between "barely" and "clearly noticeable (1.5)
I Stop	0.16	0.17	Between "clearly noticeable" and "strong" (2.3)
II Start	0.18	0.15	"Barely noticeable" (1.0)
II Stop	0.17	0.20	Between "barely" and clearly noticeable" (1.2)

parison between ratings of the male "experts" and those of the male "normal" subjects. No values are given for the acceleration and jerk corresponding to the mean ratings, shown in Table 15, in which the scale used was the same as that for Table 14. Observe that in all but one test, the "experts" rated the condition less severe than the "normals" and the differences in ratings are substantial for most of the conditions for Vehicle I, in which all seated subjects faced sideways.

TABLE 15.

RIDE QUALITY COMPARISONS OF "EXPERTS" AND "NORMALS"
(AFTER CUSSIK AND MOORING [15])

Vehicle and Condition		Mean Judgement	
		Male "Normal"	Male "Experts"
I	"Jerk" at Start 1	1.7	1.2
	"Jerk" at Start 2	1.7	1.1
	"Jerk" at Start 3	1.5	0.9
I	"Jerk" at Stop 1	2.3	1.9
	"Jerk" at Stop 2	2.2	1.6
	"Jerk" at Stop 3	2.3	1.5
II	"Jerk" at Start 4	1.0	0.9
	"Jerk" at Start 5	1.0	1.1
II	"Jerk" at Stop 4	1.2	0.8
	"Jerk" at Stop 5	1.3	0.8

PART II

CONCLUSION

It is tempting to provide, as Gebhard [1] has done, a summary table of jerk and acceleration values that might be taken as "nominal" or "acceptable" for various types of vehicles and conditions. Certainly, for public mass transport, steady non-emergency accelerations in the range 0.11 g to 0.15 g fall in the "acceptable" range for most studies, and could be larger. It is unlikely that values of jerk larger than 0.30 g/sec would be acceptable for most public transportation. Beyond this, however, the available results on comfort do not provide a satisfactory basis for choosing any particular acceleration-jerk profile in preference to any other. The wide variability in method and type of results sought precludes a useful condensation of results. There appears to be extreme sensitivity in the results to the environmental and test conditions and no study has specifically addressed whether or not the results obtained are repeatable. Moreover, the effect of different populations on test results has not been adequately reported, and difficulties with subjects who "learn" the test during the experiment leave questions about reliability of the results. In addition, although the International Organization for Standards [20] has specifically included different comfort limits for different durations of exposure to whole-body vibration, none of the studies surveyed here addressed the question of how the extent and the duration of a test affected results. In fact, no studies have been found that examined passenger response to frequency of start-stop motions, such as occur in short-haul transportation systems. All studies found delt essentially with single-transient tests.

Finally, no large-scale studies have been found that show how well objective or subjective test results correlate with ridership in actual transportation systems.

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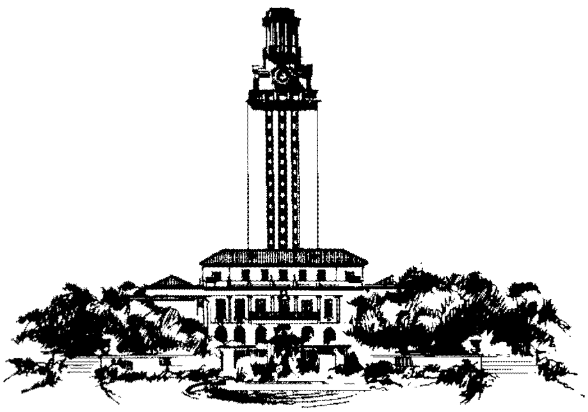

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