# NCTA TECHNICAL REPORT

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# COMPARISON OF NOISE AND VIBRATION LEVELS IN RAPID TRANSIT VEHICLE SYSTEMS

Report by

OPERATIONS RESEARCH INCORPORATED

April 1964

National Capital Transportation Agency
[illegible] Eye Street, N.W., Washington, D.C. 204[illegible]

Operations Research Incorporated
1400 Spring Street, Silver Spring, Maryland, 20910
Telephone: 588-6180, Area Code 301

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C. E. KEISER

1 - Copy given to Clark

15 May 1964

Mr. Charles E. Keiser
General Superintendent of Engineering
Chicago Transit Authority
Merchandise Mart Plaza
Chicago 54, Illinois

Dear Mr. Keiser:

On behalf of the National Capital Transportation Agency and Operations Research Incorporated, I wish to express appreciation for your generous cooperation in placing at our disposal the train and other facilities for the noise and vibration measurement program completed early in 1963. We appreciate very much the time and effort you and your staff gave the survey team during our visit.

I am enclosing two complimentary copies of the final report prepared by Mr. Davis. This report presents the results of the noise and vibration survey for all the cities where measurements were taken. We hope you find it interesting and useful.

Sincerely,

OPERATIONS RESEARCH INCORPORATED

E. W. Marlowe

E. W. Marlowe
Program Director

Enclosure
EWM:lg

Santa Monica • 225 Santa Monica Boulevard, Santa Monica, California, 90401

# COMPARISON OF NOISE AND VIBRATION LEVELS IN RAPID TRANSIT VEHICLE SYSTEMS

by

Edward W. Davis

Contributions by
M. J. Zubkoff

April 1964

*Prepared by*
Operations Research Incorporated
Silver Spring, Maryland
Technical Report 216

Operations Research Incorporated
1400 Spring Street, Silver Spring, Maryland, 20910
Telephone: 588-6180, Area Code 301

April 6, 1964

National Capital Transportation Agency
1634 Eye Street, N.W.
Washington 25, D.C.

Dear Sirs:

In accordance with contract NTA-36, we are submitting Technical Report 216 entitled, "Comparison of Noise and Vibration Levels in Rapid Transit Vehicle Systems," in fulfillment of Task 1.4.

Yours truly,
OPERATIONS RESEARCH INCORPORATED

Harold O. Davidson
Vice President
Director, Logistics and Operations Division

HOD:kaf

Santa Monica • 225 Santa Monica Boulevard, Santa Monica, California, 90401

# FOREWORD

This year marks the centennial of the world's first rapid transit system, opened for service in London on January 10, 1863. In subsequent years the original London Underground was greatly expanded, and similar systems were constructed in other major cities. Following this initial period of development there was, however, a marked decline in new construction. The resultant contraction of the market for equipment inhibited investments in the improvement of transit technology at a time when advancing automotive technology was exerting its full impact on urban transportation. In this climate it might have seemed reasonable to suppose that the whole concept of rail passenger transportation was inadequate to modern needs and destined for the graveyard of archaic technologies. In any case this view gained considerable credence in the United States, and was at least partially correct.

Expanding automobile traffic created increasing interference with, and was itself inhibited by, the particular form of rail transportation known as electric street railways, streetcars, or trams. A majority of these systems were therefore abandoned in favor of motor buses, which are much better adapted to operation in mixed vehicle traffic on general thoroughfares. The functional obsolescence of rail technology for this particular application had no bearing at all on its suitability for high-capacity, exclusive right-of-way elements of urban transportation systems, although it did inhibit the advancement of the technology.

It is significant in this regard that although many cities replaced their streetcar services with motor-bus lines, no cities abandoned their rapid transit systems despite the fact that the older systems were built to standards of performance and comfort that are now considered obsolete. On the contrary, investments in the expansion and modernization of older transit systems have been made in Paris, London, Berlin, Hamberg, Stockholm, Moscow, Leningrad, Chicago, New York, Philadelphia, Osaka, and Tokyo. Moreover, in the same period entirely new transit systems have been or are being constructed in Barcelona, Cleveland, Vienna, Montreal, Nagoya, Oslo, Rotterdam, San Francisco, and Toronto. In addition some cities (Stuttgart, for example) are partially relocating remaining streetcar lines to newly constructed exclusive rights-of-way as the first stage of a conversion into modern rapid transit systems.

The current expansions and new constructions of rapid transit systems are too numerous to be dismissed as a series of accidental circumstances contrary to a general trend. They seem, rather, to define a new trend—a technological renaissance of rail passenger transportation. The extent to which modifications of, or major departures from the established technology may be required in the application of basic rail transit concepts to meet modern standards of speed, comfort, and convenience has not, however, been entirely clear. In particular, a major question has arisen in connection with the promotion of a transit vehicle design, currently used in the Paris Metro system, which departs from the steel-wheel and rail technology of vehicle support and guidance.

To begin with it should be noted that there is no a priori reason for assuming that the idea of supporting a transit vehicle with steel wheels rolling on steel rails is inadequate for modern applications. Whoever thinks otherwise should reflect on the fact that the wheels of his automobile turn quietly and smoothly on their axles by virtue of steel wheels rolling on steel surfaces, i.e., roller bearings. In regard to speed, note that the maximum normal operating speeds attained by steel-wheel and rail vehicles exceed by a wide margin the performance of any other form of public surface transportation vehicle, and the now "obsolete" PCC-type streetcar had an acceleration well above that of contemporary motor buses.

In the absence of objective evidence, however, there has been a persistent body of opinion that contemporary applications of the basic steel-wheel and rail concept cannot satisfy modern standards of quietness and ridability, and that it is therefore necessary to adopt a major departure in transit technology. Impelled by this conviction, officials of the Paris Metro transit system and a group of French manufacturers set out to develop pneumatic-tired vehicles, and succeeded—albeit at the expense of a more complicated vehicle running gear and track system.

Despite the impression of demonstrated superiority of the pneumatic-tired vehicle conveyed by press reports,* no substantial evidence has ever been developed that allowed a comparison of its characteristics with those achieved by other engineering development groups (in Europe, principally, but also in North America and Japan), which had devoted equally competent technical efforts to improved applications of the simpler steel-wheel and rail concept. Thus, although transportation planners might delight in the rich variety of alternative designs emerging from this technological renaissance, they have had equal reason for despair in the poverty of information for choosing among them.

Recognizing the inadequacy of existing information on noise and vibration levels in contemporary transit systems, the National Capital Transportation Agency judged that it should acquire such objective evidence as could be obtained at reasonable cost to support the Agency decisions. Although the investigations were specifically designed to satisfy the information requirements of the National Capital Transportation Agency, these requirements are basic to any system's planning project. Therefore, the results should be of interest and value throughout the industry.

Harold O. Davidson
Vice President
Director, Logistics and
Operations Division

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* For example, TIME Magazine, June 29, 1963, p. 80, and The Washington (D.C.) Post and Times Herald, August 5, 1963, p. B1.

# ACKNOWLEDGMENTS

The National Capital Transportation Agency furnished an engineer who participated as an active member of the field engineering party, and contributed significantly to the effort.

Bolt, Beranek, and Newman, Inc., Cambridge, Massachusetts, provided professional service and equipment support to the project for data collection and initial data reduction.

Grateful appreciation is extended the following organizations, who participated in this study by generously donating equipment, personnel, and information and without whose cooperation this study could not have been accomplished.

AB Stockholms Sparvagar
Azienda Tranviaria Municipale, Milan
Berliner Vekehrs - Betriebe Gesellschaft
Budd Company, Philadelphia
Chicago Transit Authority
Hamburger Hochbaln, A. G.
International Union of Public Transport, Brussels
Kiepe Vertriebsgesellschaft, M.B.H., Dusseldorf
Metropolitano de Lisbon
Metropolitan Transit Authority, Boston
Patentes TALGO, S. A., Madrid
Philadelphia Transportation Company

Regie Autonome des Transports Parisiens, Paris
Schindler Wagons S. A., Switzerland
Societe Generale de Traction et d'Exploitations, Paris
Societa per la Strada Guidata, Milan
SOREFRAME Mfg Co., Lisbon
Toronto Transit Commission
Waggonfabrik Uerdingen, Dusseldorf

The contribution of the following organizations is also acknowledged:

ASEA, Sweden
Brown Boveri Company, Switzerland
Berlin Oberbaurat
Foreign Operations Limited, New York
New York City Transit Authority

# SUMMARY

## PROBLEM

1. The National Capital Transportation Agency (NCTA) has been assigned by the Congress of the United States the responsibility for design and implementation of a rapid transit system to serve the National Capital Region (NCR). It is hoped that construction of the system will begin in 1964 and initial operations will be started in 1968.

2. In support of the NCTA program, Operations Research Incorporated was given the task of conducting measurements of vibration and noise levels to which passengers are subjected on existing rapid transit systems. As part of the task it was necessary to carry out an extensive field measurement program on rapid transit systems in the USA, Canada, and Europe.

### Specific Objectives

3. This report presents the results of a study of rapid transit vehicle noise and ridability, undertaken to fulfill a need for basic data on these characteristics of existing rapid transit systems. The objective of this study was to obtain noise and ridability data which might be helpful in setting vehicle design criteria. A secondary objective was to determine the relative quietness and ride smoothness of rubber-tired and steel-wheeled rapid transit vehicles to assist in the comparison of these systems.

## SCOPE

4. To accomplish the study objectives, it was necessary to undertake a field measurement program. This involved the selection of instrumentation for the measurements and the design of a suitable test procedure to collect the information on a comparative basis. It also required the enlistment of operating transit agencies in the USA, Canada, and Europe for participation in the tests.

5. During the course of the study some 13 field tests were conducted. Measurements were made inside rail transit vehicles in Berlin, Hamburg, Lisbon, London, Paris (rubber-tired vehicle), Stockholm, Toronto, Boston, Chicago, New York, and Philadelphia. In addition, data were collected in a modern city bus operating on the streets of Washington, D.C., and in one of the original TALGO passenger trains near Madrid, Spain. A new rubber-tired vehicle being tested in Milan, Italy, was also inspected.

6. The standard test procedure followed throughout the study involved the simultaneous measurement of noise and vibration in the interior of a train of vehicles operating at controlled speeds on sections of straight level track in subway. Because the study was oriented towards passenger comfort, no consideration was given to noise and vibration at points away from the vehicles. Noise in underground stations is included, however, because of its relation to passenger opinion of system quietness.

## LIMITATIONS

7. The vehicle analysis is limited to a comparison of noise and ride smoothness for conditions of subway operation at speeds of 15 mph and 30 mph. Some data are also presented for higher speed conditions in those cases where such data could be obtained.

8. All comparisons are presented on a vehicle-system basis; that is, one vehicle operating on its particular roadbed is compared with other vehicles operating on their respective roadbeds. The results do not indicate how a particular vehicle will rank when operated on a roadbed or type of track construction other than its own. However, sufficient data on track and roadbed are presented to permit some general cross-predictions.

## FINDINGS

### Noise

9. Significant differences in loudness were measured among existing rapid transit systems. The relative average loudness levels, in phons, derived from the measurements made in this survey on various rapid transit trains running underground at 30 mph were:

| | |
|---|---|
| Philadelphia | 103 |
| New York | 98 |
| Chicago | 98 |
| Boston | 97 |
| Lisbon | 97 |
| London | 93 |
| Stockholm | 92 |
| Toronto | 90 |
| Paris (Rubber-tired) | 89 |
| Hamburg | 87 |
| Berlin | 85 |

The systems in the United States were found to comprise the loudest group. This is significant because it represents the total experience of the majority of United States residents with rapid transit systems. They do not have the opportunity to compare the quieter rapid transit systems with other modes of travel, and their attitude toward rapid transit is influenced adversely.

10. No significant advantage in quietness was found for rubber-tired systems over the best steel-wheeled systems. Lowest noise levels inside steel-wheeled vehicles were measured inside vehicles in Berlin, Hamburg, and Toronto. The noise levels measured inside these vehicles in subways were found to be no higher than those inside the Paris rubber-tired vehicle in subway as well as those inside a modern bus operating on open expressway.

11. The lowest noise levels in underground stations during train arrival and departure were measured in Berlin and Toronto, and were lower than those measured for the Paris rubber-tired vehicle. Station noise during periods of train movement in these three systems was found to be less than the background noise of city traffic on open streets.

### Ride Smoothness

12. Two separate sets of measurement equipment were used to collect vibration data simultaneously. Three analysis methods were

employed in evaluating the results, using passenger comfort criteria developed by various researchers. The results of each analysis were cross-compared to determine those systems judged best by all three techniques. These were:

- Hamburg
- Stockholm
- Chicago
- Toronto

Systems giving average ridability characteristics were:

- London
- Paris (Rubber-tired)
- Berlin
- Washington, D. C. (Transit bus)
- Lisbon

The systems giving below average ridability characteristics were:

- Boston
- Paris (Steel-wheeled)
- New York
- Philadelphia
- Lisbon
- TALGO

A number of qualifications that must be attached to these ratings are discussed in the body of the report. Despite incomplete data sets, there is evidence that Berlin also should belong to the "best" group.

13. Complete correlation of the vibration data collected (and of the noise data) with the design, construction, and maintenance factors influencing them was beyond the scope of this study. However, an attempt is made to correlate some observed system conditions with measurement results. Enough information is presented herein to permit identification of these systems judged consistently best in all respects, so that the field has been narrowed to a small number for further investigation.

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# I. INTRODUCTION

## OBJECTIVES AND SCOPE OF REPORT

1.1 This report presents the results of a study of rapid transit vehicle noise and ridability undertaken with the general objective of obtaining comparative data on noise and vibration levels inside rapid transit vehicles operating on existing systems in the USA, Canada, and Europe.

1.2 Comparative noise and ride data on existing rapid transit vehicle systems were virtually nonexistent; comparisons heretofore have generally been made on the basis of subjective opinion formed during rides in vehicles in scheduled service, irrespective of differences in operating speed, train length, etc. As a result, there exists much confusion about the extent of actual differences among systems and about the value of certain features in particular systems. This study was undertaken as a first step towards the identification of those systems having superior ride characteristics and low noise levels.

1.3 To obtain data that could be used for identification of real differences among systems, it was necessary to undertake a field measurement program. This involved the selection of instrumentation, the design of a standard test procedure to be repeated in each system, and the enlistment of the cooperation of operating transit agencies in the USA, Canada, and Europe.

1.4 During the course of the study, a wide variety of data was collected on vehicle systems, both old and new. The majority of operating rapid transit systems in North America and Europe were included in the measurement program, and general data on each of the systems tested, along with specific data on the vehicles tested, are included in Section III.

1.5 Another objective of the measurement program was to obtain noise and ride data on rubber-tired systems in a manner suitable for comparison with conventional steel-wheeled vehicles operating on steel rails. In accomplishment of this objective, measurements were made inside the Paris Metro rubber-tired subway vehicle and inside a modern diesel bus operating in the Washington, D. C., area.

1.6 Because this study was oriented towards passenger comfort in moving vehicles, no consideration was given to noise and vibration levels measured at points distant from the vehicles. However, station noise during train arrival and departure may contribute significantly to passenger opinion of system quietness. Since this type of noise is most difficult to control in underground locations, it was included in the study.

1.7 An attempt has been made in this report to compare the noise levels encountered by the passenger in modern rapid transit vehicles with the noises encountered on city streets and in other transport vehicles. In some cases this is done by comparison with data obtained by other researchers. A general comparison of transit vehicle ride smoothness with other forms of transportation is not attempted. However, a limited comparison of rubber- and steel-wheeled systems is afforded by the data presented on the two rubber-tired systems.

## NOTES ON COMFORT MEASUREMENT

1.8 Noise and ride smoothness are obviously only two of the several factors that combine to give an overall impression of "comfort" to the passenger.

1.9 As normally discussed in vehicle riding, comfort involves such factors as heating, lighting, seating, noise, and vibration. In addition, the discomfort produced by acceleration and braking, as well as vehicle behavior on curves, affects the opinion of the passenger about the comfort of his trip.

1.10 Because the judgment of comfort is a complex subjective decision process based on reaction to the combination of factors just mentioned, the measurement of comfort in quantitative terms is extremely difficult and has not been accomplished in 31 years of vehicle ride research.

1.11 It is generally recognized, however, that noise and ride smoothness are two of the more important factors influencing passenger opinion of ride comfort. The relative importance of these two factors to each other is not known, nor is it possible to judge, except on a qualitative basis, the combined effect of both.

1.12 It is possible to measure each factor separately, rank the results using known human response criteria, and judge the combination on a qualitative basis. This is the approach taken in this report.

1.13 Noise measurements were made inside moving vehicles simultaneously with the recording of vibration levels, using two separate sets of measuring equipment. The noise data are evaluated independently of the vibration data, and the systems ranked in terms of quietness. Likewise, ridability data are evaluated separately, and the systems ranked in terms of ride smoothness. Then, those systems ranked as consistently superior or consistently poor in both quietness and ride smoothness are identified, and the reasons explored. Finally, those systems characterized by differences in ranking of quietness and ridability are identified, and the significance of these differences is examined.

## STUDY LIMITATIONS

1.14 In setting the scope of this study to include a large number of systems, both European and North American, it was necessary to limit the amount of data collected on each system. It was physically impossible, within the time allowed, to obtain data on every factor contributing to noise and vibration inside the vehicle.

1.15 For example, it was not possible to obtain either a quantitative or a consistent measure of the contribution made to ride smoothness by track and roadbed condition. An attempt was made to minimize the effects of difference in track condition among the various systems by always obtaining data on sections judged by the host agency as being among the best in that system. In some cases, the contribution of the roadbed is apparent in the measurement results, in others it is estimated, based on the best available information.

1.16 In the absence of quantitative data on track condition, the system comparisons presented in this report are on a "vehicle-system" basis, where vehicle system is defined as a particular vehicle operating on a particular roadbed. Thus, the measurement results obtained in the Hamburg vehicle operating on its roadbed can be compared with the results obtained in the Stockholm vehicle operating on its roadbed. However, similar results for the Hamburg vehicle might or might not be obtained on the Stockholm roadbed.

1.17 Because the problems of noise and vibration control inside the vehicle are normally greatest for conditions of subway operation, the measurement program was limited to conditions of subway operation only, except in the case of the city bus. The range of test speeds was limited to a low speed of 15 mph and a high speed of 30 mph, and these two speed conditions were met in the majority of cases. In some cases data were also collected at higher test speeds, as supplementary information. The implication of the limitation on maximum test speed is discussed in Section II.

1.18 It is recognized that passenger opinion of ride quality and comfort is influenced by a large number of environmental factors (lighting, heating, etc.) in addition to the behavior of the vehicle on straight track, curves, grades, and at stations. The work done in this study is a logical first step towards a complete comparison of all aspects of vehicle ride comfort. The measurements were made on sections of straight, level track to permit interpretation of the data by methods generally accepted for judging vehicle ride comfort. The behavior of vehicles on curves is not necessarily disclosed by the measurement results on straight track. Therefore, the next logical step in the measurement of overall ride comfort would be the development of instrumentation and methods of analysis for comparing vehicle comfort on curves.

# II. DESCRIPTION OF TEST PROCEDURE

## STUDY CONSTRAINTS

2.1 The constraints imposed on the data-collection phase of this study were numerous and exacting. Most limiting, of course, were the cost constraints, which dictated that the data collection and analysis be carried out in the shortest possible time and at the least possible cost. Secondly, the constraints imposed by the measurement equipment had an effect on the design of the experiment and the data analysis method. Thirdly, the constraints imposed by line geography and operating procedures in each of the systems to be measured influenced the amount of data that could be collected and also the design of the experiment.

2.2 The study had to be designed so that data could be collected in a similar manner on a variety of systems in the least possible time and with a minimum of inconvenience to the cooperating agency. This meant that the measurement equipment had to be highly portable, have its own power source, and require a minimum of setup time. It also meant that the test had to be designed to permit collection of data in a train operating in normal traffic during normal working hours.

2.3 In the face of these constraints, the overall requirement of the study was, of course, that it produce a valid indication of the ride smoothness and noise levels encountered in each particular vehicle system. By "vehicle system" is meant a specific combination of vehicle and roadbed. For example, the study results should permit a comparison of the Paris vehicle on its particular roadbed with the Berlin vehicle on its particular roadbed.

## MEASUREMENT EQUIPMENT

2.4 The first major problem encountered in this study was the selection and procurement of instrumentation for the measurements. Existing equipment for vibration measurement did not meet the requirements of weight and mobility imposed by the objectives of this project. In particular, the power requirements of most vehicle-ride measurement instrumentation were considered prohibitive because of the inclusion of European systems in the measurement program. The Ride Recorder, a spring-driven mechanical device that records on a roll the approximate acceleration in three directions, has been used by some railroads and manufacturing companies for making comparative riding tests. This device has lower frequency response and accuracy than was desired for these measurements. However, it was found to give a good "feel" for the relative ride smoothness of different vehicles. One of these devices was donated by the Budd Company, calibrated by the maker, and was used throughout the study as a supplementary source of data.

2.5 In a pilot study described below, the use of portable magnetic tape recorders to record both noise and ride data was tested and proved feasible. Tape recorders have been used, of course, for some time in noise control studies, but applied only recently to the problem of vibration measurement in the lower frequency ranges (below 20 cycles per second). The technique calls for special amplifiers, electric accelerometers, and laboratory analysis equipment. In addition, it is necessary to record the data at a very slow speed and replay the tapes at a higher speed in the laboratory, which has the effect of reducing the length of data sample available for analysis. A minimum test run length of 60 sec was required to ensure sufficient length for accurate analysis after the speed scaling.

2.6 It was recognized that this constraint would influence the design of the test and might limit the range of test speeds that could be included in the measurement program. For reasons already explained, the tests were to be limited to conditions of subway operation only. However, in most rapid transit systems the station spacing on underground sections of line is such that a 60-sec run at high speed is not possible without running through stations, after allowing for acceleration time.

PILOT STUDY

2.7 In conjunction with Bolt, Beranek, and Newman, Inc. of Cambridge, a pilot study of noise and vibration measurement was made on a branch of the Boston Metropolitan Transit Authority (MTA), which very generously provided a special test train and crew for this purpose. Figure 1 shows the equipment setup during the Boston pilot study. Because of the 60-sec test run requirement, it was necessary to carry out this pilot study on a section of elevated track where the maximum test speed could be safely maintained between stations and curve speed restrictions were not a constraint. The same requirement did not exist in the case of noise data, however, and it was possible to collect data at the desired test speeds in the subway.

2.8 During the pilot study some six successive runs were made over the same section of track. Data were collected on vertical, horizontal transverse, and longitudinal accelerations from two positions in the test car at two test speeds. To obtain the necessary freedom of train movement, it was necessary to conduct this test between midnight and 5 A.M.; the entire test required some 6 hr to complete, exclusive of prior arrangements and schedule planning.

2.9 The pilot study revealed one obvious disadvantage of the test procedure, which was a result of equipment limitation. The tape recorder used, which was the only battery-operated recorder with suitable frequency response characteristics, had only one recording head. This meant that the vibration components (vertical, horizontal, and longitudinal) had to be measured by making successive runs over the same section of track (since three recorders were not available). This proved to be highly unsatisfactory because of the time required to collect the data.

2.10 However, the pilot study indicated that, with some changes in the test procedure, magnetic tape recorders could be used to collect vibration data. The incentive to use such recorders for this study was particularly strong because of the flexibility afforded in data reduction; once collected, the data are always available and can be analyzed in a number of different ways.

2.11 The mechnical recorder was found to give repeatable results that agreed generally with the data results of the magnetic tape analysis, and it was adopted as a source of supplementary information. The method of analysis of the magnetic tape records was found to be unsatisfactory and was changed accordingly. Also, the test procedure was

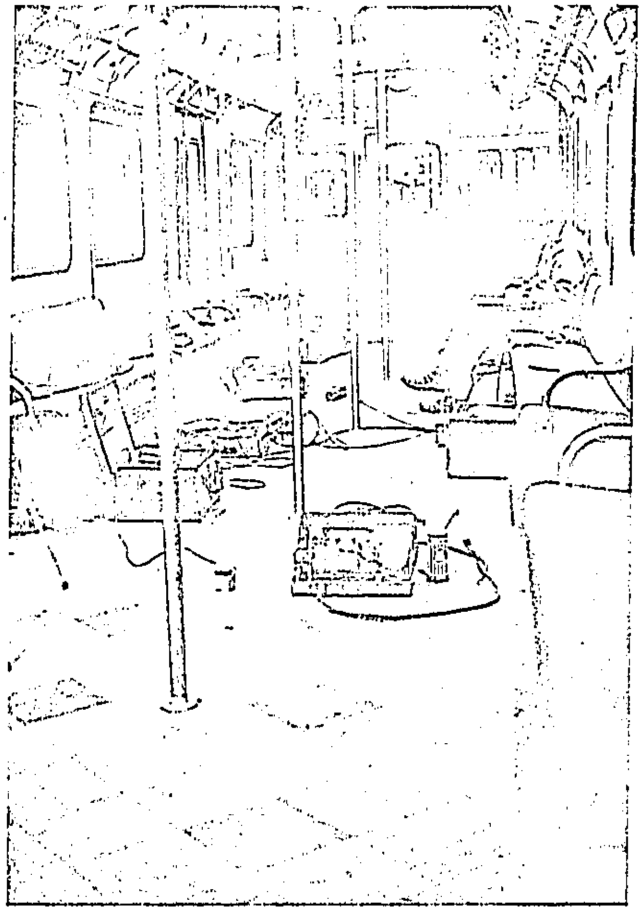


FIGURE 1. INTERIOR VIEW OF TEST CAR IN BOSTON PILOT STUDY. MECHANICAL RIDE RECORDER MAY BE SEEN IN FOREGROUND BESIDE ELECTRIC ACCELEROMETER

changed to reduce the amount of data collected and permit simultaneous recording of only vertical and horizontal transverse data, from one position in the car. The amount of equipment required for data collection was reduced as a result of these procedural changes. Final instrumentation for future tests consisted, in addition to the mechanical recorder, of two portable tape recorders (equipped with preamplifiers, accelerometers, and supplementary equipment) for vibration recording, and one tape recorder with supplementary equipment to record noise levels. The instrumentation was selected so that all supplementary equipment fitted into two medium-sized suitcases; with tape recorders included, the equipment package weighed about 170 lb, was air-transportable, and could be set up for data collection in 30 to 45 min. The NCTA provided instrumentation specified by ORI; Bolt, Beranek, and Newman, Inc. also provided instrumentation as well as personnel to operate it and perform the initial portion of the data reduction.

## STANDARD TEST PROCEDURE

2.12 The revised experimental procedure was tested with the cooperation of the Philadelphia Transportation Company (PTC). This test resulted in the adoption of a "standard test procedure" that was followed in most of the succeeding tests conducted on 11 different European and North American transit systems. The standard test procedure was carried out as follows: simultaneous noise and vibration recordings were made from the third car of a four-car train of empty cars; vibration pickups (electric accelerometers) were always located on the floor over the front bogie of the test vehicle. Noise recordings were made near the center of the test car with all windows and doors closed. All data were obtained on straight, level track in subway; a minimum of 60 consecutive seconds of data was taken at test speeds of 15 mph and 30 mph. Data at higher speeds were also obtained from the same measurement positions when time and conditions permitted.

2.13 All conditions of the standard test procedure for collecting samples of vehicle noise and vibration data were followed in 8 of the 13 test cases described in this report. In London and Paris the standard test procedure was followed, but using an eight-car and a two-car train, respectively. In Berlin, Lisbon, and Madrid (TALGO train), the magnetic tape recorders could not be used for vibration measurement and four-car trains were not available for the tests. Noise recordings were made in each of these three cities, however, and some ride data obtained with the mechanical recorder, although only at the higher test speeds.

2.14 In addition to the vehicle measurements described in the preceding paragraphs, tape recordings were made of the noise levels in selected subway stations of most of the systems visited. Placed near the center of the passenger loading platform, the recorder was switched on at the sound of an approaching train and left on as a train entered, stopped, and left the station. Multiple samples were taken in most systems to obtain comparative conditions from city to city and to ensure that an abnormally high level did not result in a particular station because of differences in braking rate, "flat" wheels, or other occurrences. Figure 2 shows the recording of station noise in Paris, and Figure 3 shows the magnetic tape recorders used to collect vibration and noise data.

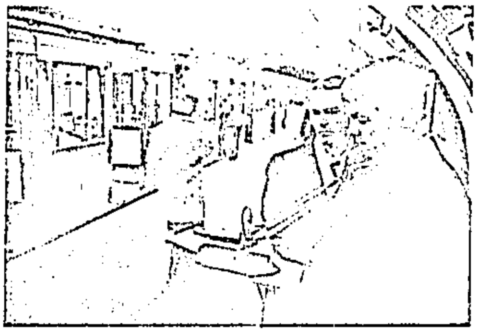


FIGURE 2. RECORDING STATION NOISE LEVELS IN PARIS

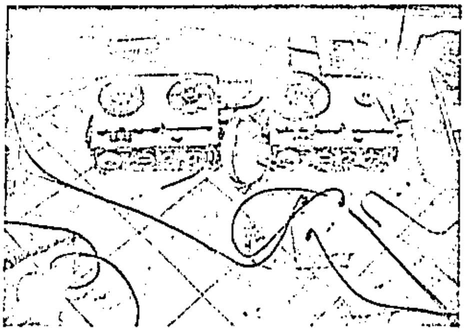


FIGURE 3. MAGNETIC TAPE RECORDERS USED FOR COLLECTING BOTH VIBRATION AND NOISE DATA

## RELATION OF TEST RESULTS TO SYSTEM CHARACTERISTICS

2.15 The test results presented in this study are probably the best available comparison of comfort standards (i.e., noise and vibration levels) of the various vehicle systems studied. There is, of course, some danger in attempting to extrapolate the results obtained in one vehicle on one section of line in a system to the system as a whole. This obviously cannot be done with some of the results obtained because of the test constraints. For example, in both Boston and Philadelphia, data were obtained under conditions that were not typical of the whole system. In all of the other systems visited, however, the standard test procedure was carried out on sections of line selected by the host agency as being among the best in the system (in subway) and in trains made up of the most modern vehicles currently in operation. Therefore, the data in these cases should indicate the highest level of comfort offered by each transit system. Results presented for measurements made at 30 mph in subways are probably the best possible indication of the average noise and vibration levels experienced in normal service because this is, generally speaking, the maximum average speed at which any of the tested systems is capable of operating.

## III. DESCRIPTION OF VEHICLE SYSTEMS

3.1 During the course of this study, 11 operating transit systems in the USA, Canada, and Europe were visited. In each case, the host agency generously provided a special test train and operating crew, so that it was possible to control the test conditions as described in Section II. This section describes for each transit system the equipment and track sections used in the tests. The completeness of the descriptions varies because it was impossible to obtain the desired amount of information in every case. European systems are described first, then North American systems, in alphabetical order.

### BERLIN

3.2 Before World War II, the Berlin subway system (BVG) was one of the largest and most modern underground railway systems in Europe. The system suffered extensive damage during the war, and most of the rolling stock was confiscated by the Russians in 1945 and put into operation on the Moscow Metro. However, in rebuilding their system, the Berliners experimented widely on vehicle and roadbed design, and the system is again one of the most modern in Western Europe. The system is distinguished by features that were not found in any of the other systems visited during the course of this study.

3.3 Although the portion of the underground system in East Berlin is no longer open to West Berlin traffic, the system in West Berlin comprises some 50 route miles, with planned eventual expansion to 120 miles. On the new G line, opened in September 1961, the average speed (including station stops) is approximately 21 mph, which is among the highest for any underground line in Europe. The maximum speed on this line is 45 mph, with an average station spacing of 0.5 mile. Figure 4 shows the interior of the Berlin subway station, and Figure 5 the recording of station noise levels.

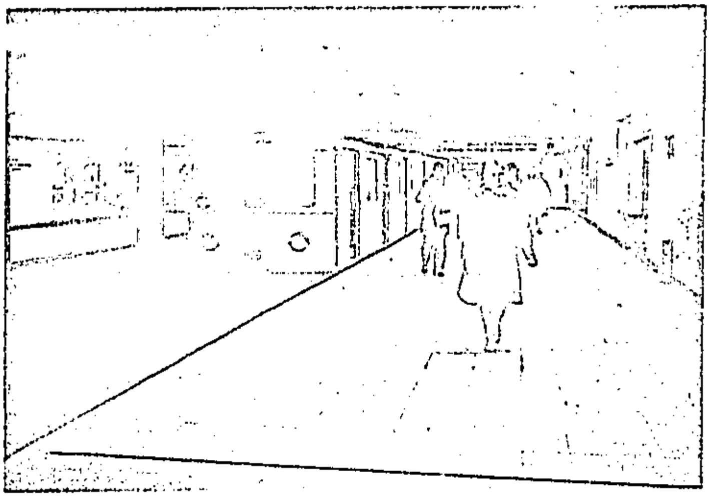


FIGURE 4. INTERIOR VIEW OF BERLIN SUBWAY STATION

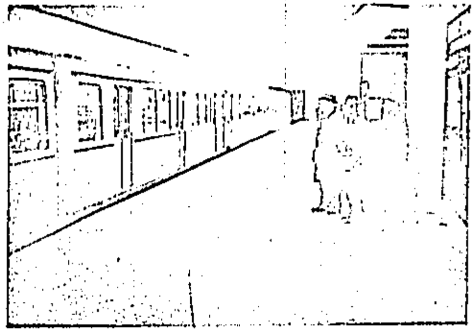


FIGURE 5. RECORDING NOISE LEVELS IN BERLIN SUBWAY STATION

3.4 As early as 1956 a prototype of a vehicle that incorporated an all-electric braking system was tested. This vehicle has since been adopted as standard equipment in two basic sizes. The Berlin system is similar to London's in that each has subways of different cross sections, requiring both large and small vehicles that are not mutually compatible. However, both size vehicles used in the Berlin system are identical in design except for major dimensions. In addition to the all-electric braking system, these vehicles feature an unusual bogie design. The bogies are distinguished by the use of one large axle-suspended traction motor mounted longitudinally to drive both axles (see Figure 6). Two bogies per car are used, so that all axles in a train are motored. The bogie frame is of all-welded, hollow-box sections; no end transoms are provided. The bogie is constructed so that the motor and axles form one unit and the bogie frame is a separate unit. The two units are isolated from one another at all contact points with rubber buffers. The motors are resiliently mounted on the axles, and the suspension system is all-rubber, employing bonded rubber chevron units both for the axle housing and between bogie and car body.

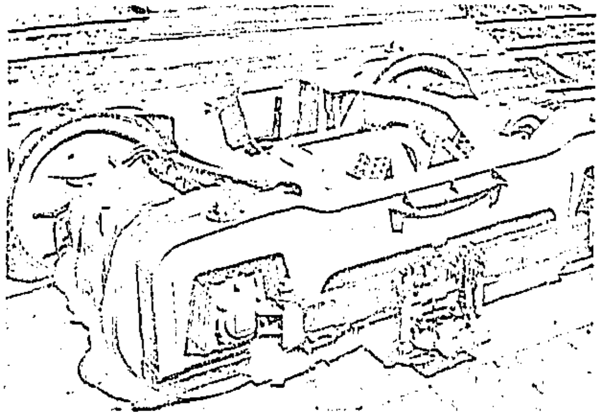


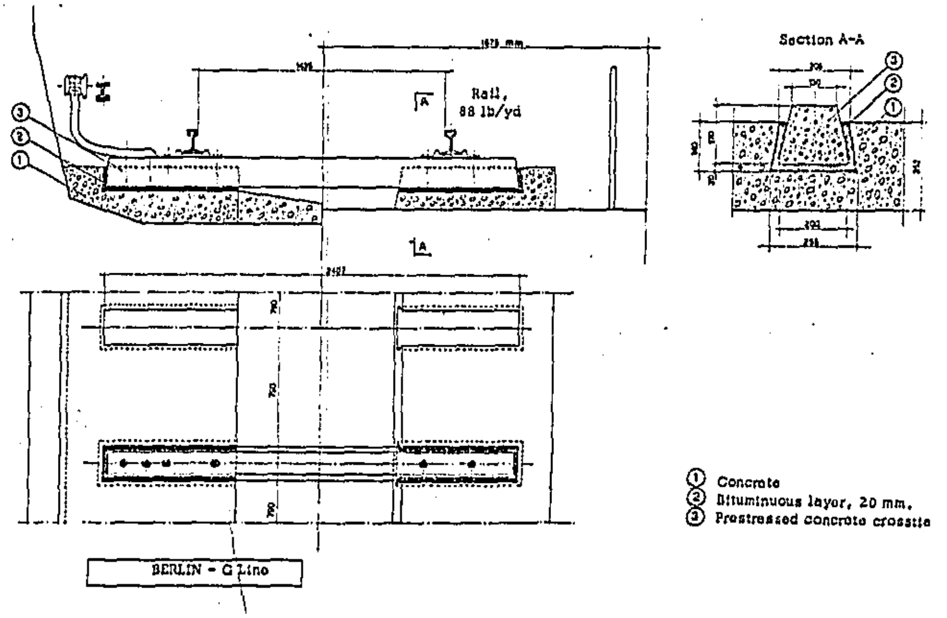
FIGURE 6. MOTOR BOGIE USED ON NEW BERLIN VEHICLES

Courtesy of DUWAG

3.5 The car body is of light, welded steel construction. A layer of asbestos-base sound insulator, 3 mm thick, is sprayed on the underside of the corrugated floor sheets to insulate the car body from noise. In addition, all interior surfaces of the bare car shell, including the corrugated floor sheets and the roof sheets, receive a layer of sprayed cork granules 5 mm thick. Plywood paneling is used extensively on the car interior.

3.6 The large profile cars are approximately 52 ft long, 11 ft high, and 8.6 ft wide. Seating space for 36 passengers and standing room for 144 is provided. The weight of an empty car is 54,000 lb.

3.7 Much experimentation has been carried out in track and roadbed construction techniques and noise-vibration control. In addition to using standard ballasted track on wooden crossties, one new line employs track on concrete crossties resiliently mounted in the concrete roadbed. A cross-sectional view of this type of track construction is shown in Figure 7. The noise data presented in this report were obtained on trackwork of this type on the new G line. Although experience with this type of installation has been favorable, an intensive test program of still newer track mounting methods is currently underway. Emphasis is being given to methods of mounting the track directly on the concrete roadbed. One mounting method currently being tested is shown in Figure 8. Four experimental test sections are located in various parts of the system, and noise and track vibration data are being collected in an effort to determine the best mounting technique.



Courtesy of ATM, Milan

FIGURE 7. METHOD OF TRACK INSTALLATION ON NEW G LINE, BERLIN

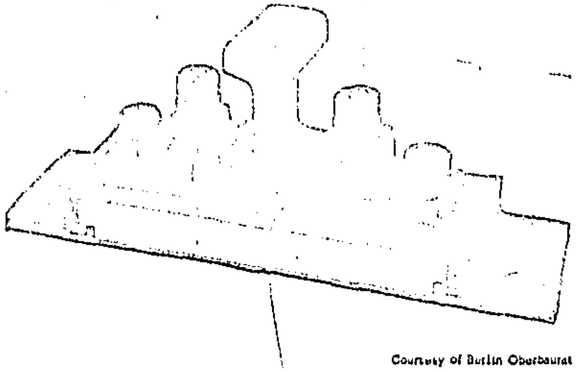


FIGURE 8. CROSS-SECTIONAL VIEW OF EXPERIMENTAL TRACK MOUNTING TECHNIQUE CURRENTLY UNDER STUDY IN BERLIN (LIGHT GREY AREAS ARE RUBBER)

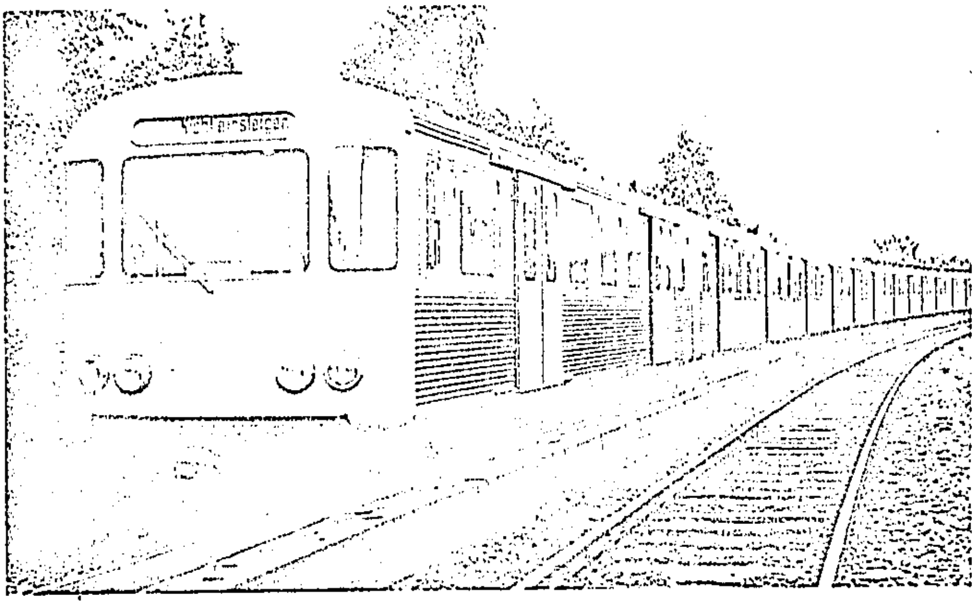
Courtesy of Berlin Oberbaurat

3.8 Unfortunately, during the survey team's visit to Berlin, the complete instrumentation package was not available. The magnetic tape recorders could not be used for vibration recording, so that the only data obtained on vehicle ridability were taken with the mechanical recorder. Noise recordings were made in the usual manner, both inside the vehicle and in stations. A four-car test train was not available, however, and all data obtained during the test runs were made from the second car of a two-car train of new large-profile vehicles.

HAMBURG

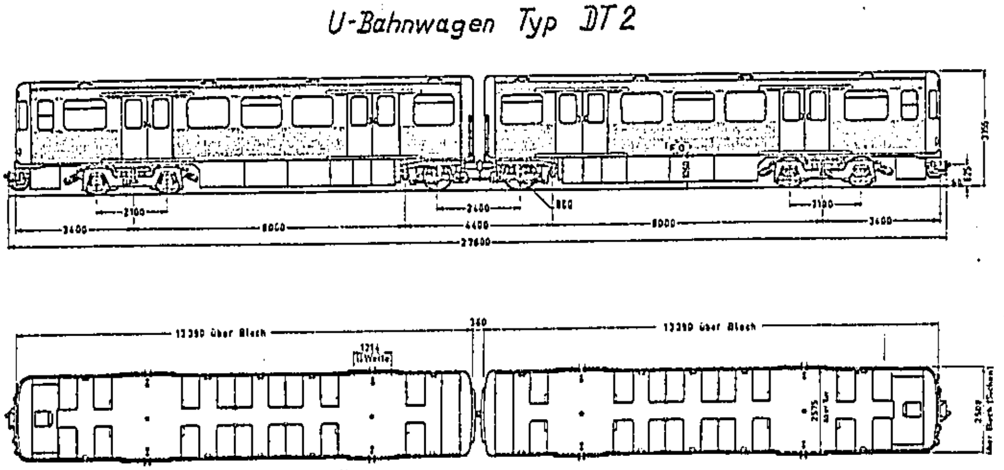
3.9 In January 1961 the Hamburg Transit Authority (HHA) introduced a new series of articulated motor coaches, known as the DT-2 series, on the 45-mile underground system. The general design objective in producing these cars was to obtain a vehicle that would be esthetically pleasing for 20 years, operate economically on the existing system, and be adaptable to changes in technology. The maximum speed of these vehicles is 45 mph; their average speed (including stops) is approximately 19 mph on underground lines. Figures 9 and 10 show the DT-2 vehicle.

3.10 The car body and interior were designed at the College for Industrial Design at Ulm. Emphasis was placed on design for function and low maintenance, and this is reflected in the extremely clean, uncluttered lines of the vehicle and in the construction materials used. The outer panels of the car are of unpainted stainless steel, and synthetic materials have been used extensively in interior fittings. The seats, interior panels, and even the ceiling and roof of the vehicle body are of fiber glass or plastic. Noise insulation under the vinyl flooring is provided by a layer of laminated plywood coated with 2 mm of PVC composition. The empty weight of each vehicle is 38,600 lb. The electrical controls are designed for eventual full automatic operation, and pneumatic brakes have been discarded in favor of an all-electric braking system.



Courtesy of HHA

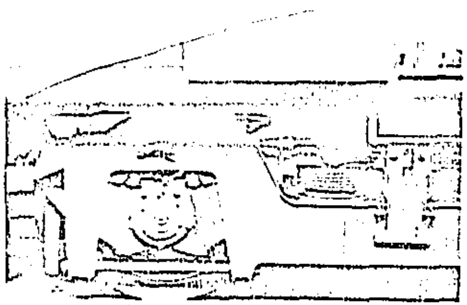
FIGURE 9. EXTERIOR VIEW OF NEW HAMBURG VEHICLES

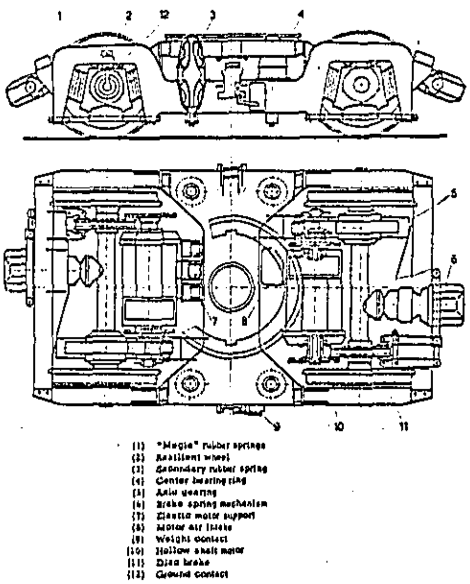


Courtesy of HH

FIGURE 10. GENERAL DIMENSIONS OF DT-2 VEHICLE IN MILLIMETERS

3.11 The bogies used on most of the DT-2 vehicles are manufactured by Link-Hoffmann-Busch (LHB), who developed the bogies in conjuntion with the Ulm design school. The bogies are of all-welded steel construction and are equipped with two 110-hp hollow-shaft motors each (see Figure 11). The articulated bogie in each set of two vehicles is nonmotored. The brakes on these bogies are spring-actuated disc brakes; the articulated bogies are designed to permit separate operation of the vehicles over short distances for maintenance purposes. Resilient wheels of all-welded construction are used on all bogies of the new vehicles; it was reported that these wheels reduce the vertical accelerations at the axle some 30 percent below conventional wheels. The LHB bogies are equipped with an all-rubber suspension system similar to that used on the Berlin and London vehicles except that a bell-shaped rubber bolster spring is used.





Courtesy of HHA

FIGURE 11. LINK-HOFFMAN-BUSCH MOTOR BOGIE

3.12 In addition to the LHB bogie, HHA is currently testing a newer bogie on the DT-2 vehicles, known as the Minden-Deutz bogie. It is manufactured by the Klockner-Humboldt-Deutz Company, has a combination of steel spring and rubber suspension, and is some 500 lb lighter than the LHB bogie. Oslo is considering this bogie for use on the subway vehicles that will begin operation sometime in 1964.[1/] Unfortunately, a comparison test between the riding qualities of the LHB and Minden-Deutz bogies was not possible during the survey team's visit to Hamburg. However, HHA has since reported that subsequent tests indicate that the Minden-Deutz bogie, shown in Figure 12, has superior riding qualities.

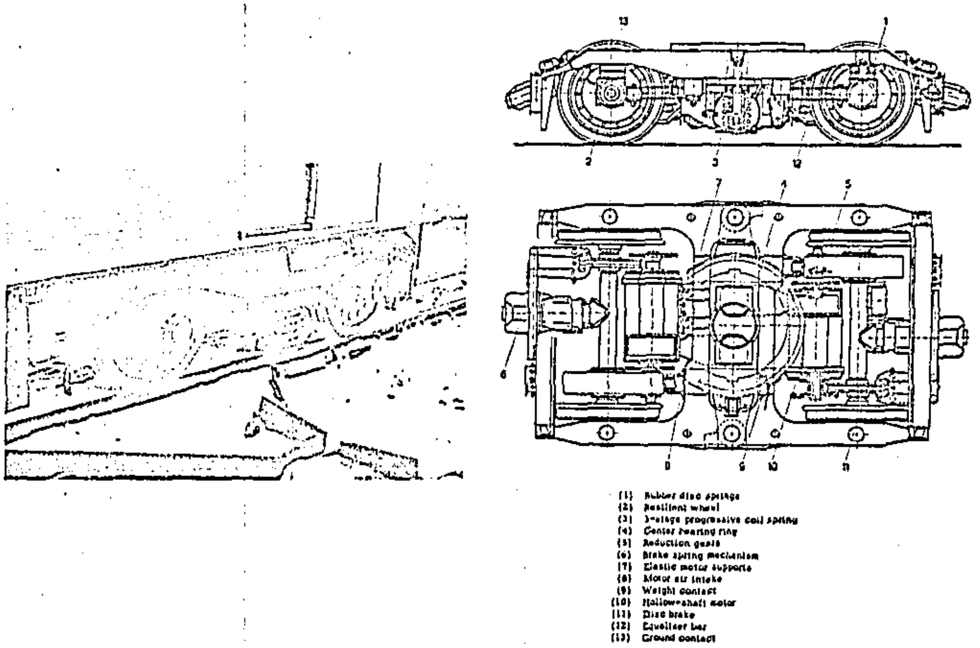


FIGURE 12. MINDEN-DEUTZ MOTOR BOGIE

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[1/] N.A. Christensen, Chief Engineer, Oslo Transit Co., private communication.

3.13 The vehicle noise and vibration data presented in this report were obtained in a test run of DT-2 vehicles equipped with the LHB bogie. Recordings were made in the third car of a four-car train in accordance with the standard test procedure. The test runs were made in a section of the Ochsenzoll-Rathaus subway line on straight level track. All data were taken on welded rail, laid on wooden crossties set in ballast. An additional feature of this otherwise standard mounting technique is the use of wood pads between rail and tieplate. Figure 13 shows a Hamburg subway station, and Figure 14 the interior of a DT-2 vehicle.

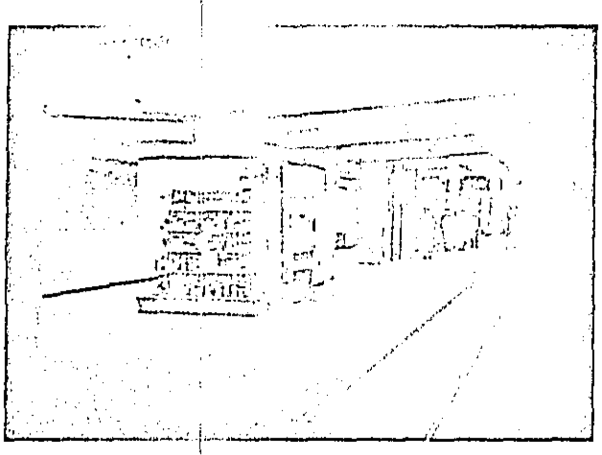


FIGURE 13. INTERIOR VIEW OF A HAMBURG SUBWAY STATION

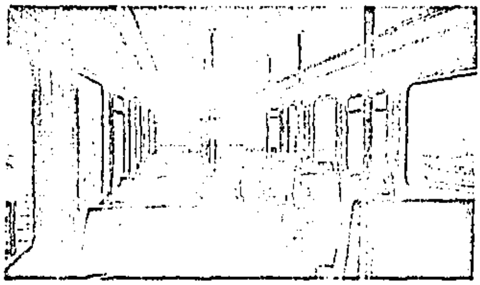
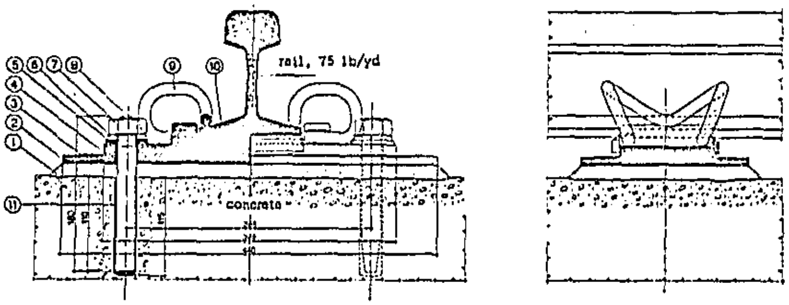


FIGURE 14. INTERIOR VIEW OF HAMBURG DT-2 VEHICLE

3.14 HHA also has a 500-meter test section of track mounted directly on concrete, which is similar to mountings in Toronto and Philadelphia. It was not possible to obtain comparative data on this experimental section, but the track mounting detail is of interest in comparison with other methods. Figure 15 shows the general scheme of this installation. The most interesting features are the unusual spring rail clip and the use of an epoxy resin mortar to glue the rail baseplate to the roadbed. This installation was adopted in the first line of the new Milan, Italy, subway after an exhaustive study of methods of laying track directly on concrete. 2/



(1) Special mortar of epoxy resin and sand
(2) Steel plate, 10 mm.
(3) Polyvinyl insulation
(4) Steel tie plate, 14 mm.
(5) Insulating washer
(6) Steel washer
(7) Nut
(8) Bolt
(9) Steel rail clips
(10) Rubber pad, 10 mm.
(11) Expoxy resin adhesive

HAMBURG - Test Section

Courtesy of ATM, Milan

FIGURE 15. TRACK MOUNTING TECHNIQUE ON EXPERIMENTAL SECTION OF CONCRETE ROADBED

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2/ Azienda Tranviaria Municipale, Milano. Supporto Cementizio e Provvendumenti Anti-Vibranti, Milano, September 1961.

## LISBON

3.15 Opened in 1959, Lisbon's subway has approximately four miles of double track in the shape of a "Y". A total length of approximately 20 miles is planned. The 24 vehicles presently in operation on the subway were designed and constructed by LHB, the German firm that built the new Hamburg vehicles. An additional order of 14 vehicles is being built under license by the SOREFRAME Manufacturing Company, Lisbon, Portugal. Figure 16 shows a Lisbon subway station and Figure 17 the general configuration of a subway vehicle. Each car is 53 ft long and weighs approximately 81,400 lb empty. Trains are normally made up of two cars, semi-permanently coupled. Each car carries 44 seated passengers and 100 standing passengers. The maximum vehicle speed is 36 mph; average speed (including stops) is 17 mph; average station spacing is 0.40 miles.

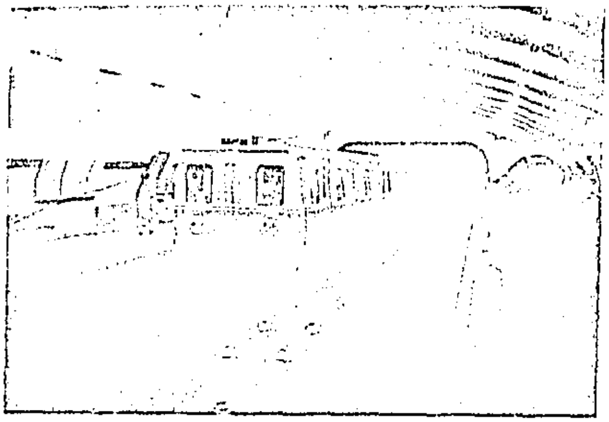
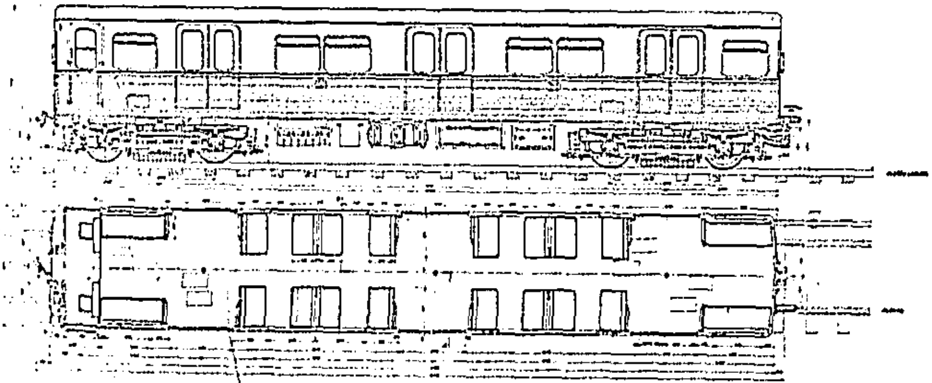


FIGURE 16. INTERIOR VIEW OF LISBON SUBWAY STATION



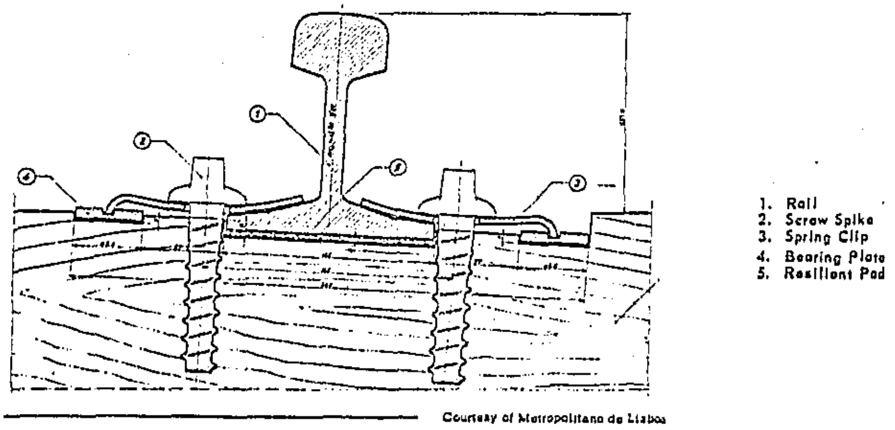
Courtesy of Metropolitano de Lisboa

FIGURE 17. GENERAL FEATURES OF VEHICLES USED IN LISBON

3.16 The vehicle body is of welded steel construction; during construction all interior surfaces of the bare car shell, including the roof and floor sheets, receive a layer, 3- to 4-mm thick, of cork-asbestos, sound-absorbent material called "insumate." The interior surfaces of the doors, which are of aluminum, also receive this treatment. Because of the mild climate in Lisbon, there is no heating system in these vehicles. Ventilation is provided by a small port at the front of each car; in addition, the windows can be partially opened. The interior of the vehicle, including floor and ceiling, is finished in wood paneling.

3.17 Each bogie has two frame-suspended 120-hp motors. Axle and bolster suspension is provided by a combination of coil springs and steel-leaf springs in a relatively archaic arrangement (compared to other vehicles included in this study). The bolster springs are two-stage; the second stage comes into operation when the vehicle load reaches 13,000 lb. Damping is provided by vertically oriented hydraulic shock absorbers. Rheostatic braking is used to 10 mph and then supplemented by air brakes. Composition brake shoes are used.

3.18 Unfortunately, it was impossible to obtain data in the standard test manner in Lisbon. Only two-car trains could be used, and the magnetic tape recorders were not available for vibration recording. Some data were obtained, however, with the mechanical recorder from the second car of an empty two-car train, and the noise recordings were also made, but only at a test speed of 30 mph. Recordings of station noise were made in the standard manner. Test runs were made on ballasted track laid on wooden crossties. (See Figure 18.)



Courtesy of Metropolitano de Lisboa

FIGURE 18. TRACK MOUNTING ON WOODEN CROSSTIES, LISBON

3.19 Most of the data collected in Lisbon were affected by the severe rail corrugation that has plagued that system's engineers for two years. The corrugations occur chiefly near stations; the passage of vehicle wheels over the washboard rail surface produces high noise levels inside the vehicle and extremely high noise levels inside the stations. Ride quality is also affected, but not in proportion to the noise levels produced. The cause for the rail corrugation is not known; studies to date have had little success in determining whether brake shoes, track mounting, or other factors are responsible.

## LONDON

3.20 About 4000 vehicles operate on London's vast underground system. Containing some 244 route miles, it is one of the two largest underground systems in existence. Approximately three-fourths of the underground mileage in London consists of small (12-ft) diameter tunnels, or tubes, which require rolling stock smaller in size than that operating on the surface lines and in cut-and-cover subways.

3.21 The conventional-sized[3] Metropolitan Line stock operates over the far-reaching surface lines at speeds up to 65 mph between stops, which (by skipping stations) are 15 miles apart. The small-sized[4] tube stock vehicles operate in the majority of tunnels beneath the city and also extensively on surface lines.

3.22 The 1961 model A60 vehicles employed on the Metropolitan Line were described by London Transport engineers as being the quietest, most comfortable riding vehicles currently in operation. However, a test run of 60 sec in subway was not feasible, and instead data were collected in a mixed train of 1959, 1962 tube stock vehicles. These vehicles are built of steel with aluminum paneling and weigh from 42,000 lb (non-motored trailer vehicle) to 52,000 lb (motored driver) each. They are employed in mixed trains of seven or eight vehicles so that about 50 percent of the vehicles are motored. Motored cars have two 80-hp motors per vehicle (one per bogie). General dimensions of the tube stock vehicals are shown in Figure 19.

3.23 The tube stock vehicles operate on lines with an average station spacing of 0.87 mile. Their maximum speed between stations is 45 to 50 mph, and the average scheduled speed (including station stops) is approximately 23 mph.

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[3] 53 ft long, 9.7 ft wide, 12.1 ft high.

[4] 52 ft long, 8.5 ft wide, 9.6 ft high.

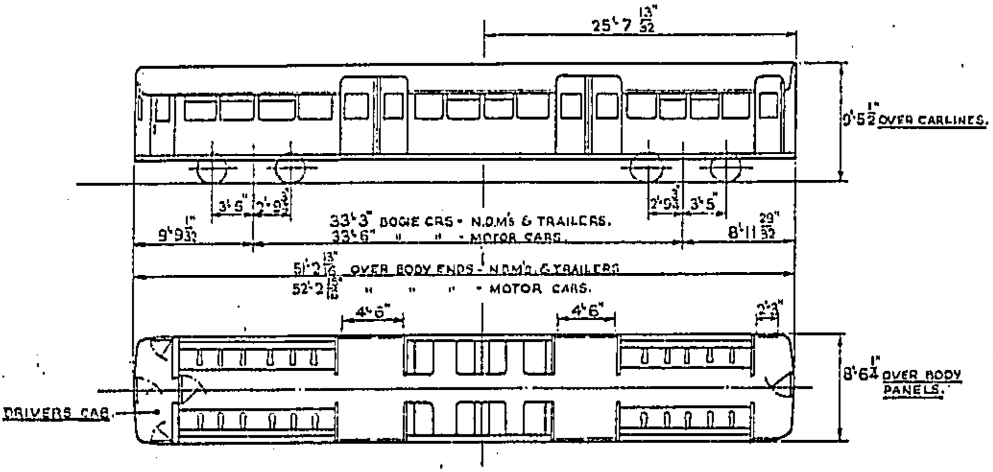

FIGURE 19. GENERAL DIMENSIONS OF LONDON TUBE STOCK VEHICLES

3.24 The car body is constructed of aluminum alloy sheets rivited to a steel frame. Side panels, end panels, and roof sheets are all of aluminum. All exterior paneling has a layer of canvas secured to the inner sides to reduce vibration. Grooved maple boarding is used as interior finishing material above a layer of canvas insulation and corrugated steel floor sheeting. Plastic paneling, wood, and some aluminum striping is used for interior fittings. The car ceilings are made of sound-absorbent acoustical fiberboard material. An interior view of one of the tube stock vehicles is shown in Figure 20.

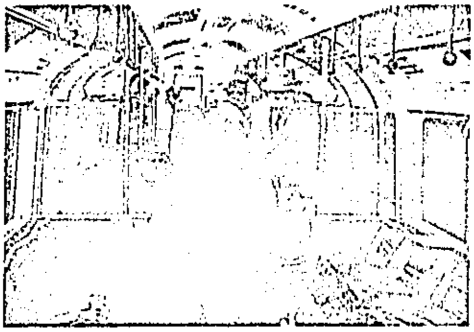

FIGURE 20. INTERIOR VIEW OF TEST TUBE STOCK VEHICLE

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FIGURE 21.
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3.25 The motor bogies used on the 1962 tube stock vehicles are shown in Figure 21. These bogies are asymmetrically designed and of conventional, riveted steel plate construction. Each bogie has an axle-hung, nose-suspended 80-hp motor mounted on roller suspension bearings on the inner axle. An all-rubber suspension system is employed in the bogies of these vehicles. The bogie bolster, usually mounted on coil springs, is supported at each end by two cylindrical rubber springs in the form of an inverted "V," laterally inclined to absorb all side forces. Hydraulic shock absorbers are used to damp both vertical and lateral oscillation. The axle suspension is also of rubber, the axlebars being located between bonded rubber chevron units housed in a cast steel yoke.

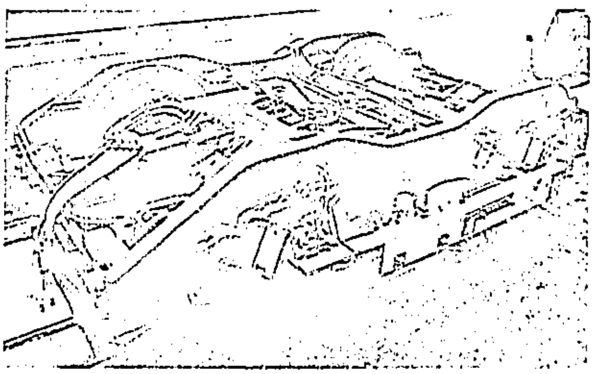


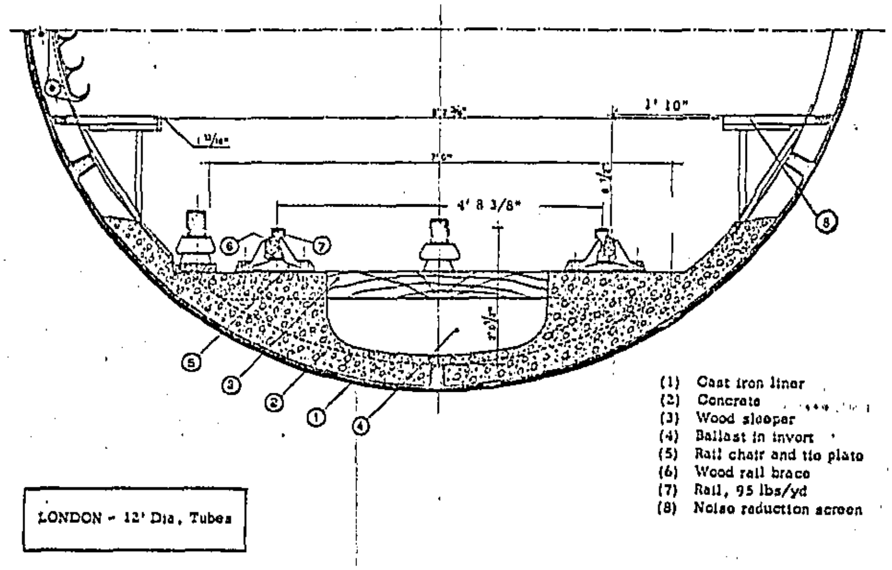
FIGURE 21. MOTOR BOGIES USED ON 1959–1962 TUBE STOCK VEHICLES

Courtesy of London Transport

3.26 Spoked wheels are used on the motor bogies as a noise control measure. Unfortunately, it was not possible to obtain comparative data on spoked- and solid-wheel bogies during the short time available.

3.27 In most tube sections of the London underground system, running track is laid without ballast to achieve the maximum operating space.

3.28 Figure 22 shows a cross-sectional view of track and roadbed construction in the 12-ft diameter tubes. Running track in the tube sections is generally welded rail, set in cast-iron chairs laid directly on wood crossties, with ballast in invert as shown in the figure. The chair is fastened to the sleeper with three screw spikes. The rail is held in the chair by a timber key, but in the future a metal key will be used. The same type of track construction will be used on the 11-mile Victoria Line, which is currently under construction. Some type of noise-reduction baffles is also planned. 5/ The noise-reduction screens shown in Figure 22 are of asbestos and are mounted only in certain sections of the system. Similar screens were the first such noise-suppression devices used in any subway. They were tested experimentally in London tube sections as early as 1939. 6/



Courtesy of ATM, Milan

FIGURE 22. CROSS SECTION OF STANDARD TUBE SECTION, LONDON

3.29 London data presented in this report were obtained from the sixth car of an empty eight-car train of 1959-1962 tube stock vehicles. Test runs were made in the standard manner between Chancery Lane and Stratford on the Central Line. Some data were obtained at 40 mph in a section of tunnel equipped with the asbestos noise-reduction screens.

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5/ H. C. Havers, Civil Engineer, London Transport Board, private communication, May 1963.

6/ J. S. Trevor, "Silencing London's Tubes," Bulletin of the International Railway Congress Association, May 1939.

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MADRID (TALGO TRAIN)

3.30 The TALGO company in Madrid recently put into operation a prototype train of the newly developed TALGO II vehicles. The new vehicles are 33 ft long (compared to 18 ft for the TALGO I vehicles), employ a completely redesigned running gear, and have many improved operating features. The SAAB Swedish resilient wheel is used on the axles of these cars.

3.31 Unfortunately, during the survey team's visit to Madrid the TALGO train was undergoing modifications and could not be used for a test run. A demonstration trip in one of the original trains was made during a normal run between Madrid and a nearby town. During this trip some noise recordings were made and ride data collected with the mechanical recorder.

3.32 The run was made over sections of track described as being among the worst in Spain and scheduled for complete replacement sometime this year. The misalignment was visible to the naked eye over short distances, and rail joints were in particularly poor condition. As a result of these conditions, the data presented in this report for the TALGO train should not be taken as representative.

PARIS

3.33 In recent years the rubber-tired subway vehicle operated by the Paris METRO has received much attention among rapid transit planners, primarily because it is the only such vehicle in existence and represents a dramatic approach to the solution of some of the problems associated with steel-wheeled systems, particularly noise control. Since one of the primary objectives of this study was to obtain comparative noise and ride data on the rubber-tired vehicle, the visit of the study team to Paris was undertaken with great interest.

3.34 The present model rubber-tired vehicle was introduced in 1956 on one branch line (Line No. 11). The success of the venture up to 1962 prompted conversion of Line No. 1, the main line, to rubber-tired operation. At the time of the team's visit in January 1963, this conversion was complete except for lengthening of station platforms to accommodate longer trains. In the conversion of Line No. 1, the wooden runways used on Line No. 11 were abandoned in favor of concrete runways (see Figure 23), upon which the rail is laid, with rubber pads between rail and tie plate. Average station spacing on the Paris METRO is 0.3 mile, among the lowest of any underground system in the world. On Line No. 11 the average speed (including stops) is approximately 17 mph. However, because of an average station spacing of 0.4 mile on Line No. 1, the average speed is expected to be about 19 mph. The maximum speed between stations on this line is approximately 35 mph.

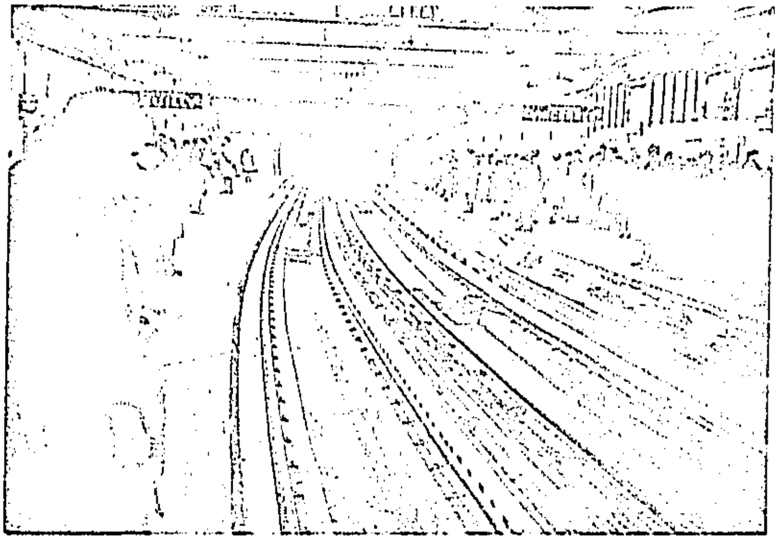
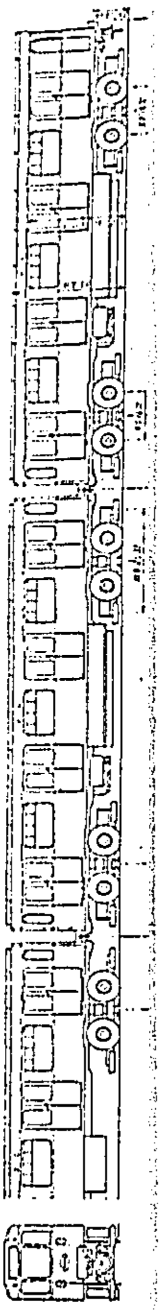
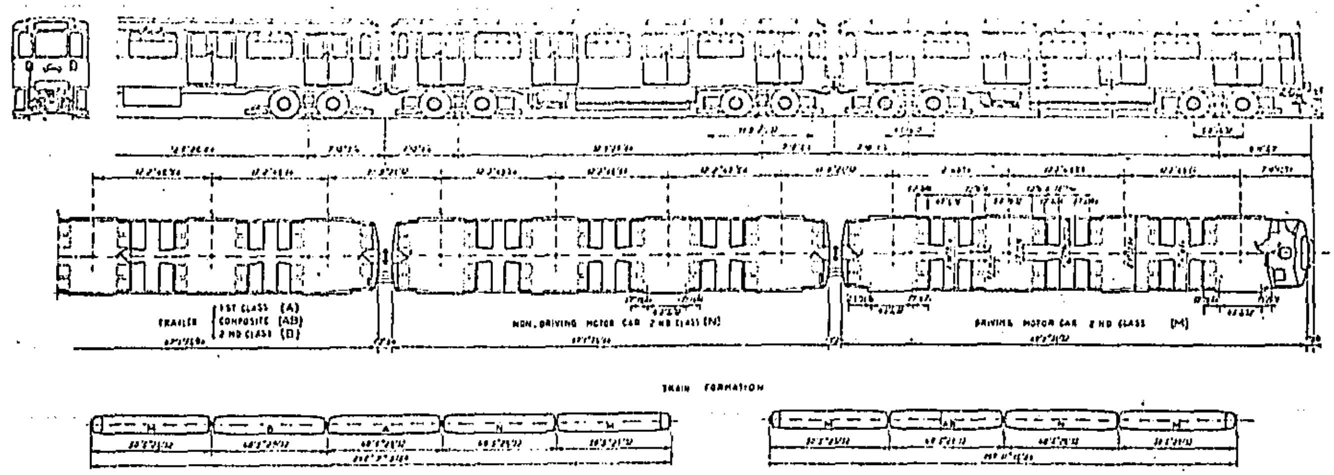


FIGURE 23. INTERIOR VIEW OF STATION ON LINE NO. 1. CONCRETE RUNWAYS FOR RUBBER TIRES CAN BE SEEN BESIDE EACH RAIL

3.35 Figure 24 shows a rubber-tired vehicle in a station, and Figure 25 provides technical data on the vehicle. Ventilation in these vehicles is provided by open ports in the clerestory. Although this arrangement contributes to the overall noise level inside the vehicles, they were found to be very quiet during operation.

FIGURE 24. RUBBER-TIRED VEHICLE IN STATION ON LINE NO. 11





## RUNNING GEAR

| | |
|---|---|
| Running tyres : Michelin Métalic F. 16. | |
| Tread radius, unladen | 20 ins. |
| Tyre pressure : motor car | 128 p.s.i. |
| Tyre pressure : trailer | 92.4 p.s.i. |
| Guiding tyres, Michelin | |
| Tread radius, unladen | 11 3/4 ins. |
| Tyre pressure | 142.2 p.s.i. |
| Safety wheels : radius | 17 3/4 ins. |
| Between centres, running tyres | 6 ft. 6 ins. |
| Track gauge | 4 ft. 8 3/4 ins. |
| Distance between guide bars | 8 ft. |
| Height of centres of guide bars | 7 ins. |
| Wheelbase, running wheels | 5 ft. 3/4 ins. |
| Wheelbase, guide wheels | 11 ft. 2 ins. |

## BODY

| | |
|---|---|
| Overall length. | |
| Driving motor car | 50 ft. 6 ins. |
| Other cars | 48 ft. 6 1/2 ins. |
| Body length. | |
| Driving motor car | 49 ft. 2 ins. |
| Other cars | 43 ft. 11 ins. |
| Width | 7 ft. 4 1/4 ins. |
| Total height | 11 ft. 5 3/4 ins. |
| Height of floor | 3 ft. 10 1/2 ins. |
| Platform height | 3 ft. 6 ins. |
| Distance between pivots | 32 ft. 9 1/2 ins. |
| Number of doors per side | 4 |
| Available width, open door | 4 ft. 2 ins. |
| Door spacing | 11 ft. 10 ins.<br>12 ft. 3 ins. |

## TRACTION

| | |
|---|---|
| Line supply voltage | 600 V |
| Number motors per motor car | 4 |
| Number motors per train | 12 |
| Supply voltage, motors | 30? V |
| Continuous output, motors | 90 hp |
| Max. normal speed, motors | 3,500 r.p.m. |
| Weight, motor | 1,100 lbs. |
| Camshaft equipment | |
| Operation : Jeumont-Heidmann electric or electro-pneumatic (C.E.M.) | |
| Acceleration control, synchronised chrono-amperemetric. | |
| Average starting acceleration, (adjustable from 1.1 to 1.4 m/s²). | 1.2 m/s² |
| Graduation of acceleration adjustable from 0.4 to 0.8 m/s². | |

## BRAKES

| | |
|---|---|
| Number shoes per bogie | 8 |
| Number brake cylinders per bogie | 4 |
| Compressor, Westinghouse 21 cu. ft./min. at 113.7 p.s.i.. | |
| Direct electro-pneumatic service brake - 5 notches on master controller, 1 E.P.V., graduated (Jourdain-Monneret) per car. | |
| Continuous automatic type emergency brake, Westinghouse T.V. | |
| Graduation of max. deceleration | 0.8 m/s² |
| Emergency deceleration | 2.5 m/s² |
| Average deceleration (normal stop) | 1.45 m/s² |

## BOGIES

Durand worm drive (Renault bogie).
Chenard & Walker double reduction drive (Alsthom bogie).

## WEIGHT

| | unladen | normal load |
|---|---|---|
| Driving motor car | 49,810 lbs. | 74,054 lbs. |
| Non-driving motor car | 48,047 lbs. | 73,393 lbs. |
| Trailer | 33,604 lbs. | 60,169 lbs. |

## CAPACITY

| | PASSENGERS | | | |
|---|---|---|---|---|
| | Seated | Standing | Total | Tip-up seats |
| Driving motorcar (2nd. cl.) | 24 | 135 | 159 | 28 |
| Non-driving motor car 2nd. | 24 | 142 | 166 | 31 |
| Trailer 1st. | 16 | 73 | 89 | 15 |
| Trailer 2nd. | 8 | 69 | 77 | 16 |
| 4-car train 1st. | 16 | 73 | 89 | 15 |
| 4-car train 2nd. | 80 | 481 | 561 | 103 |
| 4-car train | 96 | 554 | 650 | 118 |
| 5-car train 1st. | 24 | 142 | 166 | 31 |
| 5-car train 2nd. | 96 | 554 | 650 | 118 |
| 5-car train | 120 | 695 | 816 | 149 |

1/ "Pneumatic Tired Trains on the Paris Metro" R. Ruhlmann, RATP, 1959.

FIGURE 25. TECHINICAL DATA ON PARIS PNEUMATIC-TIRED VEHICLE

3.36 Figure 26 shows the motor bogie, including the inside steel wheels. In normal operation the steel wheels are not used, except for switching. The pneumatic tires support the steel wheels a short distance above the rails as shown in Figure 27. The suspension system is a combination of air-steel spring. A constant-volume, variable-pressure air cylinder with lateral steel-spring stabilizers is used at the bogie. Anti-roll bars are also used because of the narrow wheel base. Rubber is used in motor mounts and at connection points in the bogie construction.

3.37 Two 90-hp axle-hung motors are used in each bogie. An unusual design feature is that the bogie frame is slung under the axels instead of being mounted over them as is the usual practice. The frame carries the horizontal guide wheels, brake rigging, and accessories.

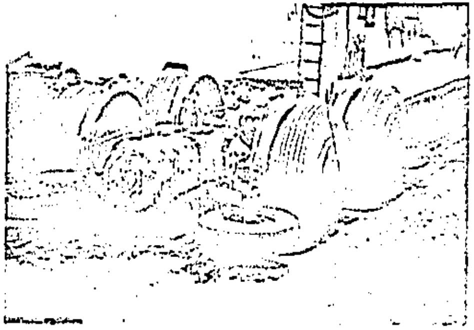
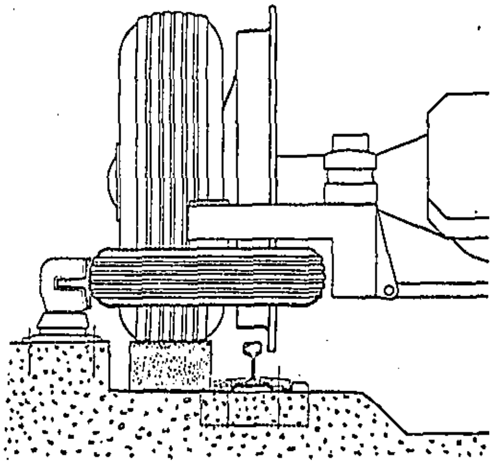


FIGURE 26. BOGIE USED ON THE RUBBER-TIRED VEHICLES



Courtesy of RATP

FIGURE 27. GUIDANCE SCHEME USED ON PARIS RUBBER-TIRED VEHICLES

3.38 Through the generous cooperation of METRO and S.G.T.E. [7] officials, arrangements were made for a comparison test of the pneumatic-tired and steel-wheeled vehicles on a section of the newly converted Line

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[7] Societe Generale de Traction et d'Exploitations, builders of the rubber-tired system.

No. 1, on January 10, 1963. Although a four-car train could not be arranged, the tests were carried out generally in accordance with the standard test procedure described in Section II. In each case, measurements were made over the front bogie of the lead car in a two-car train. Data were obtained between Berault Station and St. Mande-Tourelle on a section of straight, level track in the subway. Test conditions were carefully controlled to ensure data accuracy, and multiple runs at each test speed were made. Duplicate measurements were made by METRO engineers during these tests for a cross-check of results; Figure 28 shows a French engineer making sound measurements during one test run. Station noise levels were also recorded in selected subway stations during normal midday operations for comparison with levels in other systems.

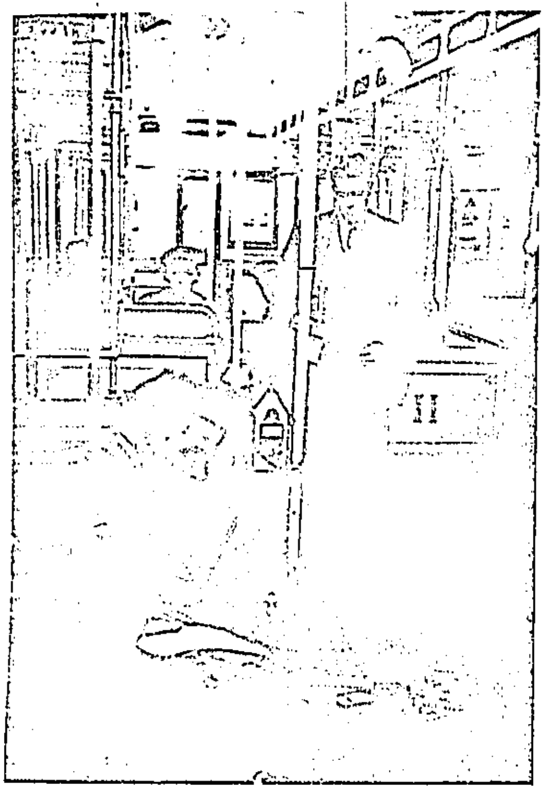

FIGURE 28. INTERIOR VIEW OF PARIS STEEL-WHEELED TEST VEHICLE. FRENCH ENGINEER IS SHOWN COLLECTING NOISE DATA

## STOCKHOLM

3.39 Four vehicle types are currently operating on the 25-mile Stockholm underground system, which began operation in 1950. Six- and eight-car trains are operated at an average speed (including station stops) of 16 to 18 mph. Average station spacing on the underground portion of the system is approximately 0.6 mile, and average speed between these stations is approximately 19 mph. Maximum speed between stations is 42 mph.

3.40 Each of the four vehicle types is a variation of the original C1 vehicle; all are similar in appearance, being approximately 57 ft long and 12 ft high. However, the empty weight of the latest model (type C4) has been reduced from the C1 weight of 66,000 lb to a value of 52,200 lb. Figure 29 shows a Stockholm subway station, and Figure 30 the general dimensions of a subway vehicle.

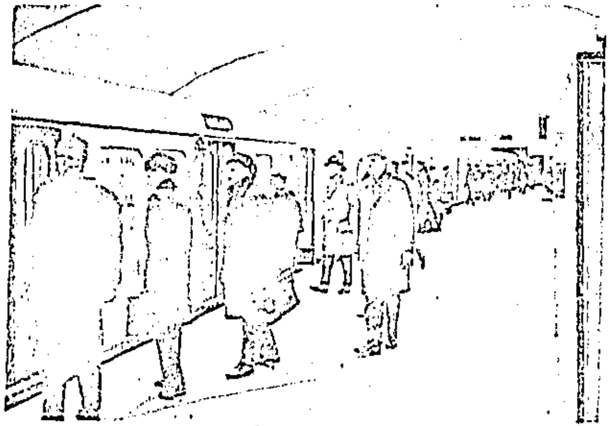

FIGURE 29. STOCKHOLM SUBWAY STATION

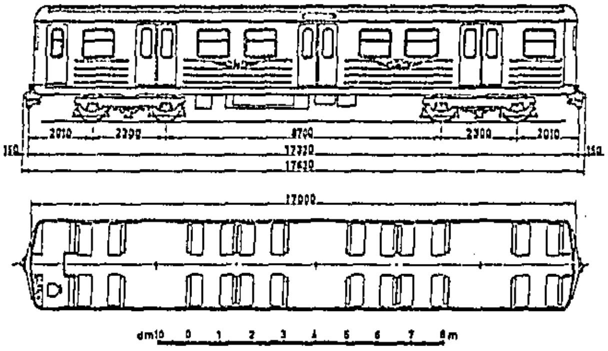

FIGURE 30. GENERAL DIMENSIONS OF STOCKHOLM VEHICLES IN MILLIMETERS

Courtesy of Stockholm Sporvagar

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FIGURE 3
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3.41 The car bodies are of all-steel construction, with noise insulation provided by laminated wood flooring and rubber mats above the steel floor sheeting. Other noise-reduction features include a rubber-mounted compressor unit, motor-generator set, and fan motor. Ventilation is provided by a centrally located fan in the roof of the vehicle. Figure 31 shows the interior of a Stockholm vehicle.

3.42 The bogies are of welded steel construction; two rubber-mounted 110-hp motors are provided on each bogie. Axles are cushion-suspended with cylindrical rubber mountings in the side frames. Additional vertical springing is provided by helical springs between the side beams and the box-section beam that bears the car body on rubber buffers (see Figure 32). Solid steel wheels of 34 in. diameter are currently used; resilient wheels are being tested as possible future equipment.

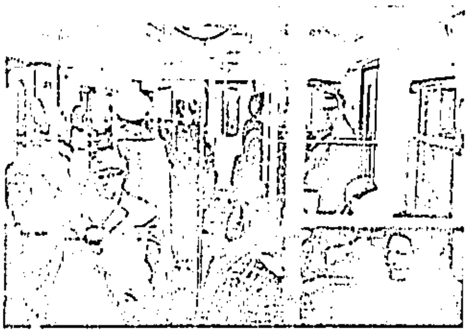
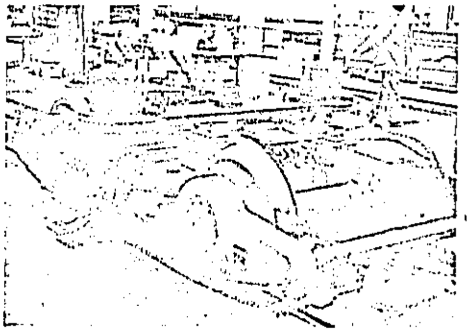


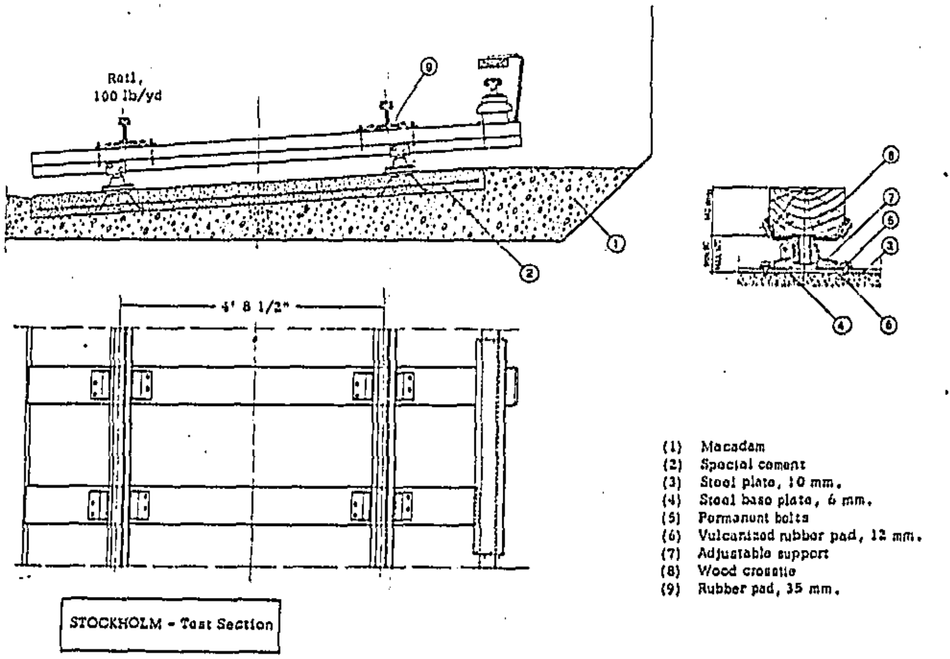
FIGURE 31. INTERIOR VIEW OF STOCKHOLM VEHICLE DURING RUSH HOURS

FIGURE 32. MOTOR BOGIE USED ON STOCKHOLM VEHICLES (TYPE C3)



3.43 In general, welded rails laid on wooden ties, set in ballast, are used throughout the system, with rubber pads between the rail and tie plate. In one experimental subway section, ballast has been eliminated, and the track is mounted, in an unusual manner, to the concrete roadbed (Figure 33). It was possible in this study to obtain samples of data on both types of roadbed.

3.44 The Stockholm data presented in this report were obtained in test runs on the main subway line between T-Centralen and Skanstull stations. All measurements were made in the third car of a four-car train of new C4 vehicles in the standard test manner, at speeds of 15 and 30 mph.



Courtesy of ATM, Milan

FIGURE 33. TRACK MOUNTING TECHNIQUE, EXPERIMENTAL SECTION OF CONCRETE ROADBED

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## TORONTO

3.45 In early 1961, the Toronto Transit Commission (TTC) put into operation the first of 36 cars of unusual design. While these cars incorporate many advanced features, they are of primary interest for two reasons: (1) having a length of approximately 75 ft, they were the longest cars tested during this study and are probably the longest rapid transit cars in the world, and (2) except for the underframe ends, they are of aluminum alloy construction with an unpainted exterior. These cars were ordered as the result of six years' experience with six shorter aluminum cars initially procured for comparison purposes by the TTC.

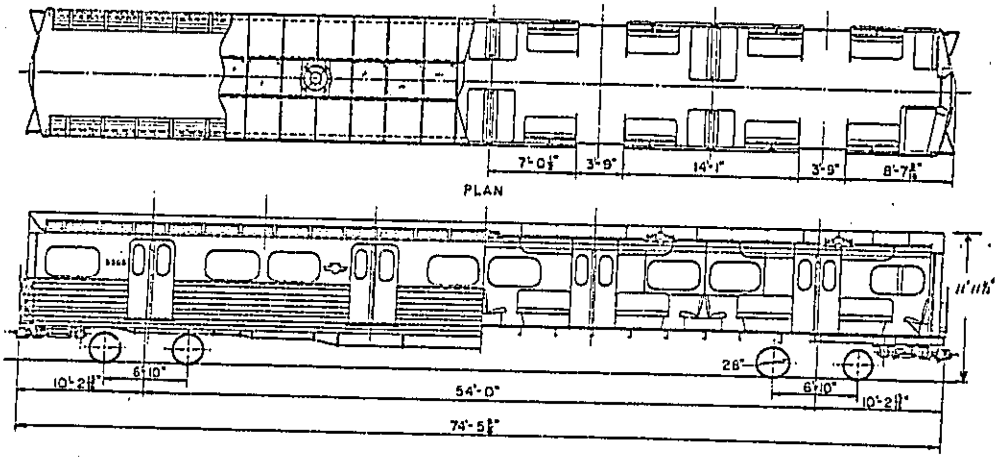
3.46 Average station spacing on the Toronto underground system is 0.41 mile; vehicles operate at an average speed (including stops) of 16 mph. Maximum speed of the new vehicles is 48 mph; however, in normal operation the performance of the new vehicles must be held lower than the maximum possible speed to match the performance of the older cars.

3.47 The new cars are 74.47 ft long, 10.25 ft wide, and 11.9 ft high. The weight of an empty vehicle is 59,800 lb; seating accommodation is provided for 84 passengers with standing room for 226, bringint the total capacity to 310 passengers per car. The general arrangement of the vehicles is shown in Figures 34 through 36. Aluminum extrusions are used extensively in construction of the car body. There is reportedly no acoustical insulation in the side walls or roof of these vehicles, the only insulation in the floor is provided by a heavy coat of anticorrosive paint on the underside of the metal floor sheets, above which is a layer of aluminum-faced plywood. Vinyl asbestos tiles are glued directly to this layer of plywood, forming the interior floor of the vehicle. The windows are non-opening; the pressure ventilation system used is designed to reduce noise transmission. The ceiling and interior panels are of laminated colored plastic fastened with aluminum snap-on moldings.

3.48 The bogies are equipped with two 125-hp frame-suspended motors. Bogie frames are of cast-steel construction, and inside journal bearings are used. Only small amounts of rubber are used in the construction of these bogies, in contradiction to the apparent trend towards more rubber in most of the other vehicle systems studied. The suspension system is a combination of air and steel springs. Steel coil springs provide axle suspension, and the bolster suspension is provided by an air cushion with internal steel coil springs that support the entire weight of the vehicle. Additional stabilization is provided by hydraulic shock absorbers mounted horizontally and vertically, as shown in Figure 37.

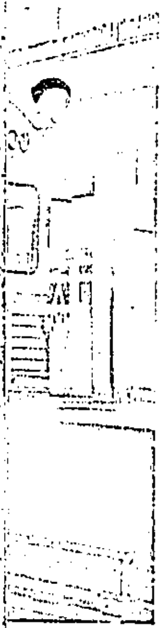
Courtesy of TTC

FIGURE 34. EXTERIOR VIEW OF NEW TORONTO ALUMINUM VEHICLES

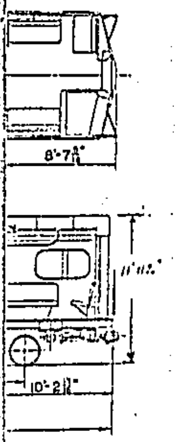


Courtesy of TTC

FIGURE 35. GENERAL DIMENSIONS OF NEW TORONTO VEHICLE



Courtesy of TTC



Courtesy of TTC

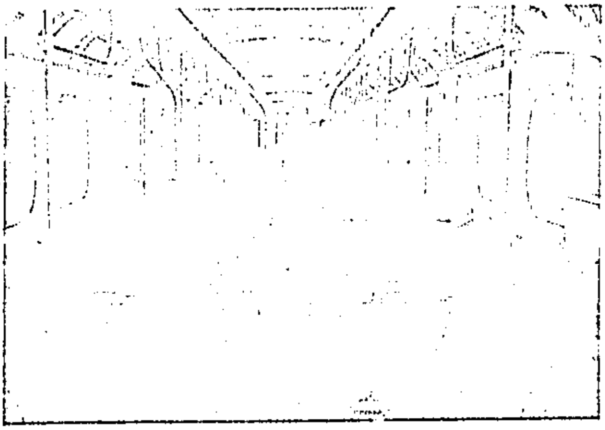
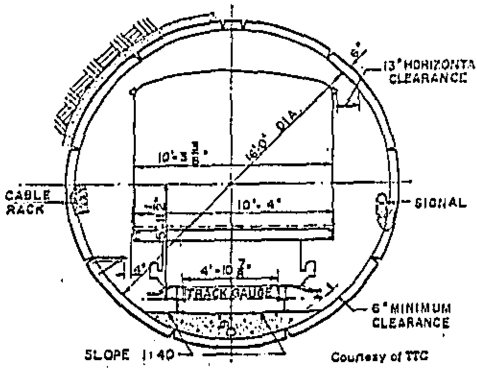


FIGURE 36. INTERIOR VIEW OF TORONTO TEST VEHICLE

Courtesy of TTC

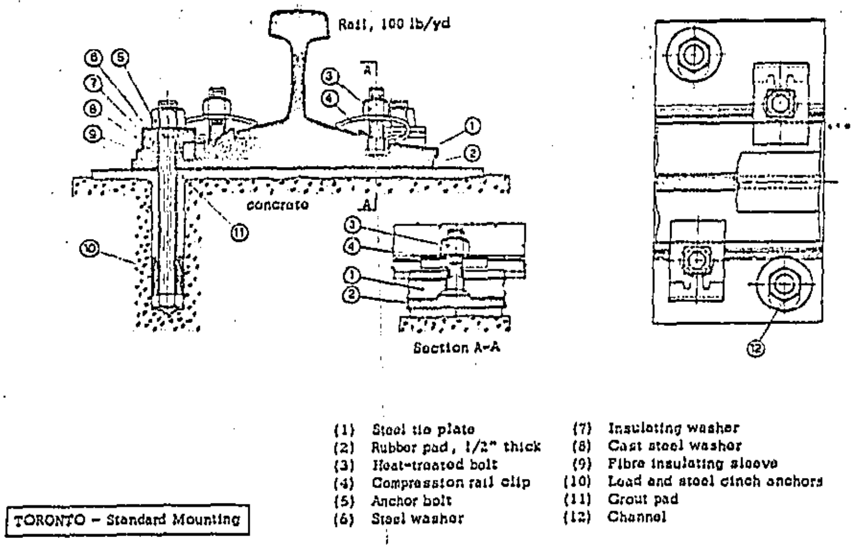
FIGURE 37. MOTOR BOGIE USED ON NEW TORONTO VEHICLES

3.49 The data presented in this report were obtained in the third car of a four-car test train provided by the TTC. Noise and vibration recordings were made in the standard test manner, at 15 and 30 mph on a section of the new University Line extension, opened in February 1963. Geography of the line required that the test runs be made in the tube sections of this line, which is composed of both box-shaped and 16-ft diameter tunnel sections. Figure 38 shows the arrangement of the vehicle in a standard tube section. In both the old and new sections of the Toronto system, all track, except special work, is laid directly on the concrete roadbed without ties or ballast. True vertical alignment in laying the rail is obtained by building up a concrete pad between the roadbed and tie plate in a manner similar to the Hamburg method. Figure 39 shows the mounting techniques.



Courtesy of TTC

FIGURE 38. GEOMETRY OF TRAIN IN TUBE SECTIONS



Courtesy of ATM, Milan

FIGURE 39. TRACK MOUNTING TECHNIQUE, TORONTO

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# CORRECTION!

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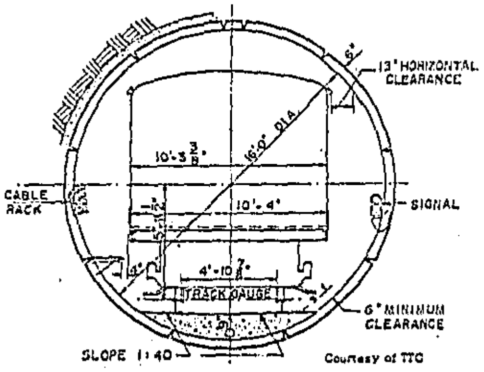
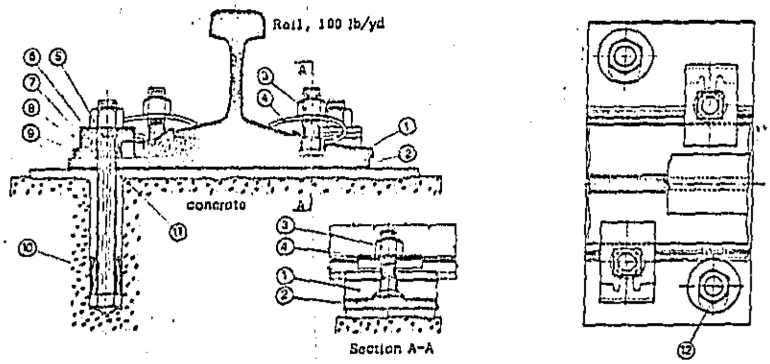
3.49 The data presented in this report were obtained in the third car of a four-car test train provided by the TTC. Noise and vibration recordings were made in the standard test manner, at 15 and 30 mph on a section of the new University Line extension, opened in February 1963. Geography of the line required that the test runs be made in the tube sections of this line, which is composed of both box-shaped and 16-ft diameter tunnel sections. Figure 38 shows the arrangement of the vehicle in a standard tube section. In both the old and new sections of the Toronto system, all track, except special work, is laid directly on the concrete roadbed without ties or ballast. True vertical alignment in laying the rail is obtained by building up a concrete pad between the roadbed and tie plate in a manner similar to the Hamburg method. Figure 39 shows the mounting techniques.



Courtesy of TTC

FIGURE 38. GEOMETRY OF TRAIN IN TUBE SECTIONS



(1) Steel tie plate
(2) Rubber pad, 1/2" thick
(3) Heat-treated bolt
(4) Compression rail clip
(5) Anchor bolt
(6) Steel washer
(7) Insulating washer
(8) Cast steel washer
(9) Fibre insulating sleeve
(10) Lead and steel cinch anchors
(11) Grout pad
(12) Channel

TORONTO - Standard Mounting

Courtesy of ATM, Milan

FIGURE 39. TRACK MOUNTING TECHNIQUE, TORONTO

POOR COPY

3.50 One unusual feature of the Toronto system is the use of sound-absorbent material under the platform overhangs and along tunnel walls to reduce noise. A glass fiber material was originally used, but this has been discarded in favor of an asbestos-base material. Station recordings were made in Toronto in both tube- and standard-box sections. The interior of a box-section station can be seen in Figure 40, which also shows the old installation of glass-wool blankets under the platform overhangs.

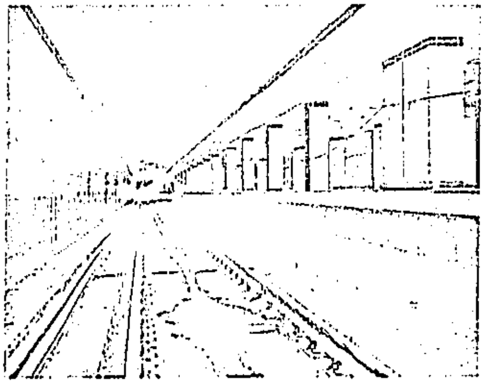


FIGURE 40. VIEW OF SUBWAY STATION SHOWING SOUND-ABSORBENT MATERIAL MOUNTED UNDER PLATFORM OVERHANG

## BOSTON

3.51 As explained in Section II, Boston was the site of the pilot study that began this measurement program of noise and vibration in rapid transit vehicles. The MTA operates approximately 35 route-miles of a rapid transit system in this city, about 11 miles of which are underground and 8.5 miles consist of elevated structure. The pilot study required that six successive runs be made over the same section of straight, level track with a constant speed of 30 mph for at least 60 consecutive sec. The one elevated line was the only portion of the system on which these test constraints could be met within time limitations.

3.52 The vehicles used in the test were 1956 model cars. Weighing approximately 58,000 lb empty, they are 55 ft long, 12 ft high, and 9 ft wide. Their maximum speed is 55 mph, and average speed (including stops) is approximately 21 mph on this line, which has an average station spacing of 0.7 mile.

3.53 The car body is of all-welded steel construction. Car interiors are finished in formica and stainless steel; the floor is vinyl-asbestos tile covering a layer of plywood and metal floor sheeting. Formica is also used for the car ceiling. Windows are nonopening, and a pressure ventilation system is provided.

3.54 The bogies are inside-journal type, of cast-steel construction, and equipped with two frame-mounted 100-hp motors. The suspension system consists of coil steel springs at the journals and air cushions at the bolsters. Solid 28-in. diameter wheels are used on the bogies.

3.55 All vibration data presented in this report were obtained in the third car of a four-car train of empty cars operating on elevated track above city streets. The elevated structure is of wood and steel construction and was erected prior to 1935. The test runs were made on nonwelded rail laid on wooden sleepers. Some noise data were obtained in the same train operating underground on nonwelded rail laid on wooden crossties set in ballast. No recordings of station noise were made in Boston.

## CHICAGO

3.56 The Chicago Transit Authority (CTA) operates a rapid transit network containing some 70 route miles. About 10 miles of the total are underground, and the rest are surface or elevated. About 6 miles of surface line are laid in the median strip of the Congress Street Expressway, where the average speed including stops is 25 mph. Although some data were collected during a 50-mph run on the Congress Street line, the majority of Chicago data presented in this report were obtained in test runs on the Dearborn Street (opened in 1951) and State Street (opened in 1943) subways. On these lines, which have an average station spacing of 0.5 mile, the average speed (including stops) is approximately 21 mph.

3.57 All test data in Chicago were collected from the third car of a four-car train of empty 1958 model vehicles. These vehicles, shown in Figure 41, are 48 ft long, 12 ft high, 9 ft wide, weigh 44,000 lb empty, and have seats for 51 passengers. One unusual feature of these cars is an all-electric braking system which has been a standard feature of all CTA vehicles since 1950.

3.58 The car body is constructed of steel framing and aluminum sheathing. The roof structure is also aluminum sheathing, and the floor construction is metal sheeting, plywood, and rubber floor covering. The interiors of the car are furnished with synthetic enamel over aluminum panels, and have leather- or plastic-covered spring seats. Ceilings are finished in tempered masonite. Ventilation is by overhead ducts, and windows can be partially raised.

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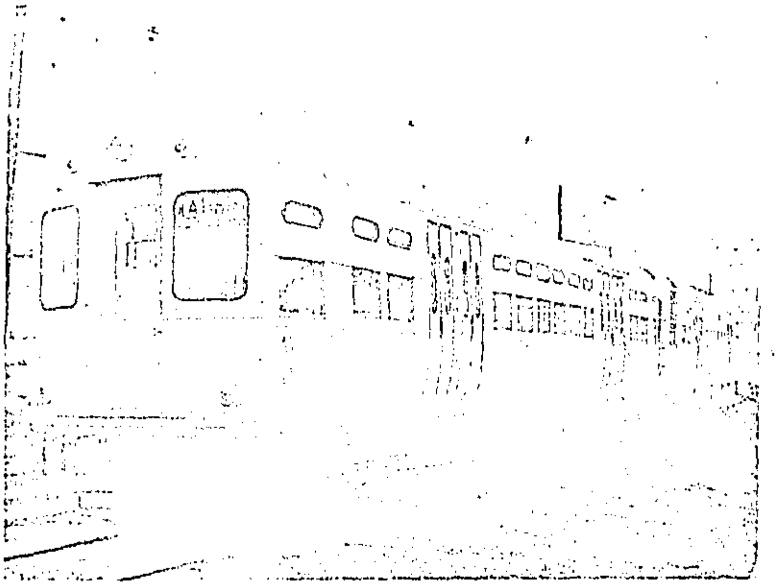


Courtesy of St. Louis Car Co.

FIGURE 41. EXTERIOR VIEW OF VEHICLES USED IN CHICAGO TESTS

3.59 The bogies are of the inside-journal type, with a cast-steel frame, and are equipped with two 55-hp frame-mounted motors. The suspension system employs rubber at the axles and steel coil springs with a rubber cone insert at the body bolsters; solid 26-in. diameter wheels are used on the bogies.

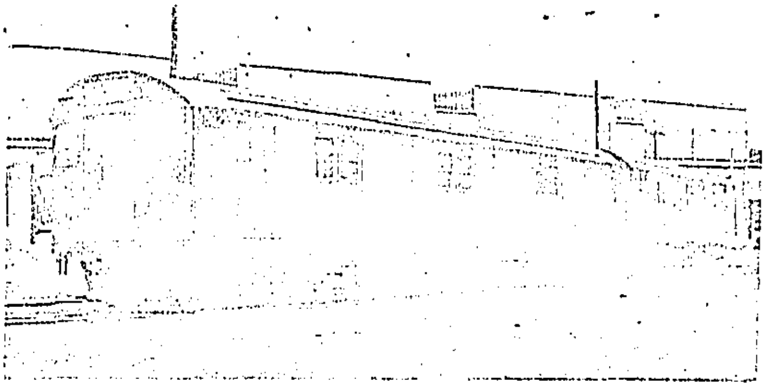
3.60 The test runs in Chicago were made on welded rail laid on short wood crossties set in concrete, both with and without rubber pads between the rail and tie plate. Noise recordings were made during test runs in tube sections on the Dearborn Street Line and in standard box-sections on the State Street Line.

3.61 Recordings of station noise were made inside stations of varying size and cross section during train arrival and departure. With regard to station configuration, Chicago is noteworthy for the extreme platform lengths in one midcity section of the system. In this section, the platforms are extended the full distance between five stations, so that the total length is approximately 3000 ft.

## NEW YORK

3.62 The New York City Transit Authority (NYCTA) operates the most extensive subway system in the world, encompassing some 237 route-miles of track over which approximately 6000 rapid transit cars operate. As in the case of London, the difficulty of designing an experiment to obtain data that are typical of the system was increased by the system size and the variety of equipment in operation. With the cooperation of the NYCTA engineering department, a test was designed to obtain data in a train of late-model vehicles operating over some of the better sections of line in the system.

3.63 A train of 1960 vehicles was used in the test. These vehicles, Figure 42, are 60 ft long, 10 ft wide, and 12 ft high. Each vehicle weighs approximately 80,000 lb empty, and seats 50 passengers (maximum design capacity is 300).



Courtesy of St. Louis Car Co.

FIGURE 42. EXTERIOR VIEW OF VEHICLES USED IN NEW YORK TESTS

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3.64 Body construction is all-steel, and the floor is constructed of aluminum truss plate covered with vinyl-asbestos tile. Stainless steel and enameled aluminum are used in the car interior. Porcelainized aluminum material is used for the ceilings, in which are located six 23-inch ventilation fans, as shown in Figure 43.

FIGURE 43. INTERIOR VIEW OF NEW YORK TEST VEHICLE

3.65 The bogies are outboard-journal type of cast-steel construction. Two 100-hp motors are suspended from the bogie frame. The suspension system consists of steel coil springs at the bolsters and four steel coil springs between the equalizer bar and truck frame. Rubber vibration pads are used at all contact points.

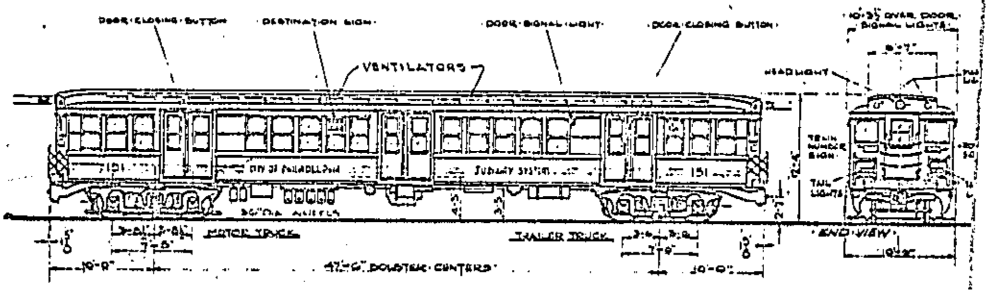
3.66 The test runs were made on sections of the express track of the BMT line between 14th Street and 57th Street in mid-Manhattan. The average station spacing is 0.5 mile; local trains average 17 mph (including stops) and express trains (bypassing some stations) average 20 to 28 mph. The test run was on wooden crossties set in concrete, with an empty invert between the rails. Some data were also obtained during a run on elevated track, where the rail is laid on full-width wooden crossties mounted on a steel structure, in a manner similar to that utilized in Boston.

3.67 Recordings of train arrival and departure were made in both center platform and side platform stations on the BMT and IRT lines. Recordings were also made of express trains passing through stations and of multiple arrivals and departures in a large station during rush hours.

## PHILADELPHIA

3.68 The Philadelphia Transportation Company (PTC) operates some 25 route-miles of elevated, subway, and surface lines in the Philadelphia metropolitan area. The most modern vehicles in operation are of 1959 manufacture. Unfortunately, however, a train composed of these cars was not available for the test runs, and it was necessary to use vehicles of 1938 manufacture. As a result, the data presented in this report for Philadelphia do not, in contrast to the data on other systems, represent information on the most modern vehicle systems currently in operation in Philadelphia.

3.69 Figure 44 shows the type of vehicle used in the test. Each vehicle weighs 112,000 lb empty and seats 71 passengers. The vehicles hav been maintained in good conditions, and all body construction is essential in its original state. Each vehicle has one motor bogie and one unmotored bogie, both having a coil spring suspension system. Solid wheels of 36-i diameter are used. The only ventilation in these vehicles is provided by a series of open ports in the clerestory. (The Paris METRO vehicles were th only other equipment tested during this study that had a similar ventilation system.)



Courtesy of

FIGURE 44. 1938 PHILADELPHIA VEHICLE USED IN TEST RUNS

3.70 The test runs were conducted in a four-track section of the Broad Street Subway on nonwelded, 62-ft rail sections laid on wooden crossties set in concrete. Screw spikes and rail clips are used between rail, tieplate, and sleepers. This track was laid in 1958 and since then has required no major repairs.

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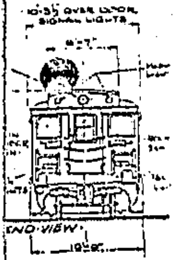

Courtesy of P

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## WASHINGTON, D.C. (BUS)

3.71 The bus used for test purposes in this study was a 1961 General Motors bus (Figure 45). The vehicle is air-conditioned and carries 51 seated passengers. It is 40 ft long, 8 ft wide, 10 ft high, and weighs approximately 21,160 lb empty. The bus is equipped with an air-suspension system consisting of four 8-in. bellows at the front and four 10-in. bellows at the rear. The power plant is a V-6 200-hp diesel engine.

3.72 The body is constructed of a steel frame with aluminum paneling. The inside surfaces of the sides and roof panels are coated with an asphalt-base sound insulation. The understructure is coated with the same material. Fiber glass insulation is used in the rear bulkhead between the engine compartment and interior. The floor is of plywood covered with a rubber carpet. Interior finishing consists of aluminum side panels and Melamine ceiling.

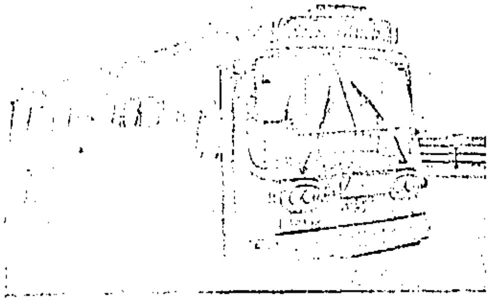

FIGURE 45. EXTERIOR VIEW OF BUS USED IN WASHINGTON TESTS

3.73 For city street conditions, test runs were made during the midmorning on Constitution Avenue and 15th Street in downtown Washington. For expressway conditions, test runs were made on a newly opened section of asphalt expressway between Washington and Dulles Airport. Test runs were made with and without air conditioning operating, but always with closed windows. In all cases, the vibration recording equipment was placed on the floor about one-third the distance between the driver's seat and the rear of the bus. The microphone for recording noise levels was mounted on a tripod near the center of the bus, as can be seen in Figure 46. All test runs were made on straight, level street (highway), and the speed was carefully controlled. More than one test run was made at each test speed to insure accuracy of results.

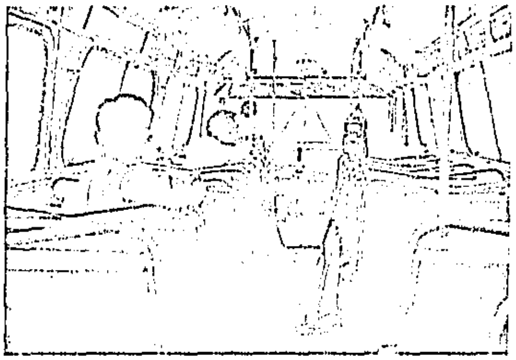

FIGURE 46. INTERIOR VIEW OF TEST BUS SHOWING LOCATION OF MEASUREMENT EQUIPMENT

## MILAN AND THE GUIDED ROAD SYSTEM

3.74 The Milan Transit Company (ATM) will begin operation of the first line of its new subway some time later this year. Approximately 9 miles in length, Line No. 1 will have steel-wheeled vehicles operating on steel rails. This line has been designed, however, for eventual conversion to the rubber-tired vehicle system designed by Dr. Raffaello Maestrelli. The ATM also plans to initially equip the future Line No. 2 with the rubber-tired vehicles.

3.75 No vehicle tests were conducted on the steel-wheeled vehicles that will operate on Line No. 1 because of construction work in progress. These vehicles are approximately 60 ft long and are of conventional design in every respect. They will operate on steel rails mounted directly on the concrete roadbed in a manner similar to the Hamburg test section.

3.76 The rubber-tired vehicle system, called "The Guided Road" by its inventors, is presently in an advanced state of development testing. A prototype vehicle train is shown in Figure 47. Employing lightweight bus-type construction and equipped with directional steering wheels on automotive-type axles, the prototype vehicles are powered by two 185-hp traction motors.

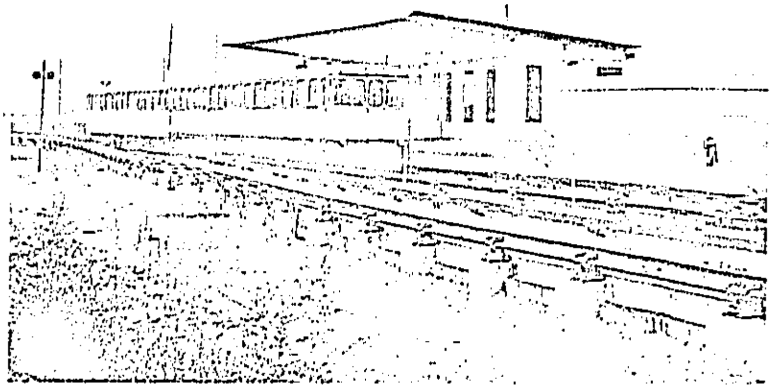

FIGURE 47. PROTOTYPE RUBBER-TIRED VEHICLE ON TEST TRACK

3.77 Each vehicle is 51 ft long, 9.4 ft wide, 11 ft high, and weighs 39,500 lb empty. Seats are provided for 36 passengers and standing room for 198. Figure 48 shows an interior view of the prototype vehicle.

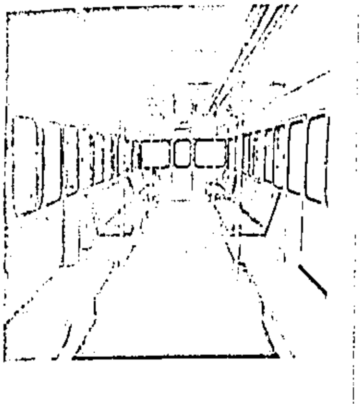

FIGURE 48. INTERIOR VIEW OF PROTOTYPE VEHICLE

3.78 Of the many similar designs tested by the Maestrelli group in recent years, this design is the first to incorporate a successful fail-safe switch. The switching principle is very simple and does not require the use of auxiliary steel wheels as does the Paris METRO rubber-tired design.

3.79 The vehicles operate on a simple concrete roadway and are guided by horizontal rubber wheels pressing against steel side rails. The side rails are also used in switching, with the aid of horizontal rubber switching wheels that project over a raised portion of both side rails. A view of the roadway, including a switch, is shown in Figure 49. A close-up view of the switching wheels is shown in Figure 50. It should be noted that the roadway design and switching principle permit installation of this system in combination with conventional rail systems, thereby allowing rubber- and steel-wheeled vehicles to operate over the same lines.

3.80 Through the courtesy of ATM officials and the Societa per la Strada Guidata ("Guided Road Company"), the prototype vehicles were inspected and test-driven on an experimental track near Chivasso. However, no measurement data is presented in this report on these vehicles. The cars inspected were undergoing modification and were not in a condition suitable for comparison tests.

3.81 An unusual amount of gear noise during operation in one direction was caused by the use of standard heavy-truck axles, and a temporary leaf-spring suspension system produced a ride judged subjectively as of only average quality. However, the designers expect both noise and ride to be drastically improved in future models.

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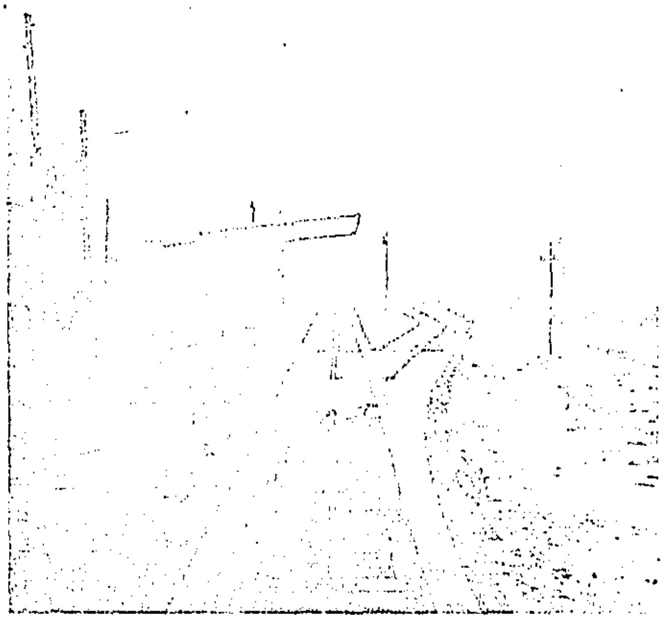

Courtesy of S.S.G., Milan

FIGURE 49. CONCRETE ROADWAY, SHOWING SWITCH

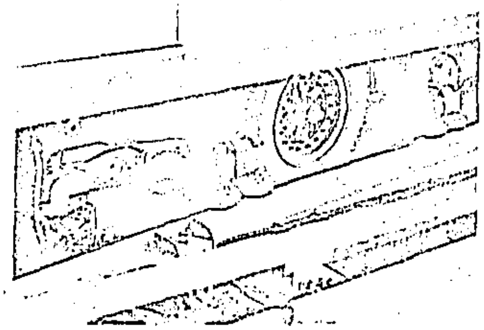

FIGURE 50. CLOSE-UP OF SWITCHING WHEELS

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# IV. NOISE MEASUREMENT RESULTS

## GENERAL CONSIDERATIONS

4.1 One of the most significant factors relating to a passenger's opinion of the overall comfort of a trip by rapid transit is the noise to which he is subjected during the course of the trip. Noise level is, obviously, secondary to trip time and convenience in determining system patronage, but it is an important factor in creating an image of the system in the public mind. This image is most important if "marginal" passengers are to be attracted, particularly during the off-peak hours, in the face of competing alternative transport means.

4.2 The generally high noise levels of subway systems in this country have no doubt helped create an impression in the mind of the U. S. metropolitan population that such noise levels are an inherent characteristic of a conventional subway operation. This impression apparently persists in spite of the obvious relation between old equipment, roadbed maintenance, and high noise level. The low noise levels associated with pneumatic-tired systems have been highly advertised, and such systems have been proposed by their advocates as the only effective solution to the subway noise problem. Little publicity, however, has been given to those achievements that have been made in the area of noise reduction in conventional subway systems. In addition, comparative data on noise levels in modern rapid transit vehicle systems have been virtually nonexistent.

4.3 Very little data, for example, have been published that would indicate the relative degree of quietness in operation that can be achieved with a conventional steel-wheel vehicle operating on two steel rails. It may come as a surprise to some that the noise level inside a modern rail subway vehicle operating in a tunnel (normally the noisiest portion of the journey) can be controlled to the same noise level inside a modern city bus operating at comparable speed with closed windows in light traffic on open city streets (normally the quietest condition).

4.4 This report presents the results of noise measurements that were made on various rapid transit vehicles in the U.S., Canada, and Europe in an attempt to document existing noise levels and to identify those systems where the greatest progress in noise control has been made. In subsequent sections the subway noise problem is briefly discussed, and the data presented and compared.

## SUBWAY NOISE PROBLEM

4.5 The major source of noise in well-designed rapid transit vehicles is the interaction of wheel and roadbed. In conventional rail transit vehicles this noise is created by the impact of steel wheels on irregularities in the running surface of steel rails. Vibrations are set up in the wheels and rails, and these vibrations are radiated as airborne noise or transmitted via the car structure into the car interior, causing other components to vibrate in the process. This noise problem (as any other noise problem) can be attacked in three ways: (a) eliminate the source of the noise, (b) introduce a barrier between the source of noise and the listener, or (c) absorb as much of the noise as possible. Each of these methods has been applied in various ways to the noise problem in rail and rubber-tired rapid transit systems, and some of the procedures encountered during the course of this study will be mentioned in subsequent sections.

4.6 Concerning travel on open track, it has been demonstrated by various researchers[1] that noise levels in the interior of the vehicle can be effectively controlled by the use of welded rail, good maintenance procedures, and the incorporation of modern noise suppression techniques in car design (i.e., judicious use of rubber in the trucks, acoustical insulation in the car body, double windows, etc.)

4.7 The noise problem of travel in subways becomes more acute primarily because the vibration set up in wheels and rails is greatly amplified by tunnel reverberation. This requires the application of noise control measures to the tunnel itself, which usually means that an attempt is made to absorb as much of the sound as possible by installing layers

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[1] C. M. Harris, Handbook of Noise Control, New York, 1957, Chapter 32.

or baffles of sound-absorbent material along the tunnel walls at wheel height. In enclosed stations, where brake squeal may add to the noise problem of train arrival and departure, sound-absorbent material may be applied along tunnel and station walls, under the platform overhang, and even in the roadbed between the rails.

4.8 Because the noise problem, as far as the passenger is concerned, is greatest during the subway portion of a rapid transit journey, it was decided to concentrate the present study on that aspect of the overall problem, i.e., to measure existing noise levels inside vehicles operating in tunnels as well as in subway stations during train arrival and departure.

## BASIS OF MEASUREMENT

4.9 The familiar unit of measurement in noise study is the decibel. Unfortunately, there is a great deal of confusion over the exact meaning of this term. For a precise definition the reader is referred to handbooks on the subject. However, since the measurement results as presented in this study may be unfamiliar to most readers, a limited discussion of the units used is warranted. Most existing noise data on rapid transit systems are presented in terms of the overall sound-pressure level in decibels, usually obtained by averaging a number of readings made with a sound level meter or so-called decibel meter. Note, however, that such a reading does not indicate the <u>loudness</u> of a noise. Two sounds ranked for loudness on the basis of their sound-pressure level in decibels might not agree with the ranking they would receive by the human ear. This is because high frequency sounds are usually more annoying to humans than are lower frequency sounds of the same sound-pressure level. In other words, a 2500-cps sound measured at 85 db might be more annoying than a 500-cps sound of 85 db.

4.10 For complex sounds, such as occur during rapid transit operations, a frequency analysis of the noise should be made by measuring the sound-pressure level in decibels in discrete frequency bands. From these readings the so-called <u>loudness level</u> (LL) can be computed, according to a computational procedure found in most noise control handbooks.[2] One common unit of measure of the loudness of a sound is the "phon," which is simply a measure of the loudness of a sound as judged by the human ear.

4.11 Figure 51 shows the octave-band sound-pressure level measurements (in decibels) made in two different rail vehicles: (a) in a TALGO train vehicle traveling at 30 mph on open track near Madrid and (b) in a vehicle of the Lisbon, Portugal, underground traveling at 30 mph in tunnel.

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[2] See Appendix C.

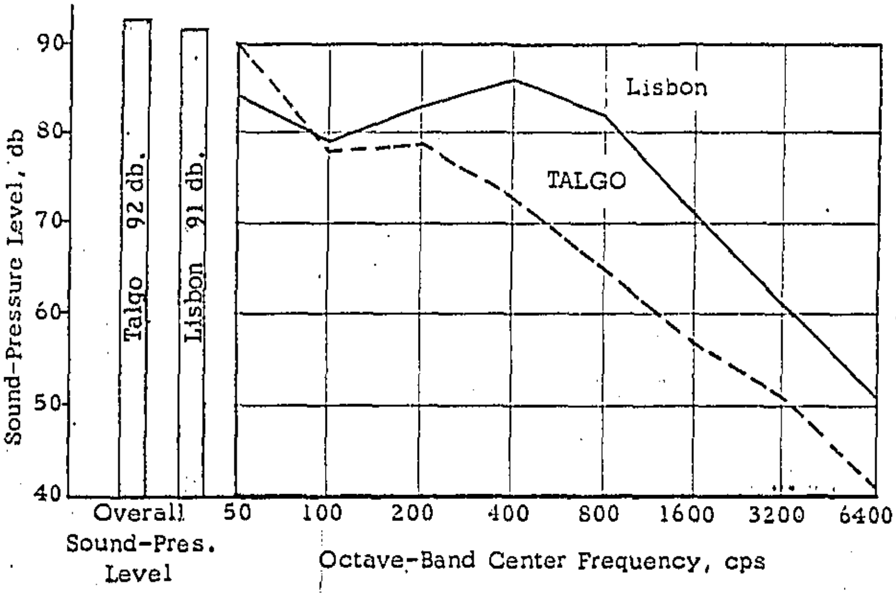

FIGURE 51. OCTAVE-BAND SOUND-PRESSURE LEVELS IN TWO DIFFERENT RAIL VEHICLES

The computed overall sound-pressure level in decibels is also shown at the left of this graph, indicating 92 db for TALGO and 91 db for Lisbon. Ordinarily a difference of 1 db is not considered significant, and on this basis the two vehicles would be ranked as about equal in quietness. However, if the loudness level in phons is calculated, using the octave-band sound-pressure levels shown on the graph, a level of 97 phons is determined for the Lisbon vehicle, compared with 91 phons for the TALGO vehicle. Since a difference of 3 phons is usually considered to be the smallest discernable difference in loudness of sounds,3/ the Lisbon vehicle would be ranked as considerably noisier than the TALGO vehicle. This reverses the ranking given by simply stating the overall sound-pressure level in decibels. The new ranking more closely approximates the response of the human ear because it weights the decibel levels in the speed interference bands (about 600 to 4800 cps) heavily as well as the higher frequency tones more likely to cause annoyance to human

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3/ L. L. Beranek, Noise Reduction, McGraw-Hill, 1960.

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passengers. It also agrees in this case with the subjective opinion formed by the study team after riding in each vehicle under similar test conditions.

4.12 This example should illustrate why it is desirable to know the frequency distribution of the sounds being compared. It gives some idea of the danger of making simple comparisons, merely on the basis of overall sound-pressure level, between complex sounds such as those encountered in rapid transit operations. Some idea of human response to the sounds in each system must be determined for comparison; the means chosen for this report is the computation of overall loudness level as described in Appendix C. The logic for this decision, instead of making a detailed comparison of the sound levels in each frequency range for each system, is best understood by examination of Figure 52. Shown here are the octave-band plots of sound-pressure as recorded on the interior of 13 vehicle systems at 30 mph (data plots of 15-mph recordings have generally the same shape for each particular system but lower by 3 to 10 db in each octave band). These data curves are best suited for detailed analysis of the sounds encountered in each system; a band-by-band comparison of all the systems was made in the computation of loudness level as described in Appendix C.

4.13 Table 1 presents some comparative data on rapid transit vehicles at two test speeds. These overall levels were computed by using the sound-pressure level in each octave band as obtained by laboratory analysis of the magnetic tapes. The 15-mph data represents an attempt to include more than one test speed, as a means of ensuring continuity of results in comparing systems. It was also hoped that the low-speed data would be useful in identifying particular noise problems and in explaining differences among systems. Unfortunately, however, it was not possible in every case to obtain data samples at the lower speed; for this reason the table is incomplete. Therefore the discussion at this point will be confined to the data obtained at 30 mph.

4.14 The lowest overall sound-pressure level at 30 mph was recorded in the Hamburg vehicle. However, on a loudness-level basis the Berlin vehicle system appears the quietest of the systems tested, although the Washington bus and the Hamburg vehicle are not significantly louder (less than 3 phons). This can be seen in Table 2, which presents the 30-mph data from Table 1 in vehicle system rank order.

TABLE 1

## NOISE MEASUREMENT DATA, VEHICLE INTERIOR IN SUBWAY

| System | Average Sound-Pressure Level, db | | Average Loudness Level, phons | |
|---|---|---|---|---|
| | 15 mph | 30 mph | 15 mph | 30 mph |
| Boston | *1/ | 95 | * | 97 |
| Chicago | 86 | 92 | 89 | 98 |
| New York | 87 | 94 | 90 | 98 |
| Philadelphia2/ | * | 98 | * | 103 |
| Toronto | 82 | 85 | 84 | 90 |
| Berlin | * | 86 | * | (85) |
| Hamburg | (78) 3/ | (80) | 83 | 87 |
| Lisbon | * | 91 | * | 97 |
| London | 83 | 87 | 84 | 95 |
| Paris (rubber tire) | 82 | 86 | (81) | 89 |
| Stockholm | 80 | 86 | 84 | 92 |
| Washington(bus)4/ | 85 | 85 | 86 | 86 |
| Madrid (TALGO)5/ | * | 92 | * | 91 |

1/ Asterisk indicates data not taken at this speed.

2/ 1938 equipment.

3/ Circle indicates lowest number in column.

4/ Bus on suburban expressway.

5/ TALGO train on open track near Madrid, Spain.

NOTE: For the 15 mph and 30 mph test runs, METRO engineers reported 73 db and 83 db, respectively, using a sound-level meter. The meter weighting scale used was not reported.

respectively, using a sound-level meter. The meter weighting scale used was not reported.

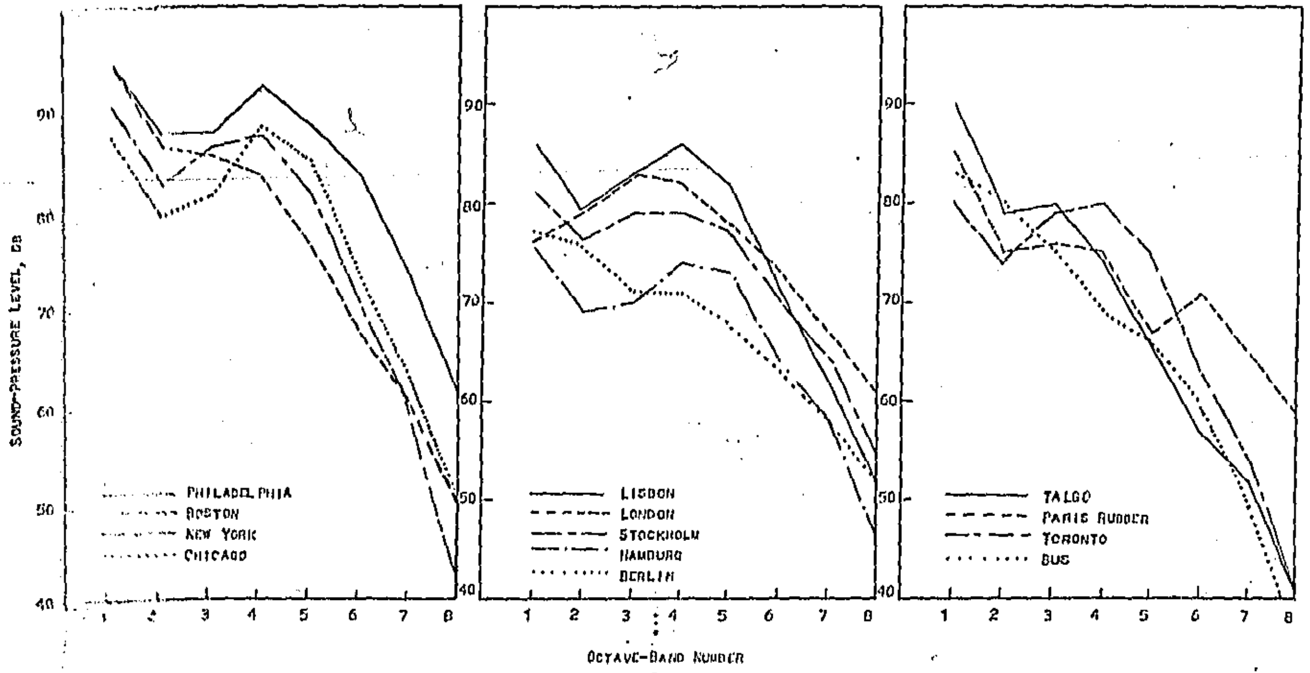

FIGURE 52. OCTAVE-BAND SOUND-PRESSURE LEVELS FOR 13 VEHICLE SYSTEMS, 30 MPH

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## TABLE 2

## NOISE DATA IN RANK ORDER, VEHICLE INTERIOR, 30 MPH[1]

| Average Sound Pressure Level, db | | Average Loudness Level, phons | |
|---|---|---|---|
| Philadelphia | 98 | Philadelphia | 103 |
| Boston | 95 | New York | 98 |
| New York | 94 | Chicago | 98 |
| Chicago | 92 | Boston | 97 |
| Madrid (TALGO) | 92 | Lisbon | 97 |
| Lisbon | 91 | London | 93 |
| London | 87 | Stockholm | 92 |
| Berlin | 86 | Madrid (TALGO) | 91 |
| Paris (rubber tire) | 86 | Toronto | 90 |
| Stockholm | 86 | Paris Rubber | 89 |
| Washington (bus) | 85 | Hamburg | 87 |
| Toronto | 85 | Washington (bus) | 86 |
| Hamburg | 80 | Berlin | 85 |

[1] All data taken in subway with exception of Washington bus and TALGO train.

4.15 If a difference of 5 phons[4] is taken as significant, the system can be ranked very generally as follows:

| | |
|---|---|
| Loudest:<br>(97 to 103 phons) | Philadelphia, New York, Chicago, Boston, Lisbon |
| Moderately loud:<br>(91 to 96 phons) | London, Stockholm, TALGO |
| Quietest:<br>(85 to 90 phons) | Toronto, Paris rubber-tired, Hamburg, Washington bus, Berlin. |

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[4] Standard noise-criteria curves, used in industrial and office noise control work, are calculated in 5-phon LL increments.

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4.16 This grouping is sufficiently accurate to permit the following observations.

- a. American systems comprise the loudest group. The quietest American system investigated[5] is louder than the loudest European system (at 30 mph) with the exception of Lisbon, where the high loudness is attributable to severe rail corrugation.
- b. The Washington bus and the Paris rubber-tired systems belong to the quietest group. However, the Berlin, Hamburg, and Toronto steel-wheeled systems also belong to this group.

## FACTORS INFLUENCING TEST RESULTS

4.17 In considering the relative position of each vehicle system, the reader should be aware that the data are in some cases influenced by test variables that were beyond the control of the research team during the time available. For example, the only data that could be obtained in an empty test train at a controlled test speed in Lisbon were obtained on sections of corrugated track. This condition undoubtedly contributed to a higher noise level than would be measured for the Lisbon vehicle on rail in normal condition, as was the case for most of the other systems tested.

4.18 Track condition was also undoubtedly a factor in producing an unusually high noise level (for open-track measurements) inside the TALGO train. In this case it was necessary to take the data during a normal run between Madrid and a point about 12 miles distant, on a section of line characterized by extremely poor maintenance. This track (nonwelded) was in an extreme state of disrepair, to the extent that often the misalignment was plainly visible with the naked eye over short rail sections. Measurements on welded track in good condition would probably produce results that would place this vehicle in the quietest group. This statement is based on the fact that such results have been achieved in comparable locomotive-drawn, long-distance rail coaches.[6]

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[5] Shortly after completion of the test program, new cars were introduced on one line of the Boston system. The only data in this report on the new cars were obtained during a normal run at 45 to 50 mph and are presented later in this section.

[6] Harris, _op. cit._, Beranek, _op. cit._

4.19 The Paris rubber-tired vehicles are ventilated by a series of open ports in the roof. Although it is true that the data presented in this report are an accurate measure of the noise levels of these vehicles as they are now operated on the Metro, it is also true that no other system tested had such a ventilation system. Closing the ventilation ports would undoubtedly lower the loudness level but the amount of decrease is subject to question. It is probable that the amount of improvement would amount to no more than 3 to 5 phons. This statement is based on measurements made during the Boston pilot study at the beginning of this project, in steel-wheeled vehicles with open and closed windows in tunnel at speeds of 15 to 20 mph. The maximum improvement in that case was on the order of 5 phons. The improvement in the Paris vehicle could conceivably be about the same at a somewhat higher speed because the ventilation ports are located in the roof of the vehicle away from the primary source of noise. Also note that the measurements in Paris were made from the front car of a two-car train, probably the most favorable position for any vehicle investigated in this study. Measurements made from the rear of a longer train with closed ventilation ports could, therefore, conceivably remain at about the same level as indicated in this report for a two-car train with open ports.

4.20 The reader should remember that the data for the bus were obtained during operating on open suburban expressway. The noise levels measured during operation in subway would be considerably higher than on open road. However, data on buses in subway could not be obtained for this study.

4.21 Considering all factors, the loudness levels indicated for the five quietest vehicle systems (85 to 90 phons) would seem to accurately bracket the lowest loudness range that has been achieved to date for steel-wheeled and rubber-tired systems, when operated in subway at 30 mph.

4.22 When operated at speeds higher than 30 mph, the noise levels will, of course, be higher than the levels indicated. In the course of normal operation in subway it is not unusual that peak speeds of 50 mph are reached, if only briefly. In an attempt to document the noise levels generated at these speeds, an effort was made throughout this study to secure samples of data at speeds above 30 mph. The results of these efforts are presented in Table 3 for those systems having the lowest loudness levels at speeds approaching 50 mph. All data presented here were obtained in empty vehicles, with windows closed. These data probably represent the maximum noise levels of rail systems that can be

## TABLE 3

## HIGH SPEED NOISE DATA

| System | Sound-Pressure Level, db | Loudness Level, phons |
|---|---|---|
| Berlin, 40 mph in subway | 86 | 91 |
| London, 40-45 mph in tunnel | 88 | 93 |
| Toronto 45-50 mph in subway | 86 | 90[2] |
| Boston, 45-50 mph in subway[1] | 86 | 90 |
| Bus, 50 mph on Dulles Access Road | 88 | 87[2] |
| Chicago, 40 mph on open track | 84 | 86[2] |

[1] New 75-ft cars introduced in April 1963.

[2] Estimate, based on measured overall sound-pressure level.

expected during normal operation of a modern well-designed steel-wheeled vehicle. The maximum levels of the bus will depend on traffic conditions and the character of the roadway. These data were obtained in an air-conditioned bus on new suburban expressway with no close traffic.

4.23 The significance of these results lies in the implication that maximum noise levels in tunnel on the interior of modern rail vehicles can be controlled to levels approximating those in modern pneumatic-tired buses operating on open expressway. In addition, the data suggest that the rail vehicle is quieter than the bus when operating on open track. The Chicago data are not conclusive proof of this, but other studies of rail vehicle noise generally concur with these findings. Based on a comparison of other data it seems reasonable to assume that the measurements on open track in Berlin, Hamburg, and Toronto would produce results with lower noise levels than Chicago. Unfortunately, it was not possible to obtain such data during the visits to these systems, or for any of the other European systems except the TALGO train, in which case the results were unduly influenced by the condition of the track. The only other data on operation not in subway were obtained in New York and Boston on elevated track; the levels in both cases, at speeds of 30 mph were higher than the results indicated here for Chicago at 40 mph.

## SUMMARY OF VEHICLE, TRACK, AND ROADBED NOISE-REDUCTION FACTORS

4.24 The data gathered in this study indicate that modern rail transit vehicle systems can be made to operate at the same levels of loudness as rubber-tired vehicle systems. In some cases the steel-wheeled systems were actually found to be quieter. For comparison purposes it should be instructive to review some pertinent features relating to noise of the three rail systems identified as quietest by the measurement results. These features are listed in Table 4.

4.25 This listing makes it possible to hypothesize on the value of some of the features. There is a danger in making broad generalizations on the basis of these results, however, because of the lack of quantitative information on the effectiveness of particular noise control measures within each system. Also it was not possible within the scope of this study to make a detailed study of the relative noise contribution of each design feature or component of a particular system. For example, the body insulation in the London vehicle might be more effective than the insulation in the Hamburg vehicles even though lower noise levels were measured in the latter, but there is no way of telling this from the data at hand. London was the only place where a test of the effectiveness of a particular noise control measure was possible. There it was determined that the asbestos baffles along the tunnel walls helped reduce the noise levels within a train traveling at 40 mph to approximately the same levels as measured at 30 mph while traveling in a tunnel without baffles. However, in that case some of the reduction was undoubtedly due to the use of longer sections of welded rail in the 40-mph test section (compared to shorter sections of nonwelded rail in the 30-mph test section).

4.26 Some interesting hypotheses are suggested, however, by Table 4. For example, the measurements were made on standard ballasted track in Hamburg but on concrete roadbed in Berlin and Toronto. The results suggest that ballast is not necessary for effective noise control. The primary reasons for the low-noise levels in Berlin and Toronto are not indicated. The results could be due to track alignment, vehicle body insulation, or the method of rail mounting.

4.27 However, the important point is that concrete roadbeds need not be

TABLE 4

TABLE 4

SUMMARY OF VEHICLE, TRACK, AND ROADBED NOISE CONTROL FEATURES, THREE QUIETEST RAIL SYSTEMS (85-90 phons)

| Feature | Berlin | Hamburg | Toronto |
|---|---|---|---|
| Tunnel configuration | Box-shaped, 11.4 ft wide by 14.5 ft high | Box-shaped, 24 ft wide by 14 ft high | 16 ft dia. tube |
| Special noise reduction features to tunnel walls | Sound-absorbent wall coating in some sections | None | Sprayed asbestos mixture on walls |
| Roadbed | Concrete | Ballast | Concrete |
| Rail weight | 82.5 lb/yd | 80 lb/yd | 100 lb/yd |
| Track mounting | Rubber pads between rail and tie plate, set on concrete crossties resiliently mounted in concrete roadbed. | Wood pad between rail and tie plate, on wood crossties set in crushed stone ballast. | Rail directly on metal tie plate; rubber pad and concrete grout pad between roadbed. |
| Vehicle wheels | Solid | Resilient | Solid |
| Use of rubber in trucks | All-rubber suspension, resiliently mounted motor (axle-suspended), rubber buffers between truck frame and motor-axle set. | All-rubber suspension, resiliently mounted motors, rubber buffers between bogie members. | Air and steel springs with rubber vibration pads. No rubber otherwise. |
| Vehicle body material and insulation | Steel with bituminous-base floor undercoating and 5 mm sprayed cork on body members. | Steel with 3 mm sprayed cork on body members. | Aluminum-alloy body construction, heavy coat of anticorrosive paint under floor. |

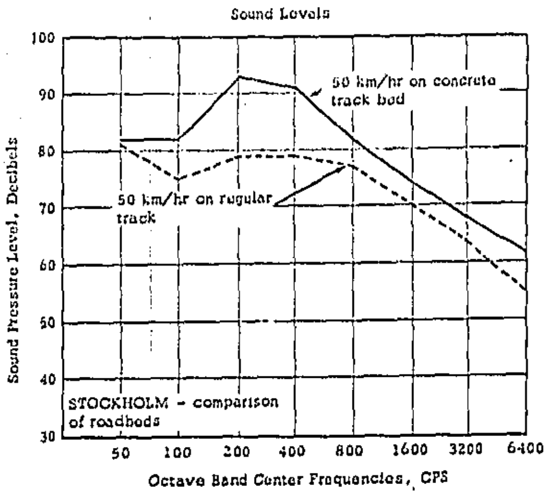


FIGURE 53. STOCKHOLM - COMPARISON OF NOISE SPECTRA FOR BALLASTED AND NONBALLASTED TRACK

a reason for higher noise levels than ballasted track construction, as has so often been the case. In both Stockholm and Hamburg, for example, noise levels on experimental sections of concrete roadbeds were observed to be higher than the noise levels measured on standard ballasted track. In Stockholm, particularly, the increase in noise when passing onto the concrete test section is so great as to be a source of annoyance. Figure 53 shows the difference in noise spectra for the two types of roadbed in Stockholm when measured from the same train. The computed loudness level indicates the magnitude of the problem in Stockholm, and illustrates that the low noise levels achieved in Berlin and Toronto on concrete roadbed are all the more significant.

4.28 Another interesting fact brought out by the comparison of system features is that of the three quietest rail systems only the Hamburg vehicles employ resilient wheels. In fact, Hamburg was the only system visited where resilient wheels are used to any great extent in subway operations. The resilient wheel has been or is, of course, standard equipment on the streetcars of many European and U. S. cities, and its value as a noise-control device is often cited. Stockholm, Berlin, Lisbon, and others were found to be currently conducting operational tests on bogies equipped with resilient wheels for possible future adoption but not primarily because of noise-control features. In Berlin the survey team was told that tests there with resilient-wheeled subway vehicle bogies indicated no significant decrease in noise over solid wheels. The apparent divergence of opinion as to the noise control value of resilient wheels for rail rapid transit vehicles suggests a need for further study in this area.

4.29 A third point brought out in the tabular comparison is that the Toronto vehicle employs almost no rubber in its bogie and suspension system in contrast with its use on the Berlin and Hamburg vehicles. The latter vehicles, in addition to all-rubber suspensions, use rubber liberally in mounting motors and as friction dampers between various components. Toronto uses neither a rubber suspension nor resiliently mounted motor, although rubber is used at one or two points in the bogie frame as a vibration damper. Toronto was the only vehicle (besides the Paris rubber-tired vehicle) included in this study that employs air-bolster suspension.

4.30 In addition, the Toronto vehicle has virtually no body acoustical insulation, compared with the other two. In view of these points, speculation naturally arises as to the reason for the comparatively low noise level of the Toronto vehicle system. There would seem to be some basis for seeking the primary causal factor in some feature of the system external to the vehicle itself. For example, the low noise levels might be due to the use of the sound-absorbent material in tunnel walls, or the significantly better track alignment and running surface combined with an acoustically superior rail mounting. With no more data than currently available, however, these are purely speculations.

4.31 Correspondingly, one can, at this point, merely conjecture as to the further decrease in noise level that could be achieved in the Toronto vehicle system by adoption of some of the features contained in the other two vehicles, such as some acoustical body insulation and resilient wheels. Likewise, it seems possible that some improvement could be attained in the Hamburg system by use of sound-absorbent material in the subway walls. In the case of Berlin the probability of a further decrease in noise level would appear to be slight, but the possibility should not be ruled out. It is feasible that some feature of the Toronto system, for example, could be utilized in Berlin to produce even quieter operation than now achieved. Obviously the degree of improvement in each case must be balanced against the economic cost of achievement, and this might rule out some of the possible alternatives. Although cost has been one reason in the past why lower noise levels have not been achieved in subway operations, an equally important reason has been lack of concern about noise. Today the wide variety of economical acoustical materials available and the increased knowledge about their use make effective noise control more a policy decision than a technical difficulty.

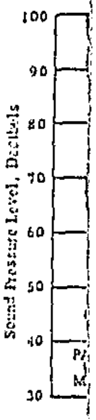
4.32 The point is that although the noise levels measured in Toronto, Berlin, and Hamburg represent the lowest yet measured for rail vehicles in subway, there would appear to be some basis for anticipating even lower noise levels in some future rail system. This might be achieved by combining the best features of these three systems as well as new ideas not yet tested.

4.33 Cost appears to be the primary obstacle to noise control, but this is not to imply that any improvement will necessarily be costly. The importance of noise in the design of a future system for the Washington, D.C., area must be established by the subway planners. The cost constraints will then determine very broadly how quiet the typical passenger's ride will be.

STATION NOISE LEVELS

4.34 The noise level inside subway stations during train movement is characterized by sudden, large changes. These sudden changes complicate the problem of presenting comparative data in a meaningful fashion. For example, the maximum noise levels during train arrival and departure occur during the time a train enters the station portion and brakes to a stop, as well as during the time of train acceleration out of the station. The maximum levels in most stations can be as high as 30 db above the background noise and typically fluctuate by this amount at least twice within a period of some 30 to 40 sec. In those cases where express-train operation through stations is encountered, the maximum levels occur for even shorter periods of time. Again, changes of considerable magnitude are involved.

4.35 For describing and comparing station noise levels, therefore, the "average" noise level conceals much about what happens. A common acoustical measurement procedure in the study of aircraft noise during takeoff is to consider the maximum sound-pressure levels that occur in each octave band during takeoff, irrespective of whether the maximum level in each band occurs at the same instant. This produces a more valid means for judging the annoyance of the overall noise level. This procedure was followed in analyzing the magnetic tape recordings made in selected subway stations during train arrival and departure. Figure 54 shows the noise spectra for two such subway stations, in terms of maximum



octave-band sound-pressure levels. Note that the arrival curve in the Paris station bends upward in the high frequency region (last octave bands) whereas the same curve for the Berlin station does not. The upward bend is caused by brake squeal, which can be one of the more annoying sounds encountered in stations. This phenomenon was encountered in many systems visited and is caused primarily by the type of brake shoes used on the trains, and the braking rate. Both the braking rate and approach speed of the trains entering a particular station may vary widely during normal operation and thus affect the overall noise level. Length of train is another factor that influences the noise, as well as "flat" spots on wheels. It is easy to see that an attempt to compare typical station noise levels may mean little unless the conditions are reasonably similar. Unfortunately it was not possible to conduct controlled tests of train noise in stations because of the short time spent in each city. The data presented for each system are generally one sample selected from those taken as being most representative of the conditions observed. In most cases four- or six-car trains were involved.

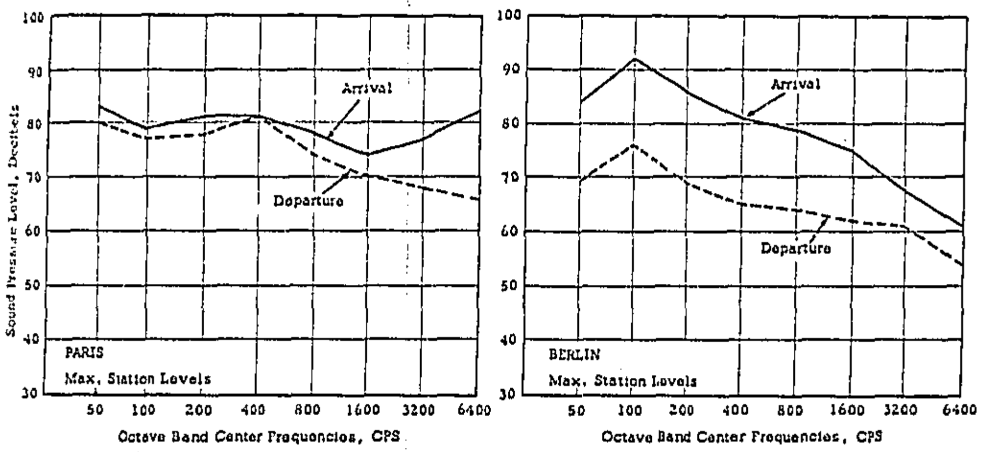


FIGURE 54. COMPARISON OF STATION NOISE SPECTRA FOR TWO SYSTEMS

4.36 The maximum octave-band sound-pressure levels shown in Figure 54 can be used to calculate overall sound-pressure level and loudness level, as explained in Appendix A. This was done for all the station recordings made, and selected results are tabulated in Table 5. The maximum overall levels during the period of passenger loading and unloading are also given to indicate the background noise level against which to compare the levels of train-produced noise. The loudness-level data from Table 5 are also shown in diagram form in Figure 55. It can be seen that the lowest maximum station loudness levels were measured for the Berlin and Toronto steel-wheeled vehicles and for the Paris rubber-tired vehicles.

4.37 The highest levels were measured on the Lisbon system for a train consisting of only two cars. The rail corrugation problem, which has already been mentioned, was the only detectable reason for such loudness. The corrugation is particularly severe on the station approach sections of track, and the noise generated by arriving trains is enough to alarm the unwary waiting passenger.

4.38 The Lisbon authorities have attempted, without success, to determine the causative factor for rail corrugation in their system. The mystery of the problem is accentuated by the relatively young age of the system (opened 1958). Although most systems visited reported the existence of rail corrugation somewhere in their system, Lisbon represents an extreme case of this phenomenon. Various hypotheses have been advanced as to the cause of rail corrugation, which was observed as early as 1890 in some systems;[7] to date, however, no generally valid method for its prevention has been discovered.

4.39 Lisbon was the only system visited where rail corrugation was actually observed to influence the measurement results. The phenomenon of brake squeal, however, was encountered in nearly every system visited, and in most cases was attributed to the iron or composition brake shoes. However, it was also noted in Paris during recordings of arrival of the rubber-tired train. These vehicles employ a brake system consisting of oiled-wood brake shoes pressing against the running surfaces of the auxiliary steel wheels. In Hamburg, where disc friction brakes are used on the nonmotored bogie of the new vehicles, some brake squeal was encountered. On the other hand, no brake squeal was observed in Berlin where an all-electric braking system is employed. In Toronto the occurrence of brake squeal was confined to trains of older cars, on which no data are presented in this report.

TABLE 5

NOISE-MEASUREMENT DATA IN SUBWAY STATIONS

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[7] Arnold Tross, "Der Mechanismus der Reibung," Glasers Annalen, December 1962. K. B. Mather, "Why Do Roads Corrugate?" Scientific American, January 1963.

TABLE 5

NOISE-MEASUREMENT DATA IN SUBWAY STATIONS

| System | Average Sound-Pressure Level, db | | | Average Loudness Level, phons | | |
|---|---|---|---|---|---|---|
| | Arrival | Stop | Departure | Arrival | Stop | Departure |
| Boston | * 1/ | * | * | * | * | * |
| Chicago | 100 | 78 | 92 | 106 | 82 | 99 |
| New York | 100 | 75 | 98 | 108 | 78 | 103 |
| Philadelphia 2/ | * | * | * | * | * | * |
| Toronto | 87 3/ | 81 | 87 | 96 | 84 | 93 |
| Berlin | 94 | 73 | 88 | 98 | 82 | 92 |
| Hamburg 4/ | 97 | 78 | 88 | 105 | 81 | 95 |
| Lisbon | 105 | 88 | 104 | 110 | 94 | 109 |
| London | * | * | * | * | * | * |
| Paris (rubber tire) | 88 | 65 | 96 | 101 | 68 | 93 |
| Paris (steel wheel) 5/ | 99 | 77 | 96 | 108 | 81 | 106 |
| Stockholm | 96 | 82 | 93 | 103 | 89 | 100 |
| Washington (bus) | * | * | * | * | * | * |
| TALGO train | * | * | * | * | * | * |

1/ Asterisk indicates data not taken.

2/ 1938 equipment.

3/ Circle indicates lowest number in column.

4/ Eight-car train.

5/ 1934 equipment.

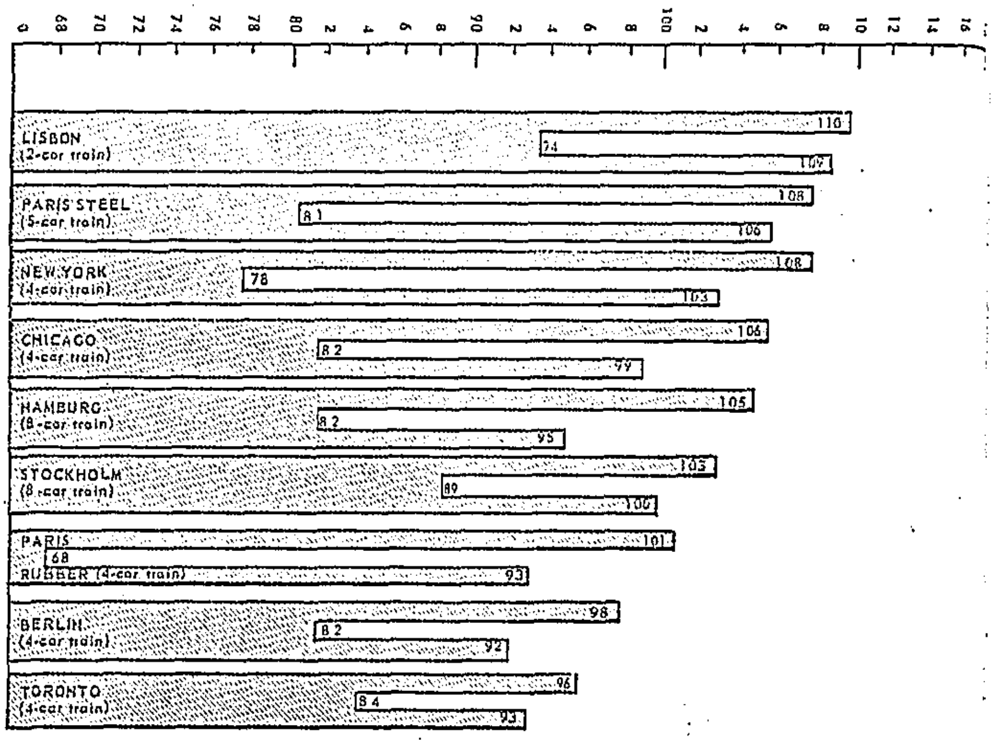

FIGURE 55. MAXIMUM STATION LOUDNESS LEVELS DURING TRAIN ARRIVAL, STOP, AND DEPARTURE

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4.40 In comparing the station noise levels shown in Figure 55, several points should be noted. First, Berlin and Toronto compete with the Paris rubber-tired vehicle as the quietest of the systems measured (no station recordings were made in Philadelphia and London). In each of these three cases the data were taken on four-car trains. The fact that only eight-car trains were available in Hamburg for the station recordings is the primary reasons why that system is displaced from the quietest group on this figure. Data taken in Chicago indicated that an increase in loudness of some 8 to 10 phons for a four-car train arrival, compared with a two-car train measured in the same station. Assuming the same order of magnitude decrease in arrival loudness for a Hamburg four-car train compared with an eight-car train, then that system as well as Stockholm would be counted in the quietest group, which would measure on the order of 96 to 101 phons.

4.41 The position of Toronto and Berlin as the quietest stations measured again reflects the efforts made by operating managements of both these systems to control noise. In Toronto strips of glass fiber sound-absorbent material similar to that used in the subway walls were originally installed under the platform overhang in stations. In the new University Street line, however, the glass wool has been discarded in favor of a coat of asbestos-asphalt mixture. The new material reportedly is not affected by dust and dirt (as is the glass wool), presents fewer maintenance problems, and is said to be more effective. In the tube section stations, a suspended ceiling of sound-absorbent material is used that also helps reduce sound reverberation time (see Figure 56).

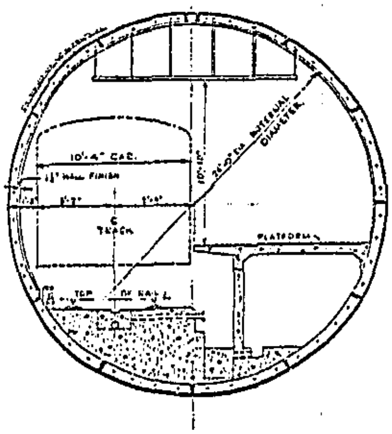

FIGURE 56. TORONTO-GEOMETRY OF TRAIN TUBE SECTION STATION SHOWING SUSPENDED ROOF

4.42 In Berlin the station walls and roof have been treated with a sound-absorbing bituminous-base material known as "phon killer." As in Toronto, sound-absorbent material is also installed along the underside of the platform facing in some stations, although not in the station for which data are given in this report. Berlin also employs another noise control measure that was not seem elsewhere; the space between the tracks in stations has been filled with blocks of a porous concrete-base sound-absorbent material (see Figure 57). Experiments are also presently being conducted to determine the effectiveness of a cork-base mixture sprayed on station walls.

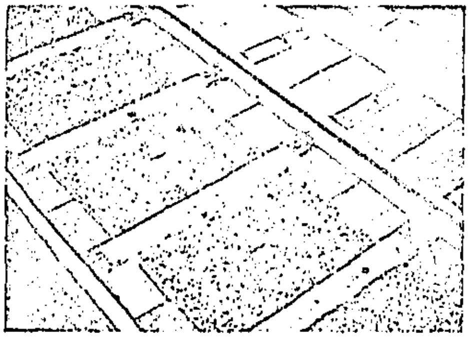

FIGURE 57. BERLIN – SOUND-ABSORBENT MATERIAL BETWEEN RAILS IN STATIONS

## RAPID TRANSIT NOISE VS OTHER TRANSPORTATION NOISES

4.43 Among transportation vehicle noises, the subway train probably enjoys a worse reputation in this country than deserved. In some cases, maintenance practices and old equipment are among the primary reasons for this, as pointed out in an earlier section. Subway noise probably ranks lower on the list of objectionable noises than in years past, however, because of the emergence of such louder noises as jet airplanes and the increase in bus and heavy truck traffic on city and suburban streets. In many U.S. municipal areas the noise from automotive traffic has reached such proportions that restricting legislation was passed. This section presents some noise data on various transport vehicles as obtained by other researchers, and compares these levels with the noise levels measured on one of the quieter rail rapid transit systems during this study.

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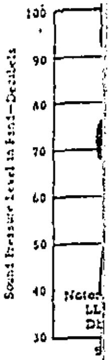

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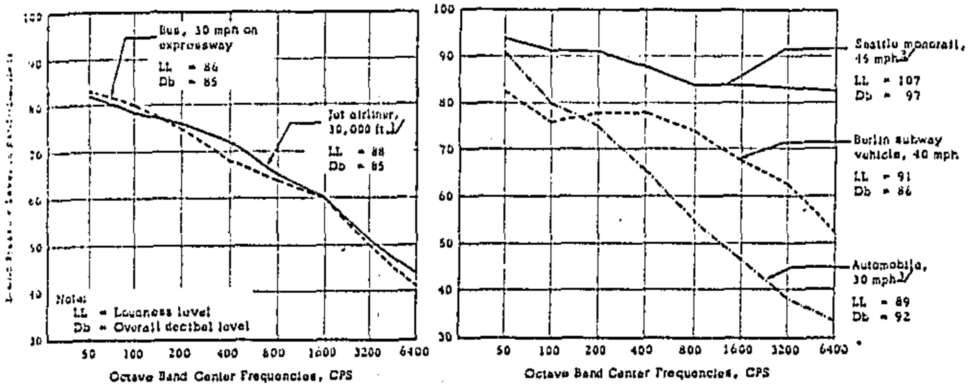
One of the more interesting facts to emerge from this comparison is that the noise levels measured on downtown city streets during daylight hours often greatly exceed the noise levels measured in most subway systems mentioned in this report.



Sources:

1/ Bolt, Beranek and Newman Inc., unpublished data

2/ Seattle Monorail, University of Washington Civil Engineering Dept., 1962

1/ Beranek, L. L., op. cit.

FIGURE 58. INTERIOR NOISE SPECTRA FOR FIVE VEHICLE SYSTEMS

4.44 The noise spectra for five types of transportation vehicles are shown in Figure 58 along with five overall levels computed from these spectra. Note that the computed loudness level in the rail transit vehicle operating at 40 mph in subway in less than the loudness level measured inside the Seattle monorail operating at 45 mph on open, elevated track. The Berlin vehicle would, of course, give quieter results on open track; in this case the monorail would be significantly louder than the Berlin rail vehicle. It will be remembered that the Seattle monorail train consists of pneumatic-tired vehicles running on an elevated concrete beam. Its quietness of operation has been praised as one of its most outstanding features.

4.45 Comparing the noise inside the jet airliner with that inside the Berlin rail vehicle, it would appear that the two are approximately the same order of magnitude in loudness. The significance of this comparison lies in the fact that the modern jet airliner is supposed to represent the ultimate in travel comfort, and passenger conversations at a distance of 2 ft are easily possible. The noise inside the airlines is, to be sure, of a different nature than that inside the subway vehicle (being more steady in level and less impulsive), but the level of annoyance, as represented by the loudness level, is about equal for the two vehicles.

4.46 The bus and rail vehicle have already been compared earlier in this section for operation at 30 mph. At that speed it has shown that the rail vehicle operating in subway was equal in quietness to the bus on open expressway. The significance of that comparison is that operation in subway normally produces noise levels inside the vehicle that exceed those produced at comparable speed on open track. At 30 mph this difference was measured to be 7 to 10 db on one rail system studied. At higher speeds the difference would be greater, of course. This comparison between the rail vehicle in subway at 40 mph and the bus on open road at 30 mph is important only in that it indicates merely a slight increase in loudness inside the rail vehicle because of the speed increase, so that the rail vehicle still compares favorably with the bus. Another important point to note is that the bus data shown here was collected inside an air-conditioned bus operating with closed windows in very light traffic. Operation with open windows in heavy traffic could produce noise levels inside the bus as high as 100 phons or more, depending on the amount of other bus and heavy truck traffic nearby.

4.47 Figure 58 shows that noise inside the rail transit vehicle at 40 mph in subway appears to be significantly louder than noise inside the automobile at 30 mph on open streets with closed windows. This comparison deserves some qualification, however. First, the noise level inside the automobile depends on the type of automobile: high-priced automobiles are quieter than low-priced automobiles[8] if the windows are always kept closed. If the windows are open even partially, the type of automobile is not as important as the condition of the road and the amount and type of surrounding traffic. In heavy traffic with open windows the noise inside the automobile will approach the level of the background traffic. For example, in city traffic, with open windows, and directly beside or behind a diesel bus or large truck, the loudness

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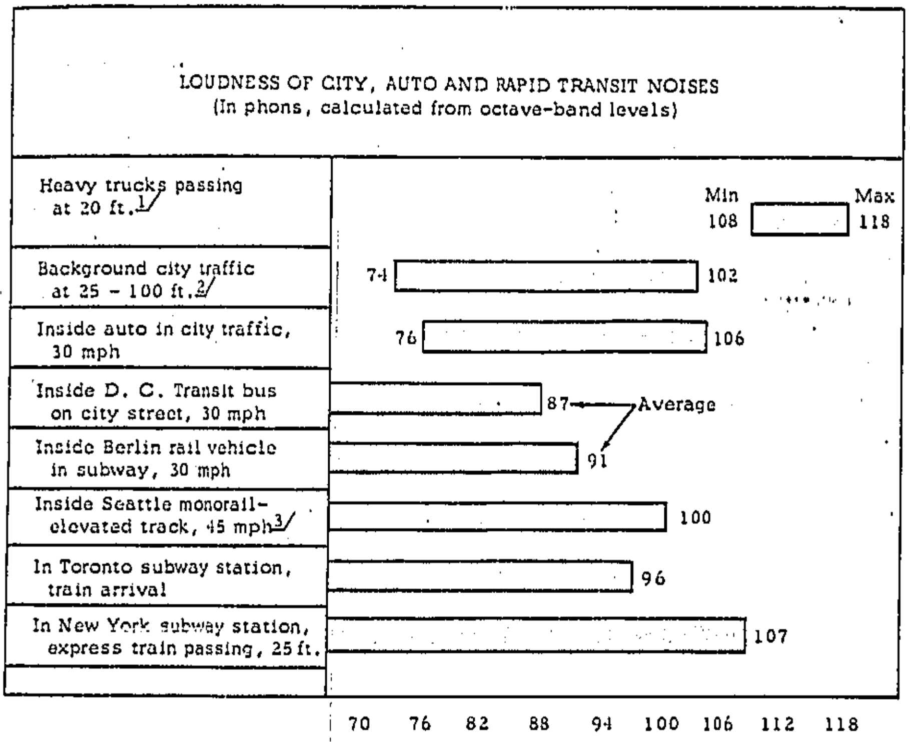
[8] Beranek, *op. cit*.

inside the automobile can approach 100 phons at a sound-pressure level of 95 to 100 db. During this study the noise level measured at the open window of a stopped automobile in downtown Washington, D.C., in light noon traffic, ranged from 75 to 85 db; buses accelerating from stops across the street raised the level to 88 db. It should be obvious from these remarks that primarily because of the surrounding traffic the noise level inside a typical commuter's automobile can vary significantly from the levels indicated in Figure 58. Noise inside the rail vehicle, operating on right-of-way in a well-controlled environment, is not subject to such variation. This depends, of course, on the system vehicle and roadbed maintenance standards.



1/ Salmon, V., "Surface Transportation Noise" Noise Control, July 1956.

2/ Combination of data from various sources

3/ "Seattle Monorail" op. cit.

FIGURE 59. LOUDNESS OF CITY AUTO AND RAPID TRANSIT NOISES

4.48 In order to obtain a better appreciation of the relative loudness of rapid transit noise and city traffic noise, Figure 59 was developed. In this comparison the results of other researchers are used in combination with data obtained by the ORI field team. This comparison shows that the noise on city streets often exceeds the noise levels encountered in two of the better rail transit systems. The noise of a New York subway train passing through a station is shown for comparison, not because it was the quietest event of this type but because it was the only such event recorded. As pointed out earlier, the noise levels encountered in New York were among the highest measured in this study. The noise of a passing express indicated here is well above that which would be encountered for the same event in a newer system such as Berlin or Toronto. Even so, however, note that the loudness of heavy trucks passing can exceed this figure. Another point to note is that the background level of city traffic noise can exceed the loudness of train arrivals in a subway station of a well-designed system. This comparison is significant because the noise of train arrivals in subway stations is the loudest noise a passenger would normally be exposed to in the course of a journey. In general, it would appear that the modern rail rapid transit vehicle system compares very favorably with other alternatives insofar as passenger exposure to noise is concerned. As the data indicate, the comparison may be very much in favor of the rail vehicle if compared with the automobile and bus in heavy traffic.

## CONCLUSIONS—CRITERIA FOR FUTURE SYSTEMS

4.49 The data collected in this study have identified the loudness range of the quietest rail systems measured as 85 to 90 phons, when operating at 30 mph in subway. It was shown that this loudness range compares favorably with pneumatic-tired vehicles at the same speed. The Berlin rail vehicle, which was quietest of all the vehicles measured at 30 mph, was also found to have a loudness of approximately 91 phons at 45 to 50 mph. These figures suggest a basis for the establishment of upper limits to use in the specification of allowable noise levels in any future rail vehicle system.

4.50 There exist today no generally accepted criteria for noise levels inside rapid transit vehicles. Northwood,[9] however, has suggested some criteria based on studies made in Toronto. He proposes the use of noise criteria curves (NC curves) developed from acoustical research into the effects of noise on workers in office buildings. These curves

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[9] T.D. Northwood, Rail Vehicle Noise, ASME-AIEE Joint Railway Council, 1962.

indicate the maximum allowable sound-pressure level in each octave band to permit a certain level of loudness. NC curve 50, for example, is the recommended upper criteria for an office conference room. In using these curves it is often desirable to specify a lower limit as well as an upper limit, to prevent relatively quiet sounds (such as conversation across the room) from becoming distracting. In such cases two NC curves are used to indicate the range of acceptability. In Figure 60, the shaded region indicates the sound-pressure levels that will permit conversation at a range of 3 to 6 ft but prevent disturbance by other conversations at ranges much greater than this. The two curves suggested by Northwood are NCA ("Noise Criteria Alternate") 65 and NC55.

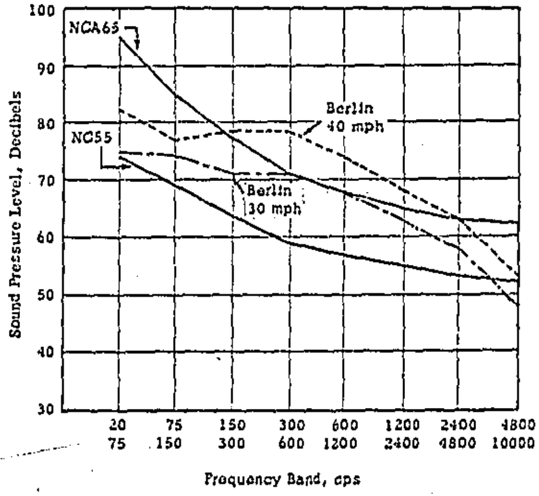

FIGURE 60. COMPARISON OF BERLIN VEHICLE NOISE SPECTRA WITH SUGGESTED DESIGN CRITERIA

4.51 It is interesting to see how the Berlin data compare with these criteria: at 30 mph the range of acceptability is met very well; at 40 mph the levels in the middle octave bands are above the recommended values. However, it would seem reasonable to expect that with normal advancements in noise control these differences in the middle band could be eliminated in a future system. As pointed out in Section II, research is continuing in Berlin. The Berlin authorities have stated their expectation that new types of track mounting being tested there now should contribute to noise levels on the interior of the vehicle that are lower than those on the present structure (which provided data for this study). Therefore, one alternative is to specify the shaded area between the curves NC55 and NCA65 as criteria for the range of allowable noise levels inside any future rail vehicle system operating at speeds of 30 to 40 mph in subway. This should result in a system quieter than any in existence today.

## V. VIBRATION MEASUREMENT RESULTS

### RIDE COMFORT CRITERIA

5.1 The determination of acceptable vibration levels in vehicle riding is a far more complex problem than the determination of acceptable noise levels. Although considerable research on the effects of vibration on the human body has been conducted, there exists today considerable disagreement among competent authorities as to the range of human response to complex motions such as encountered in vehicle riding. The extent to which the results of different researchers disagree is shown in Figure 61. This figure indicates the wide range in the magnitudes of vibration classified by various researchers as being generally unacceptable.

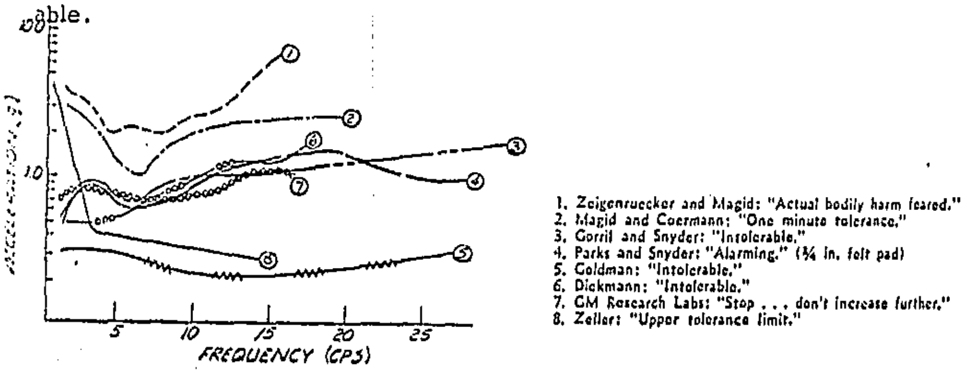

FIGURE 61. VIBRATION TOLERANCE DATA
("There are Plenty of Differences Among Ride Researchers," SAE Journal, June 1963.)

Semantic differences in subjective ride criteria may account for some of this disagreement. Some disagreement is also undoubtedly due to the influence of factors other than vibration on a passenger's subjective opinion of a ride.

5.2 The differences among tolerance criteria shown by Figure 61 are generally in regard to the effect of absolute values of vibration on the human body. There is, in contrast, fairly general agreement that the variation of vibration magnitude is more important than the absolute value at the frequencies normally encountered in rail vehicle riding. Some researchers have developed ride comfort criteria based on this hypothesis.

5.3 In view of the differences of opinion among authorities in this field, it should be obvious that determination of the absolute quality of a particular vehicle ride is at best an inexact procedure. On the other hand, it is possible to make general comparisons between different rides if the test conditions are similar and a consistent comparison procedure is used. Since the purpose of this study was not to determine the suitability of various criteria for judging vehicle ride quality, it was decided to make judgments of ride quality only on a comparative basis. To do this, it was necessary to select, from the many methods available, one ride comfort criteria computation procedure and use it as a means of obtaining numbers suitable for comparison. In the course of selecting the comfort criteria to be used in comparing the data collected in this study, many different criteria were examined.

5.4 Figure 62 shows the comfort criteria suggested by several different researchers plotted on the same graph.

5.5 These criteria apply to vertical vibrations only. It was found that few researchers have attempted to account for the difference in response of the human body to vertical and horizontal vibrations. However, two European researchers, Mauzin and Sperling, have suggested that vertical accelerations $\sqrt{2}$ times greater than lateral accelerations of the same frequency have the same comfort value. They developed "equal comfort" curves showing the response of passengers to horizontal and vertical accelerations that Loach[1/] used as the basis for establishing a quantitative method of judging the ride comfort of rail vehicles. The Loach method was used in this study for evaluation of ride data in the

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[1/] J. C. Loach, "A New Method of Assessing the Riding of Vehicle and Some Results Obtained," Journal of the Institution of Locomotive Engineers, June 1959.

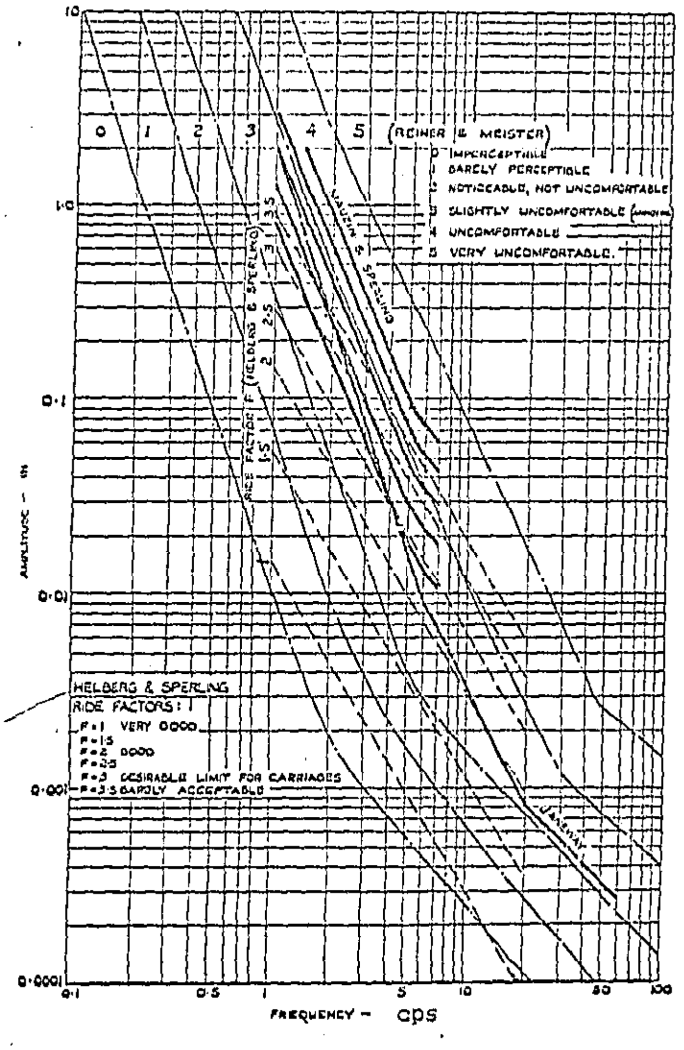

FIGURE 62. COMFORT CRITERIA SUGGESTED BY DIFFERENT RESEARCHERS

approximate frequency range 1 to 10 cps.[2] Vibration data in higher frequency ranges were evaluated with the aid of criteria proposed by Dyer, as shown in Figure 63.

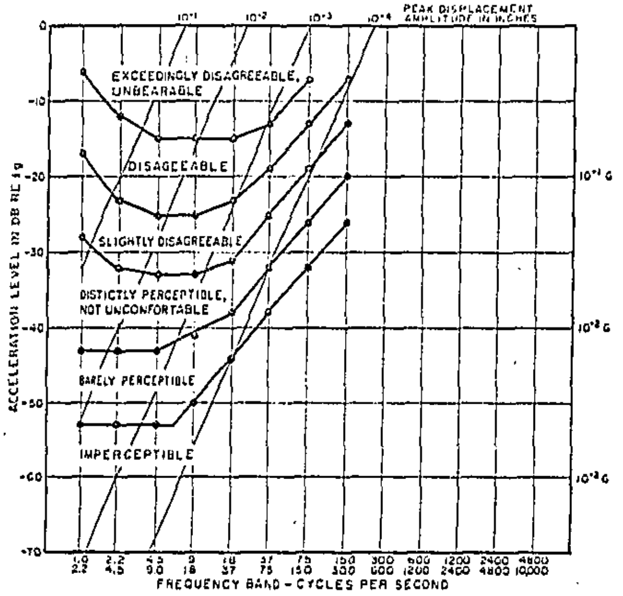

FIGURE 63. DYER COMFORT CRITERIA

5.6 Although these criteria apply only to vertical vibrations, they were modified by a factor of $\sqrt{2}$ for application to horizontal data. In the following sections, the methods of data analysis used are discussed briefly and the comparison method for each set of data is described.

## EXPLANATION OF DATA ANALYSIS PROCEDURE

5.7 Vibration data over a wide frequency range were collected in this study with the magnetic tape recorders. Because two levels of detail were required in the evaluation of these, two different analysis techniques were employed. One of these techniques was also used in processing the data collected with the mechanical ride recorder. The two techniques are as follows.

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[2] Loach and others suggest this frequency range as the most important frequency range of vibrations likely to produce discomfort in rail vehicle riding. Other researchers suggest the range is as high as 150 cps. Most agree that it is below 20 cps.

Frequency-Spectrum Analysis. This is a technique for detecting the average magnitude of vibration within discrete frequency bands, using filter networks to process data collected on magnetic tape. It is useful for analyzing data over a wide frequency range to determine in which frequency ranges the average vibration levels are highest. The technique has the disadvantage that the relative frequency of occurrence of vibration levels cannot be determined. Even though the majority of vibration energy may occur in a narrow frequency range, frequency-spectrum analysis will not indicate this. All the data collected on magnetic tape in this study were first analyzed in octave bands over the frequency range 4.5 to 1200 cps to determine the pattern of vibration.

Frequency-Amplitude Analysis. This is a detailed analysis technique for determining the frequency of occurrence of measured vibration levels. Both the magnetic tape records and the mechanical recorder records were analyzed in this manner, over the lower frequency ranges (below 10 cps). Using filter networks, it was possible to analyze the magnetic tape records over the frequency range of 2.2 to 10 cps. An electronic analyzer was used in processing the tapes, to count, electronically, the number of times the measured "g" forces exceeded given levels during each test run. The mechanical recorder records were analyzed manually.

5.8 In the following sections, the measurement results are presented and compared in three groups. The data collected on the mechanical ride recorder form one group; magnetic tape records included in the frequency-spectrum analysis form another; and magnetic tape records analyzed over low frequency ranges with the electronic analyzer form the third group. Table 6 indicates which techniques were used on each system. In the case of Hamburg, the mechanical recorder was not used for data collection. In Berlin, Lisbon, and on the TALGO train, the tape recorders were not used. In Boston, the magnetic tape data could not be used for low frequency analysis on the probability-density analyzer because of technical difficulties.

## COMPARISON OF FREQUENCY-SPECTRUM CURVES

5.9 One result of the Boston pilot study described in Section II was the determination that frequency-spectrum analysis of the vibration data collected during test runs does not provide sufficient information for comparing the ride qualities of different vehicles. This may be best understood by examination of some frequency-spectrum curves obtained in that study.

5.10 Figures 64 and 65 show the results of data analysis for three test conditions measured in the vertical and horizontal transverse directions, respectively, at the mid-car position. Both subaudible and audible

TABLE 6

DATA ANALYSIS GROUPS

| System | Frequency-Spectrum Analysis, 4.5 to 200 cps | Frequency-Amplitude Analysis, 2.2 to 10 cps | Ride Recorder Data, 1.0 to 10 cps |
|---|---|---|---|
| Berlin | NO | NO | x |
| Hamburg | x | x | NO |
| Lisbon | NO | NO | x |
| London | x | x | x |
| Madrid (TALGO) | NO | NO | x |
| Paris (rubber tire) | x | x | x |
| Stockholm | x | x | x |
| Toronto | x | x | x |
| Boston | x | NO | x |
| Chicago | x | x | x |
| New York | x | x | x |
| Philadelphia | x | x | x |
| Washington (bus) | x | x | x |

dcr

cps

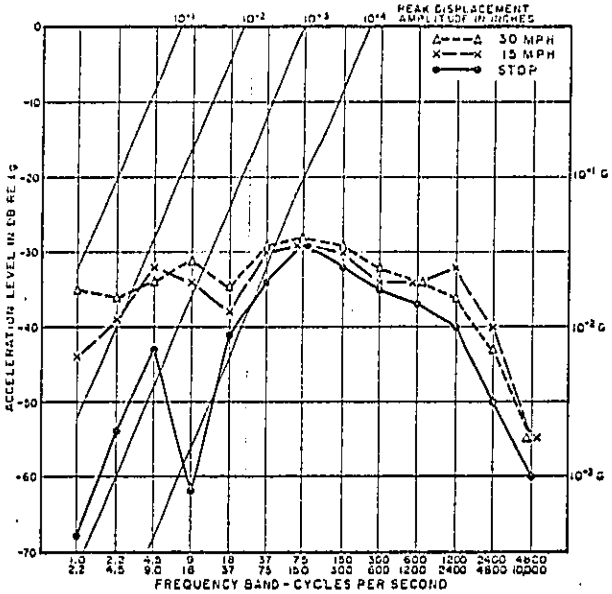

FIGURE 64. BOSTON MEASUREMENT RESULTS, VERTICAL DIRECTION, MID-CAR

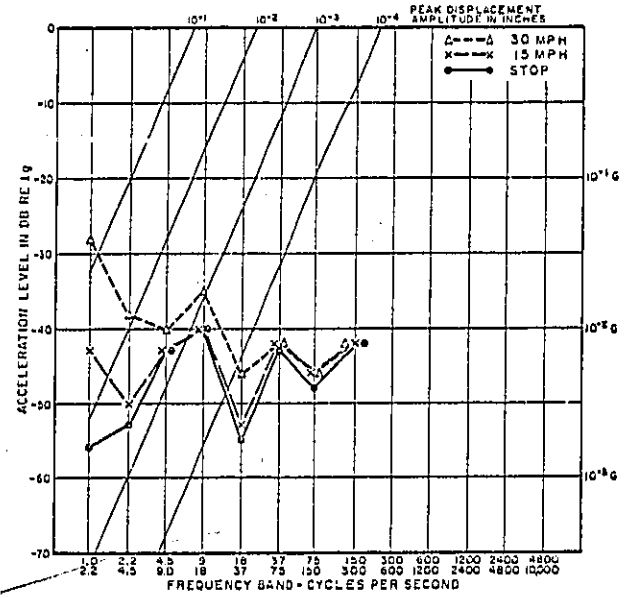

FIGURE 65. BOSTON MEASUREMENT RESULTS, HORIZONTAL TRANSVERSE DIRECTION, MID-CAR

vibration frequency ranges are covered in these graphs, in discrete frequency bands. Vertical data are plotted for the range of 1.0 to 10,000 cps; horizontal data are plotted only to 300 cps. These curves indicate the measured vibration levels in each frequency band, but they provide no indication of the relative frequency of occurrence of the measured forces. They also provide no means of determining the "average" frequency of vibration during each test run.

5.11 Note that in the case of both vertical and horizontal graphs, the shape of the 15-mph and 30-mph curves follows very closely the shape of the curve obtained by measuring the vibration levels with the train stopped, but with all auxiliary equipment operating. The vibration levels in the audible frequency bands above about 25 cps (center frequency of the 18- to 37-cps band) appear to be independent of train movement over the tracks. At both 15 mph and 30 mph the shape of the curves remains similar, showing only a small displacement with train speed above the "stop" condition. This suggests a means of estimating the contribution to passenger discomfort in these frequency bands without the necessity of making test runs at different speed conditions.

5.12 Although the general shape of the two-speed condition curves in the lower frequency bands is still similar, there is an immediate displacement from the stop condition curve with train movement, which becomes greater with an increase in train speed.

5.13 This displacement in the low frequency bands illustrates one reason for the decision to analyze the tapes in greater detail for low frequency vibration characteristics. The vibration levels in these bands are comparatively more important, from the standpoint of passenger discomfort, than the levels in the higher frequency bands, as can be seen by examination of the frequency-spectrum comfort criteria curves proposed by Dyer (Figure 63).

5.14 The foregoing remarks are in regard to Figures 64 and 65, which represent data measured at a mid-car position. However, they also apply to the data curves obtained from measurements at a position over the front truck. It was determined in the pilot study that measurement position within the car was relatively insignificant. The only noticeable difference in the measurements over the truck was an increase in the vertical vibration levels, particularly in the higher frequency bands. It was for this reason that all subsequent measurements were made over the front truck, and all comparisons made in this report are based on measurements taken from this position.

5.15 Figure 66 shows frequency-spectrum curves for test runs made in Stockholm and Paris (rubber-tired vehicle). These curves, which are typical of the curves used for system comparison, differ from those shown in Figures 64 and 65 in two respects: the frequency scale designation and the number of bands plotted. The scale designation is in terms of band center frequency instead of upper and lower frequencies as shown in Figures 64 and 65. The lowest band indication (6.25 cps) corresponds to the band 4.5 to 9.0 cps in Figures 64 and 65. The highest band indicated (800 cps) corresponds to the band 600 to 1200 cps. In between these extremes, the other indicated band center frequencies correspond to the bands shown in Figures 64 and 65 on a positional basis.

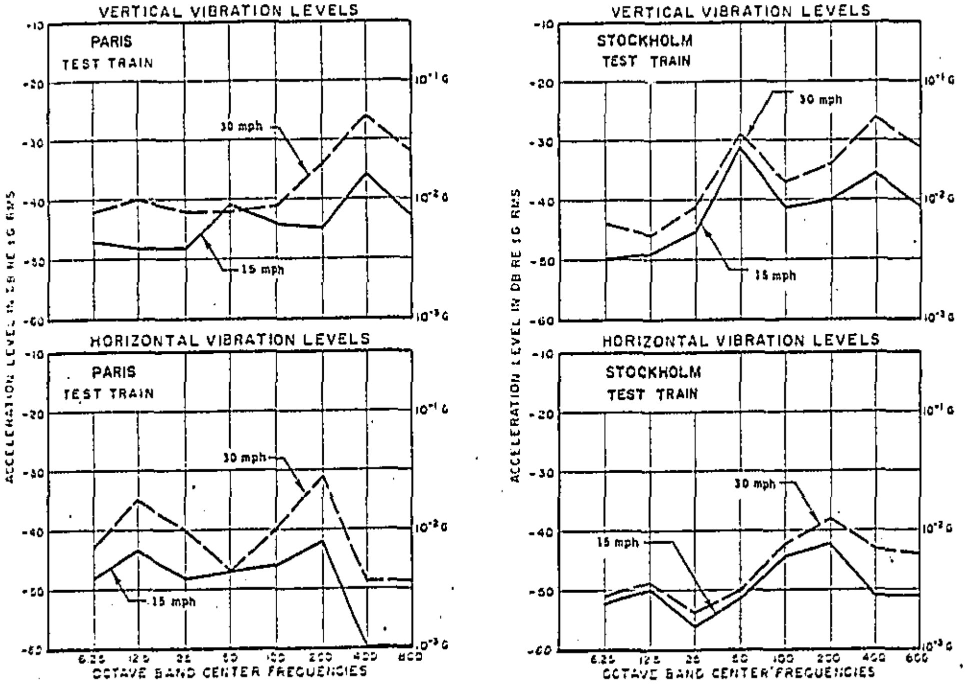

FIGURE 66. FREQUENCY SPECTRUM CURVES FOR TWO SYSTEMS

5.16 The scale in each case begins with the 6.25-cps band because no data were analyzed for lower frequency bands. An analysis including these lower ranges was made by another method permitting greater detail, and the results are presented later in this section. No data are plotted for bands above the 800-cps band since it was felt that the amount of information obtained was marginal for the cost involved. It can be seen

## TABLE 7

## COMFORT ZONE COMPARISON

| System | | Octave Band Center Frequency, cps | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.25 | | 12.5 | | 25 | | 50 | | 100 | | 200 | | 400 | | 800 | |
| | | LS | HS | LS | HS | LS | HS | LS | HS | LS | HS | LS | HS | LS | HS | LS | HS |
| London | V | 2 | 3 | 2–1 | 3 | 1 | 2 | 1 | 2–1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 2 | 3–2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Paris a/ | V | 2 | 3 | 2 | 3 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 2 | 3 | 2 | 3 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Stockholm | V | 2 | 2 | 2 | 2 | 1 | 2 | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 2 | 2 | 2–1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Hamburg | V | 2 | 2 | 1 | 2 | 1 | 2–1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Philadelphia | V | | 4 | | 4 | | 4 | | 4–5 | | 4 | | 2 | | 3 | | 2–1 |
| | H | | 3 | | 3 | | 2 | | 2 | | 2–1 | | 1 | | 2 | | 1 |
| Toronto | V | 3 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1–2 | 1 | 1 |
| | H | 3 | 3 | 2 | 2 | 1 | 2–1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| N.Y.C. | V | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 1 | 2 | 1 | 2 | 1 | 2–1 | 1 | 1 |
| | H | 2 | 3 | 2 | 3–2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Chicago | V | 3 | 3 | 2–1 | 3–2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3–4 | 1 | 3 | 1 | 2–1 |
| | H | 2 | 2 | 1 | 2–1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Washington bus b/ | V | 3 | 3 | 4 | 4 | 2 | 2–3 | 2–3 | 2–3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 2–3 | 3 | 4 | 5 | 3 | 3 | 2–1 | 2–1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Washington bus c/ | V | 4 | 4 | 2–3 | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | H | 2 | 4–3 | 2–3 | 3–2 | 1 | 2–1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Note:
1 = Imperceptible
2 = Barely Perceptible
3 = Distinctly Perceptible
4 = Slightly Disagreeable
5 = Disagreeable

LS = Low speed
HS = High speed
a/ Rubber tire
b/ Expressway
c/ City street

V = Vertical
H = Horizontal

from examination of the Dyer criteria that vibration levels in the frequency region above the 800-cps band, are least important from the standpoint of passenger discomfort.

5.17 The Stockholm and Paris curves can be compared visually, with the general conclusion that the levels measured in Stockholm are of the same magnitude as those measured in Paris. Another comparison of these curves can be made, however, using the Dyer comfort criteria proposed for interpretation of frequency-spectrum curves. These criteria offer a means of grouping the various systems according to measured vibration level in frequency zones graded for human response.

5.18 Using the Dyer criteria, it is possible to assign a number to the measured vibration level in each frequency band on each curve according to its position between the response curves. This has been done for each of the frequency-spectrum curves presented in Appendix A. The results are shown in Table 7.

5.19 For each test speed and measurement direction, the numbers shown in Table 7 can be combined over the frequency range of interest and ranked to obtain groupings of vehicle systems having approximately the same degree of ride smoothness (according to the Dyer criteria). This has been done for the 30-mph test run, and the results are shown in Table 8.

TABLE 8

VEHICLE SYSTEM RATINGS BASED ON DYER COMFORT CRITERIA
(For Frequency Range 4.5 to 37 cps)

| Group | Horizontal | Vertical |
|---|---|---|
| I (lowest vibration levels) | Chicago, Hamburg, Stockholm | Chicago, Hamburg, Stockholm |
| II (middle) | London, New York | London, New York, Paris (rubber tire), Toronto |
| III (highest vibration levels) | Paris (rubber tire), Boston, Philadelphia, Washington bus | Boston, Philadelphia, Washington bus |

5.20 In considering the results shown in Table 8, the reader should keep in mind that these groupings are based on a technique that is essentially a process for sensing energy levels in broad frequency bands. The limitations of this technique have already been pointed out. Because of these limitations, the vehicle systems have been grouped to deemphasize any attempt to rank in an absolute sense from best to worst. The purpose of this comparison is simply to identify vehicle systems with similar horizontal and vertical ride characteristics for the indicated frequency range. Two more comparisons between systems are based on ride characteristics in a lower frequency range. The results of these comparisons are discussed later in this section with the objective of identifying those systems that appear consistently "best" in each comparison.

5.21 In Figure 67 the vibration spectra for two test runs on different types of track are presented. The 40-mph data were obtained on a combination of 300-ft welded rail and shorter lengths, connected with machined fish-plate joints. The 30-mph data were obtained on 60-ft sections of track connected with standard fish-plate joints. Because of the difference in test speed, only a meager indication is provided (the test was not designed for this purpose). Nevertheless, it is interesting to note that approximately the same results were obtained at 40 mph on the welded rail as on the nonwelded rail at 30 mph. The pattern of vibration intensities is similar in both cases, lending additional support to the idea of a consistent signature for vehicles (in these frequency bands) irrespective of vibration from the track and roadbed.

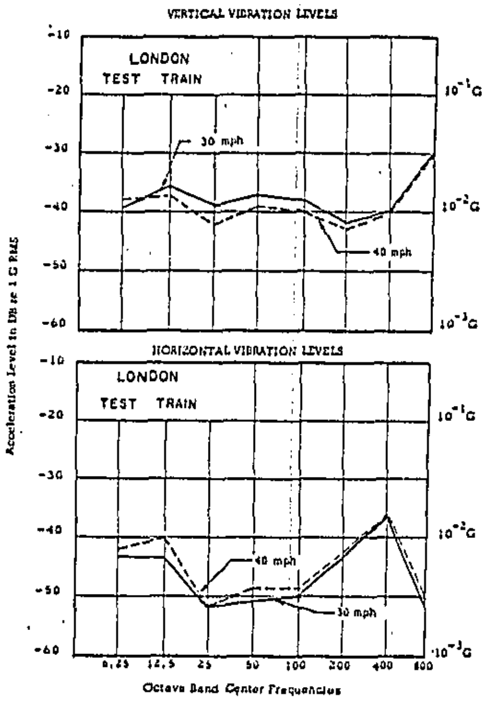

FIGURE 67. EFFECT OF TEST CAR SPEED

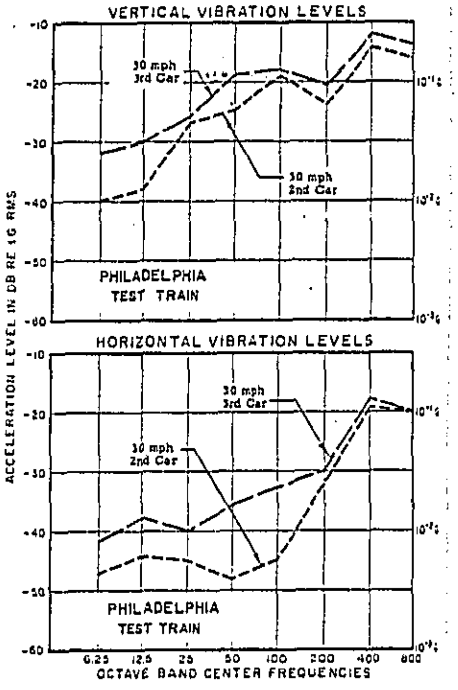

FIGURE 68. EFFECT OF TEST CAR POSITION

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5.22 The data in Figure 68 provide some indication of the effect of test car position within the test train. In these tests the recording equipment was located in the third car of a four-car train for the standard test run. A test run was also made during the return trip in the same subway section, with the equipment located in the same car, which, however, had become the second car of the train. The data indicate that the rear position produced the highest vibration levels, both vertically and horizontally.

## LOW-FREQUENCY ANALYSIS OF MAGNETIC TAPE DATA

5.23 Preliminary analysis of the vibration data in the manner described in the preceding section indicated a need for detailed analysis of the tapes in the lower frequency ranges. The analysis equipment employed did not permit interpretation of the data down to 1.0 cps; therefore, the analysis was done for the frequency range of 2.2 to 10 cps. In other words, the average frequency of occurrence of the measured vibration impulses that occurred during each 60-sec test run is within this range. It should be noted that the term "cps" as used in this report refers to the frequency of occurrence of the measured forces. It does not necessarily indicate a true sinusoidal pattern of the vibrations.

5.24 Figures 69 and 70 indicate, in graphic form, the type of initial results produced by the analysis procedure. These graphs show for horizontal and vertical measurements, respectively, the number of oscillations exceeding a given g value per second during the 30-mph test runs on six of the systems studied. Although these data were reduced further for comparisons among systems, the curves do give some idea of the physical-ride characteristics of the different systems. Steeply sloped curves on the left indicate a high frequency of oscillations of very low magnitude. Curves moving further to the right, with less steep slopes, indicate the occurrence of oscillations of greater magnitude but with a low frequency of occurrence. In general, those curves of approximately equal slope lying progressively to the right in both of these figures indicate less desirable riding characteristics. For example, it would appear that the Stockholm system gave superior horizontal ride characteristics because its curve lies clearly to the left of the other systems. In the graph of vertical data, it may be seen that the Hamburg curve lies at the extreme left, followed by Stockholm.

5.25 To facilitate better comparisons among systems, the data curves shown in Figures 69 and 70 were reduced to frequency-amplitude charts. A typical chart of this type is shown in Figure 71. This figure shows the relative frequency of occurrence of the measured vibration forces in each indicated g range. The computed average value of the measured forces

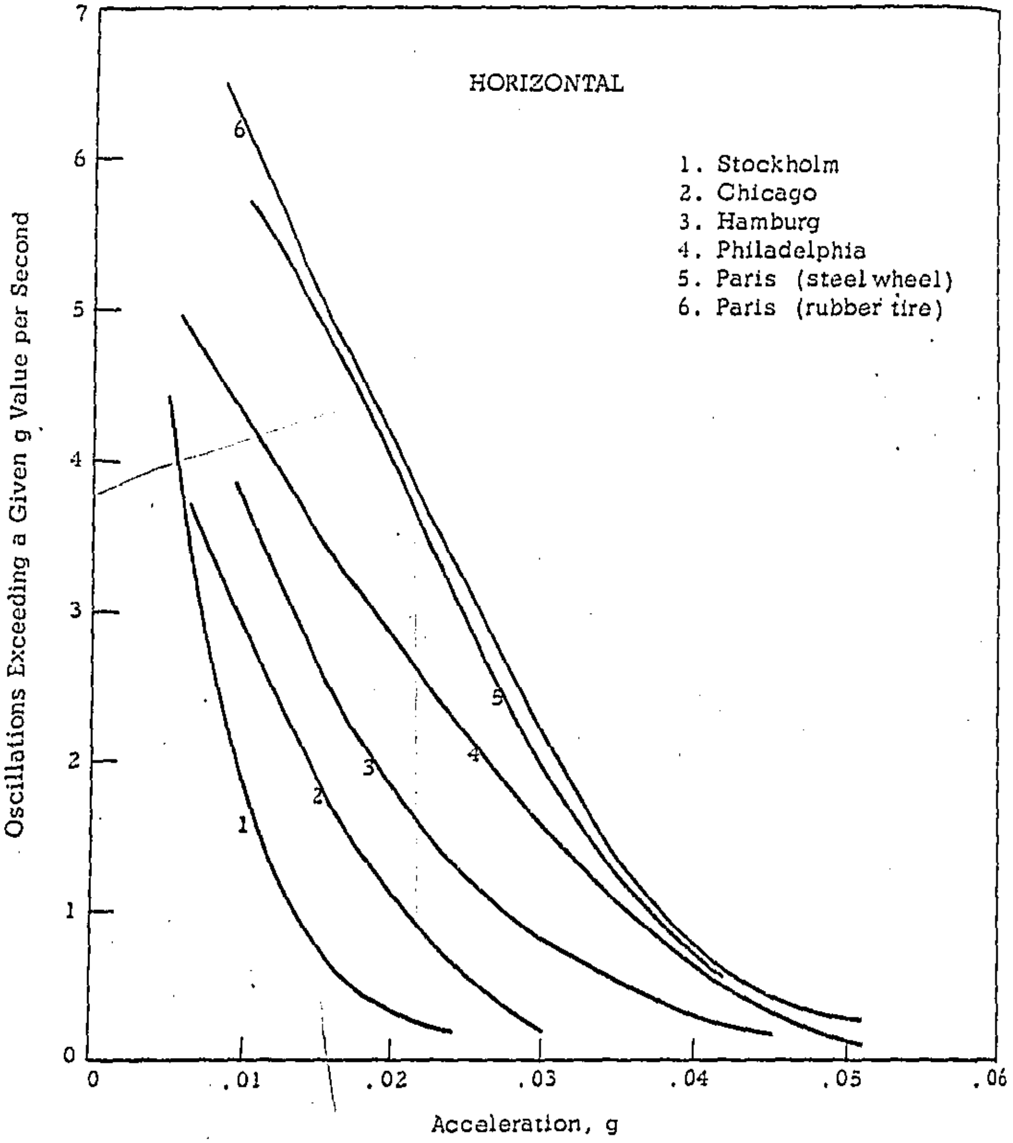


FIGURE 69. TYPICAL HORIZONTAL DATA GRAPH OF LOW-FREQUENCY TAPE ANALYSIS

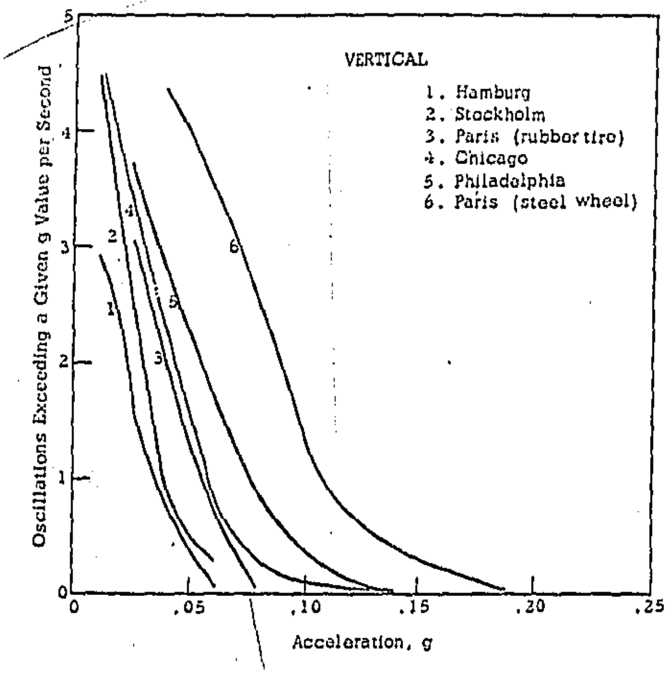


FIGURE 70. TYPICAL VERTICAL DATA GRAPH OF LOW-FREQUENCY TAPE ANALYSIS

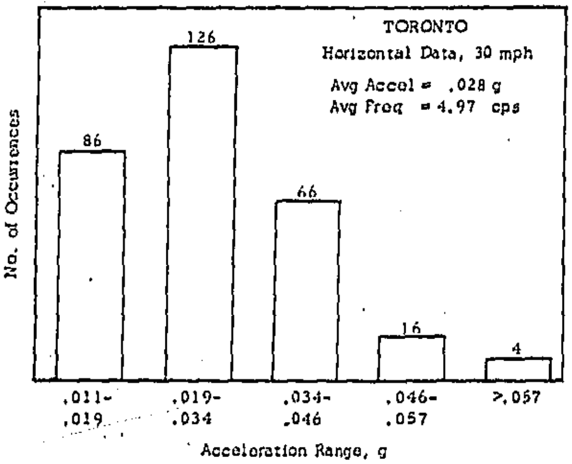


FIGURE 71. TYPICAL FREQUENCY-AMPLITUDE CHART DEVELOPED FROM INITIAL DATA ANALYSIS
(60-Sec Sample)

and the average frequency of occurrence of the oscillations is indicated on the chart. Additional frequency-amplitude charts are presented in Appendix D; however, the relevant statistics determined from these charts are summarized and discussed briefly in the following paragraphs.

5.26 Table 9 shows the computed average value and average frequency of occurrence of the g forces measured for each system analyzed in the manner described previously. Results are presented only for the 30-mph test runs. In the case of London, technical difficulties prevented analysis of the vertical data for the 30-mph test run; therefore, only vertical data at a test speed of 40 mph are presented.

TABLE 9

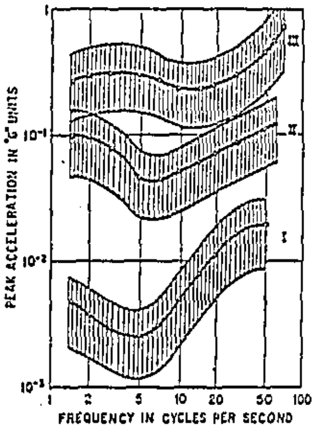
COMPARISON OF AVERAGE VALUES, LOW-FREQUENCY ANALYSIS OF MAGNETIC TAPES

| System | Average Vibration Level, g | | Average Frequency, Occurrence per Sec | |
|---|---|---|---|---|
| | Horizontal | Vertical | Horizontal | Vertical |
| Hamburg | .023 | .034 | 3.9 | 3.0 |
| London | | | | |
| (30 mph) | .028 | NA | 4.6 | NA |
| (40 mph) | .032 | .123 | 5.1 | 3.1 |
| Paris | | | | |
| (rubber tire) | .026 | .044 | 6.3 | 4.4 |
| (steel wheel) | .027 | .089 | 5.7 | 4.4 |
| Stockholm | .011 | .032 | 4.4 | 4.5 |
| Toronto | .028 | .025 | 5.0 | 5.0 |
| Chicago | .016 | .056 | 3.7 | 3.1 |
| New York | .034 | .031 | 4.0 | 4.8 |
| Philadelphia | .028 | .065 | 4.2 | 3.5 |
| Washington (expressway bus) | .108 | .035 | 8.6 | 9.1 |

5.27 One significant fact emerging from this comparison is that, for the rail vehicles, the average frequency of occurrence of the indicated vertical and horizontal g values is in a relatively narrow range of about 3.0 to 5.0 cps. Since the range of average g values is also comparatively small, the difficulty of ranking these systems in terms of ridability is increased. For both the bus and the rail systems, however, the range of frequencies is in a region considered by some researchers to be most important insofar as human discomfort is considered.

5.28 The foregoing can be seen by examination of Figure 72, in which the frequency range and the range of average values of the vertical and horizontal forces have been marked on the human response curves. Note that the measured values clearly lie in ranges of human discomfort.

5.29 Figure 73 indicates more data summarized from the frequency-amplitude graphs and is also useful in comparing the various systems. In this figure, the range of measured g forces is shown, along with the range that included 80 percent of the measured values. Displacement of a particular bar from the zero origin indicates that no forces less than this value were measured during the 60-sec test run at 30 mph. The upper value in each case is an approximation based on the highest value above which some vibrations were measured. Determination of the exact upper value is not possible since the analysis procedure merely indicated the number of times a given g value was exceeded, which is in each case approximately .05 g less than the upper value shown.



Average peak acceleration at various frequencies at which subjects perceive vibration (I), find it unpleasant (II), or refuse to tolerate it further (III). The shaded areas are about one standard deviation on either side of the mean. Data averaged from seven sources.

FIGURE 72.[3] HUMAN VIBRATION RESPONSE DATA

5.30 The large difference in the range of forces measured in the various systems is apparent in Figure 73. Note that in some cases a particular system has, relative to other systems, different rankings of horizontal and vertical forces. For example, New York produces the

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[3] D. E. Goldman, "Effects of Vibration on Man," Handbook of Noise Control, C. M. Harris, 1957.

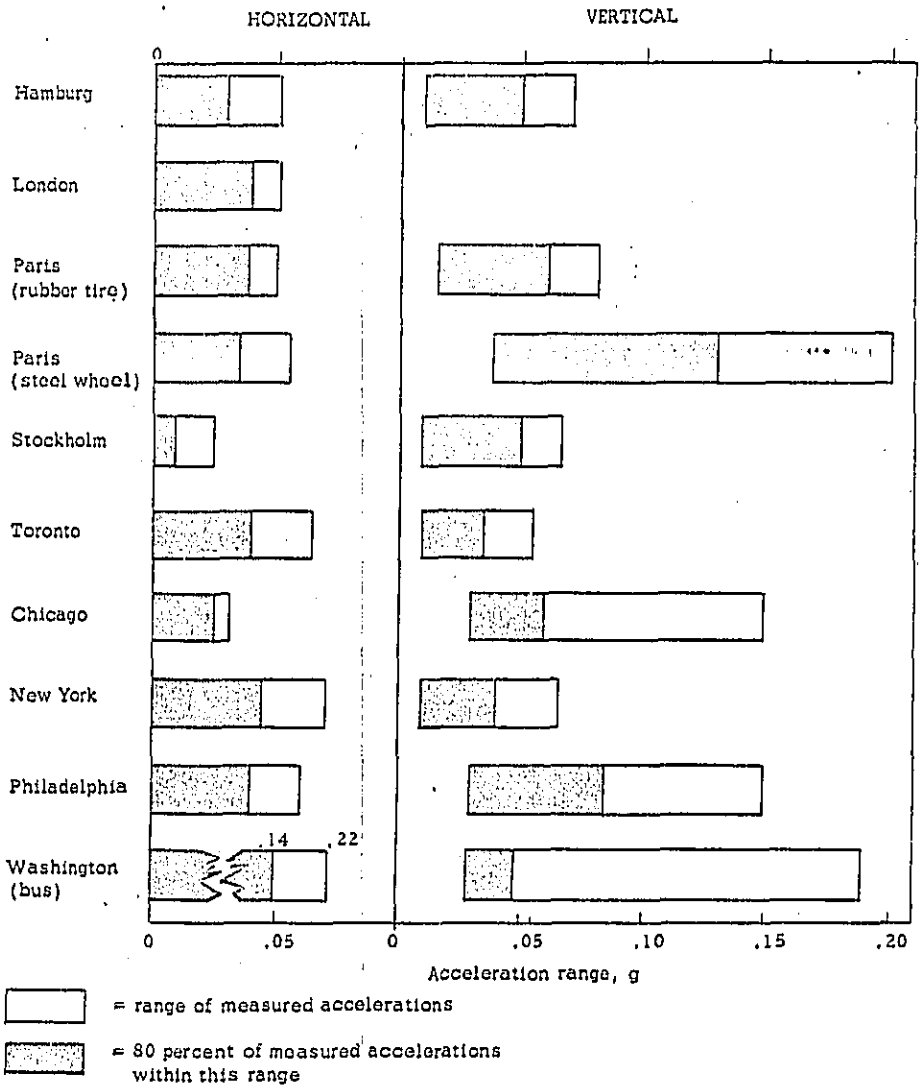

FIGURE 73. RANGE OF MEASURED ACCELERATION LEVELS

the highest g values measured horizontally, but not vertically. Obviously, in order to group these systems in regard to ridability, some method must be used to measure the combined effect of horizontal and vertical forces. There is at present no such method demonstrated as valid. However, it is possible to obtain horizontal and vertical ratings separately and to use these ratings in assigning an approximate overall group order to each system. The ratings are based on the lowest K factor, as described in the following paragraph.

5.31 The method used in this comparison for obtaining the horizontal and vertical ride indices was proposed by Loach.[4] It involves the determination of a comfort factor K that indicates the theoretical length of time an individual might ride without becoming fatigued while being subjected to accelerations of varying magnitude and frequency. In this report, computation of the comfort factor is made on the assumption that groups of vibrations having different amplitudes all occur with the same average frequency.[5] The comfort ride factor is expressed in hours; the higher the K factor, the better the ride. A factor of K = 6 hr is suggested as a standard regarded to be "adequate" by "average" passengers. However, Loach cautions that it is unwise to make too literal an interpretation of what the units mean. The chief advantage of the method is that the ride characteristics are expressed as a number, permitting easier comparison of different test results.

5.32 The results of the Loach comfort factor computation for the 30-mph test runs are indicated in Table 10.

TABLE 10

COMFORT RIDING FACTORS, 30 MPH (AFTER LOACH)

| System | Horizontal K Factor | Group Ranking | Vertical K Factor | Group Ranking | Combined Group Rank Order |
|---|---|---|---|---|---|
| Stockholm | 20.8 | (1) | 9.4 | (4) | 1 |
| Hamburg | 9.4 | (3) | 11.4 | (2) | 2 |
| Toronto | 6.7 | (8) | 12.7 | (1) | 3 |
| London | 7.5 | (6) | [*] |  | 3-4[**] |
| Paris (rub. tire) | 7.8 | (5) | 5.8 | (6) | 4-5 |
| New York | 5.6 | (9) | 9.8 | (3) | 5-6 |
| Chicago | 14.8 | (2) | 5.5 | (7) | 6-7 |
| Philadelphia | 8.7 | (4) | 4.2 | (8) | 7-8 |
| Paris (steel whl) | 6.9 | (7) | 2.3 | (9) | 8-9 |
| Wash (DC) bus | 1.0 | (10) | 7.8 | (5) | 9-10 |

[*] Data not subject to analysis.
[**] Based on relation of vertical factor to horizontal factor for 40-mph data, not shown here.

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[4] Op. cit.

[5] Loach has shown that the magnitude or error introduced by this assumption is on the order of 0.5 percent.

## COMPARISON OF DATA TAKEN WITH MECHANICAL RIDE RECORDER

5.33 The mechanical ride recorder was used throughout this study as an independent source of comparative ride data on the various systems tested. This device consists of four spring-loaded pendula, each of which activates a stylus through a system of mechanical linkages to record vibration levels on a waxed paper record. The paper record is driven at constant speed under the styli by a spring-wound motor. Two pendula are oriented for movement in the horizontal transverse direction, one for vertical movement, and the fourth for longitudinal movement. Each recording stylus is calibrated in inches-per-g.

5.34 Because the pendula are initially loaded with a tension of approximately .02 g, the ride recorder is not sensitive to extremely low forces. Also, because of the natural damping effect of the recording mechanism, the device has a limited frequency response. However, it is calibrated for the approximate range of vibration magnitude and frequency most likely to result in significant feelings of passenger discomfort. A typical record obtained with the ride recorder is shown in Figure 74. Very large displacements are easily read on the records, but a detailed frequency-amplitude analysis of each trace is often laborious. The vertical trace most often produces the greatest difficulty. With some practice, however, fairly accurate interpretation of the traces is possible. The advantage of the device is that significant differences in ride characteristics between vehicle systems are immediately apparent upon examination of the records. In this study, the results are used as a means of checking the system comparisons based on magnetic tape data.

5.35 Figures 75 and 76 show the results obtained in analyzing the records by specific amplitude ranges. The range in magnitude of the measured forces is clearly apparent in these figures, as well as the percentage of the total oscillations within specific g ranges. The total number of oscillations (N) of all magnitudes that occurred during a 60-sec period is indicated for each data sample.

5.36 Examination of Figures 75 and 76 shows that in most cases all or nearly all the horizontal forces lie within the range of 0 to 0.04 g. In most cases, the majority of vertical accelerations lie within the range of 0 to 0.07 g. The maximum forces were measured in Boston and London, where the test runs were made on unwelded track.

5.37 Table 11 indicates average values of acceleration and frequency of occurrence of the oscillations computed from the initial analysis results. If the average values in this table are compared with those shown

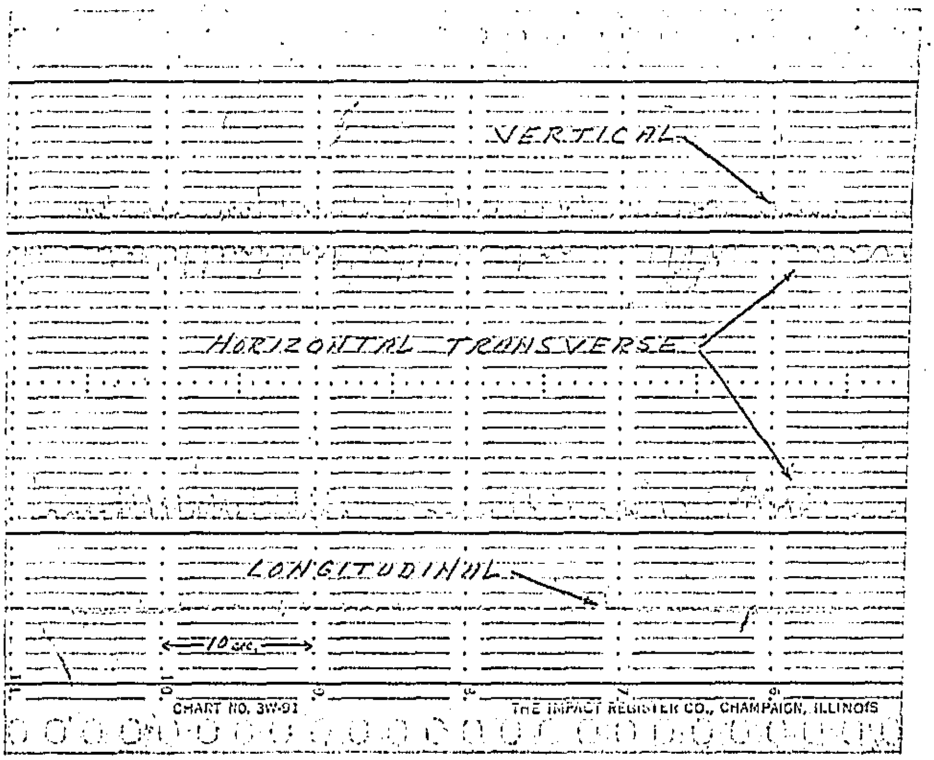
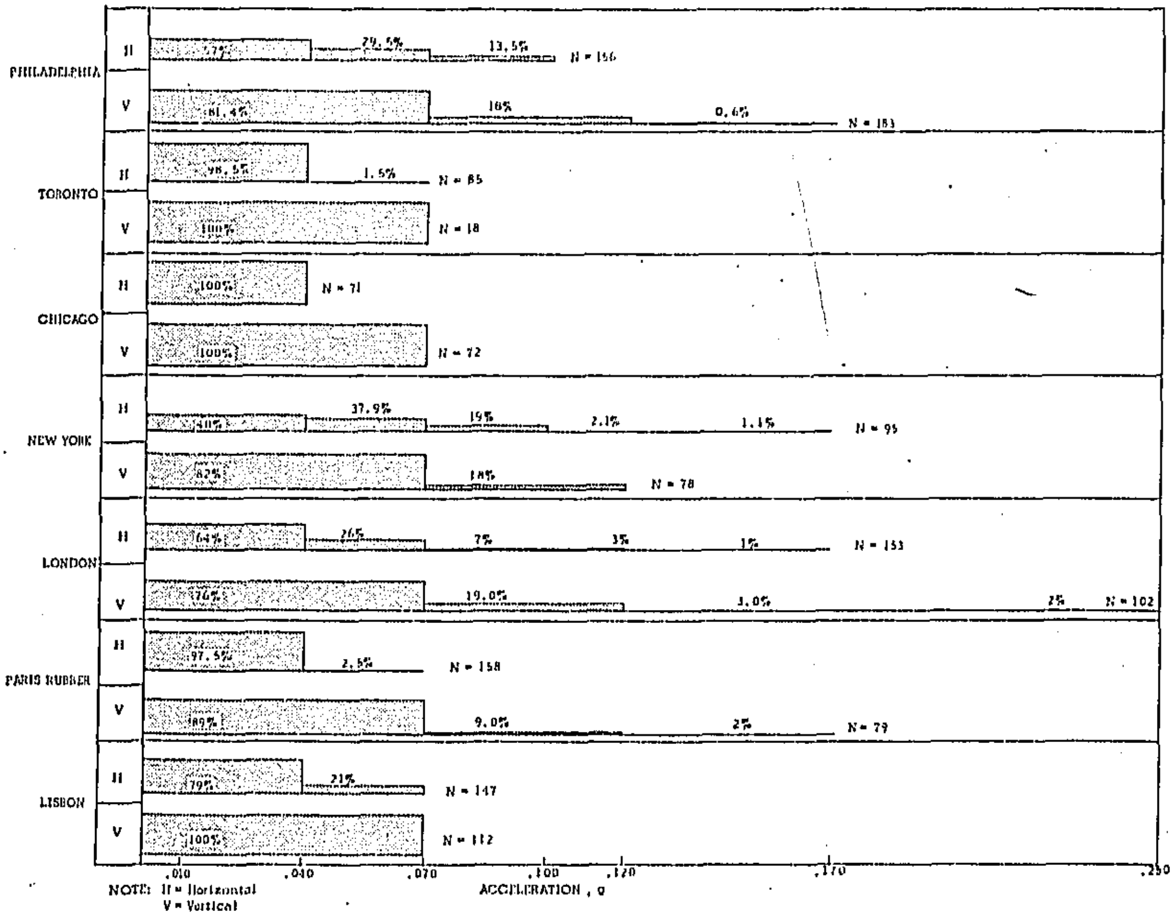


FIGURE 74. TYPICAL RECORD OBTAINED WITH MECHANICAL RECORDER



NOTE: H = Horizontal
V = Vertical

FIGURE 75. BREAKDOWN OF RIDE RECORDER MEASUREMENT RESULTS, SEVEN SYSTEMS

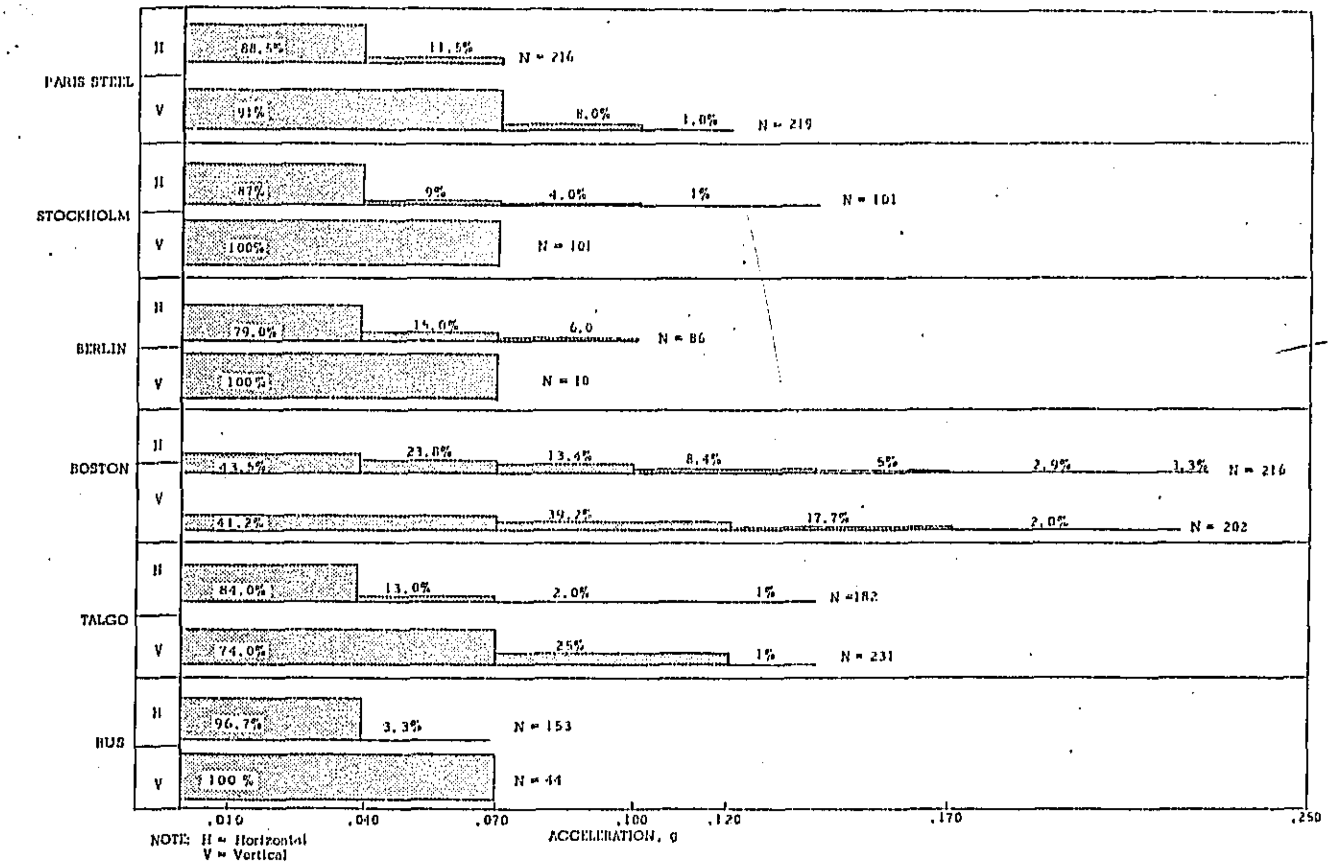


FIGURE 76. BREAKDOWN OF RIDE RECORDER MEASUREMENT RESULTS, SIX SYSTEMS

in Table 9, the difference in sensitivity of the two measurement systems is apparent. There is good general agreement between both sets of data for the computed average vibration levels. However the average frequency of measured oscillations is in every case lower for the ride recorder data because of its insensitivity to the very low magnitude g forces picked up by the electric accelerometers.

TABLE 11

RIDE RECORDER MEASUREMENT RESULTS, 30 MPH

| System | Average Vibration Level, g | | Average Frequency, occurrence per sec | |
|---|---|---|---|---|
| | Horizontal | Vertical | Horizontal | Vertical |
| Berlin | .029 | .035 | 0.7 | 0.16 |
| Lisbon | .042 | .035 | 1.2 | 1.90 |
| London (30 mph) | .038 | .055 | 2.5 | 1.70 |
| Madrid (TALGO) | .025 | .051 | 1.0 | 2.30 |
| Paris (rubber tire) | .024 | .041 | 1.6 | 1.20 |
| Paris (steel wheel) | .021 | .043 | 1.8 | 3.20 |
| Stockholm | .027 | .035 | 0.8 | 1.60 |
| Toronto | .020 | .035 | 0.7 | 0.40 |
| Boston | .064 | .081 | 2.0 | 3.40 |
| Chicago | .020 | .035 | 0.6 | 1.20 |
| New York | .050 | .050 | 0.8 | 1.30 |
| Philadelphia | .040 | .041 | 1.2 | 2.40 |
| Washington (bus) | .036 | .035 | 1.3 | 0.80 |

*/ Simultaneous measurements by METRO engineers with electric accelerometers and a direct-writing recorder produced the following 30-mph data: <u>Vertical</u> — maximum acceleration = 0.10 g, average acceleration = .05 g, average frequency of acceleration = 2.84 per sec; <u>Horizontal</u> — maximum acceleration = .015 g, average frequency = 1.3 per sec.

5.38 The ride recorder data given in Table 11 were used to compute ride comfort factors in the same manner as for the magnetic tape data. Table 12 presents the results of these computations, for horizontal and vertical measurements. The combined rank order is based on the smallest of the two comfort factors for each system.

3.39 In addition to the 30-mph data collected with the ride recorder, it was possible in several cities to obtain samples of data at speeds of

40 to 40 mph. These high-speed data were obtained for the most part during the test train's journey to or from the test areas for the 15- and 30-mph tests. In some cases the data were obtained for very short periods of time (less than 60 sec), and the conditions were not subjected to careful control. Therefore, the results of these measurements should be regarded as approximate figures only.

5.40 The results of the 40-mph measurements are shown in Table 13. It can be seen that in each case the computed 40-mph comfort factor is lower than for the corresponding 30-mph factor shown in Table 12. However, the general results are still the same; London and New York rank poorer than Berlin, Chicago, and the Washington bus.

## CROSS-COMPARISON OF 30-MPH MEASUREMENT RESULTS

5.41 The preceding sections have presented system rankings based on three separate sets of data using two different comfort ranking schemes. To facilitate identification of those systems appearing consistently in the "best" group, a cross-comparison of the ranking results was made. The format for this comparison is shown in Table 14, which permits a cross-comparison of every set of results for the 30-mph measurements.

5.42 The first three columns in the table present the group rankings for each of the three sets of data. Horizontal and vertical group rankings are indicated separately in the first two rows, and the combined group rankings is indicated in the bottom row. The "combined ranking" for each system is based on the lower of the system's two rankings (horizontal and vertical).

5.43 Four groupings are indicated within each box of Table 14. Group I consists of those vehicle systems judged best by the particular criterion used; Group II consists of systems judged not as good as those in Group I, but better than those in Group III, the lowest-ranked group. Group IV consists of systems on which no data were available for each of the indicated analysis methods. In the last four columns, systems shown in parentheses indicate that because of missing data, the group ranking is based on fewer than three sets of data techniques.

5.44 The composite group rankings, based on all three analysis methods, are indicated in the column at the extreme right of Table 14. The lower box in the column indicates the combined horizontal and vertical rankings. It can be seen that Stockholm, Chicago, and Toronto appear in Group I. These three systems were ranked consistently best with each analysis technique, as indicated by the absence of parentheses.

## TABLE 12

## COMFORT FACTORS BASED ON RIDE RECORDER DATA, 30 MPH (AFTER LOACH)

| Property | Horizontal | Vertical | Combined Rank Order |
|---|---|---|---|
| Toronto | 24.3 | 18.4 | 1 |
| Chicago | 25.3 | 17.3 | 2 |
| Stockholm | 15.0 | 14.9 | 3 |
| Paris (rubber tire) | 15.5 | 14.2 | 4 |
| Washington (bus) | 20.6 | 18.4 | 5 |
| Berlin | 13.6 | 18.4 | 6 |
| London | 8.4 | 7.1 | 7 |
| Philadelphia | 8.2 | 6.9 | 8 |
| Lisbon | 20.0 | 6.5 | 9 |
| New York | 6.5 | 10.9 | 10 |
| Paris (steel wheel) | 19.0 | 5.7 | 11 |
| Madrid (TALGO) | 13.6 | 4.5 | 12 |
| Boston | 3.1 | 3.0 | 13 |
| Hamburg | na | na | |

## TABLE 13

## SUMMARY OF RIDE RECORDER 40 MPH—MEASUREMENT RESULTS

| System | Avg Accel, g | | Avg Freq of Oscillations, sec | | Comfort Ride Factor, K | | Combined Rank Order |
|---|---|---|---|---|---|---|---|
| | Hor | Vert | Hor | Vert | Hor | Vert | |
| Berlin | .038 | .035 | 1.8 | 1.5 | 7.3 | 15.3 | 1 |
| Washington (bus) | .024 | .041 | 0.8 | 2.1 | 16.2 | 7.1 | 2 |
| Chicago | .021 | .053 | 1.1 | 1.8 | 19.0 | 6.4 | 3 |
| New York | .036 | .093 | 1.1 | 1.8 | 8.5 | 3.9 | 4 |
| London | .049 | .090 | 1.6 | 2.4 | 4.7 | 2.9 | 5 |

## TABLE 14

## CROSS-COMPARISON OF RIDE MEASUREMENT RESULTS IN TERMS OF GROUP RANKING

| | FREQUENCY SPECTRUM-ANALYSIS FS (Dyer Criterion) | FREQUENCY-AMPLITUDE ANALYSIS Accelerometer, FAA (Leach Criterion) | FREQUENCY-AMPLITUDE ANALYSIS (Ride Recorder), FAR (Leach Criterion) |
|---|---|---|---|
| HORIZONTAL | I. CHI - HAM - STO<br>II. LON - NYC - TOR<br>III. PAR$_R$ - BUS - BOS - PHL<br>IV. (BER) - (LIS) - (PAR$_S$) | I. STO - CHI - HAM<br>II. PHL - PAR$_R$ - LON<br>III. TOR - PAR$_S$ - NYC - BUS<br>IV. (BER) - (LIS) - (BOS) | I. CHI - TOR - LIS - BUS<br>II. PAR$_S$ - PAR$_R$ - STO - BER<br>III. LON - PHL - NYC - BOS<br>IV. (HAM) |
| VERTICAL | I. CHI - HAM - STO<br>II. LON - NYC - PAR$_R$ - TOR<br>III. BOS - BUS - PHL<br>IV. (BER) - (LIS) - (PAR$_S$) | I. TOR - HAM - NYC<br>II. STO - PAR$_R$ - CHI - BUS<br>III. PHL - PAR$_S$<br>IV. (LON) - (BER) - (LIS) (BOS) | I. BER-TOR-BUS-CHI-STO-PAR$_R$<br>II. NYC-LON-PHL-LIS<br>III. BOS - PAR$_S$<br>IV. (HAM) |
| COMBINED | I. CHI - HAM - STO<br>II. LON - NYC - TOR - PAR$_R$<br>III. BOS - BUS - PHL<br>IV. (BER) - (LIS) - (PAR$_S$) | I. STO - HAM - TOR - (LON)<br>II. PAR$_R$ - NYC - CHI<br>III. PHL - PAR$_S$ - BUS<br>IV. (BER) - (LIS) - (BOS) | I. CHI-TOR-STO-PAR$_R$-BUS-BER<br>II. LON-PHL-LIS-NYC-PAR$_S$<br>III. BOS<br>IV. (HAM) |

| | COMBINED GROUP RANKINGS | | | FINAL COMPOSITE RANKINGS |
|---|---|---|---|---|
| | FS - FAA | FS - FAR | FAA - FAR | FS - FAA - FAR |
| HORIZONTAL | I. HAM STO CHI<br>II. LON<br>III. TOR PAR$_R$ NYC PHL (BOS) BUS (PAR$_S$) | I. CHI STO TOR (HAM) (LIS)<br>II. LON PAR$_R$ (PAR$_S$)<br>III. NYC BOS BUS PHL (BER) | I. CHI STO (HAM) (LIS)<br>II. PAR$_R$ PAR$_S$ TOR (BER) BUS<br>III. PHL NYC (BOS) (LON) | I. CHI HAM STO (LIS)<br>II. TOR LON PAR$_R$ (BER) BUS (PAR$_S$)<br>III. NYC PHL (BOS) |
| VERTICAL | I. HAM<br>II. NYC STO TOR PAR$_R$ (LON) CHI<br>III. PHL (BOS) (PAR$_S$) BUS | I. CHI TOR STO (HAM) (BER)<br>II. LON NYC PAR$_R$ BUS (LIS)<br>III. BOS PHL (PAR$_S$) | I. TOR (HAM) (BER) BUS<br>II. STO NYC PAR$_R$ CHI (LON)<br>III. PHL PAR$_S$ (BOS) (LIS) | I. STO CHI TOR (HAM) (BER)<br>II. NYC PAR$_R$ (LIS) (LON) BUS<br>III. PHL (BOS) (PAR$_S$) |
| COMBINED | I. HAM STO TOR CHI<br>II. PAR$_R$ NYC (LON)<br>III. PHL (BOS) (PAR$_S$) BUS | I. CHI STO TOR (HAM)<br>II. PAR$_R$ LON BUS (BER) (LIS)<br>III. NYC PHL BOS (PAR$_S$) | I. STO TOR CHI (HAM)<br>II. PAR$_R$ (LON) (BER) BUS (LIS)<br>III. NYC PHL PAR$_S$ (BUS) | I. (HAM) STO CHI TOR<br>II. (LON) PAR$_R$ (BER) BUS (LIS)<br>III. (BOS) (PAR$_S$) NYC PHL |

| | | | |
|---|---|---|---|
| BER | BERLIN | NYC | NEW YORK CITY |
| BOS | BOSTON | PAR$_R$ | PARIS RUBBER |
| BUS | D.C. BUS | PAR$_S$ | PARIS STEEL |
| CHI | CHICAGO | PHL | PHILADELPHIA |
| HAM | HAMBURG | STO | STOCKHOLM |
| LIS | LISBON | TOR | TORONTO |
| LON | LONDON | ( ) | RATINGS BASED ON FEWER THAN 3 SETS OF DATA |

| | |
|---|---|
| GROUP I. | BEST RIDABILITY CHARACTERISTICS |
| GROUP II. | AVERAGE RIDABILITY CHARACTERISTICS |
| GROUP III. | POOREST RIDABILITY CHARACTERISTICS |
| GROUP IV. | NO DATA TAKEN |

Hamburg is also indicated in Group I, but that system's position is based on only two sets of data.

5.45 The most significant fact emerging from this cross-comparison of system rankings is the consistently high standing of some and the consistently low standing of others, regardless of the ranking technique used. This suggests that any of the measurement-ranking techniques used in this study can be used to determine the significant differences in the ride characteristics of various systems if consistency is maintained in the process.

5.46 In some cases, there is considerable fluctuation between groups for a particular system, depending on the measurement technique and ranking criterion used. For these systems, the final group position in the composite ranking is less certain than for those systems exhibiting more consistent positions, as pointed out above.

5.47 In regard to the rubber-tired vehicle rankings, Table 14 indicates that neither the bus nor the Paris rubber-tired vehicle appear in Group I of the composite rating. The Paris rubber-tired vehicle is clearly superior to the Paris steel-wheeled vehicle; on this basis, the claims in regard to the riding characteristics of the former appear justified. However, it would appear that these claims cannot be extrapolated to other situations, particularly where new systems are planned. The best ride characteristics measured in this study were exhibited by relatively modern rapid transit vehicle systems employing steel-wheeled vehicles operating on steel rails. The operational age of the best-ranked vehicle systems tested is indicated in Table 15, along with other pertinent data relating to ridability. [6]

5.48 Table 15 shows that most of the track-vehicle combinations tested that produced superior rides were quite new. This does not mean, however, that age alone was the primary reason for great differences in riding quality among systems. Stockholm and Chicago, both featuring older track, are included in the group measured as having superior ride characteristics. Furthermore, some of the systems that ranked poorer than the five systems shown in Table 15 featured either track or roadbed (or both) newer than the corresponding features for Stockholm and Chicago, e.g., London, 1959/62 vehicles; Lisbon, 1961 vehicles, 1961 track; New York, 1960 vehicles; Paris, 1962 track.

5.49 Insofar as type of roadbed is concerned, it would appear from Table 15 that this is not a significant factor because tests on ballast

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[6] Berlin is included in this table on the basis of the 30- and 40-mph ride recorder measurement results.

TABLE 15

SUMMARY OF SYSTEM FEATURES PERTAINING TO

TABLE 15

## SUMMARY OF SYSTEM FEATURES PERTAINING TO RIDABILITY (BEST-RIDING SYSTEMS)

| Feature | Stockholm | Toronto | Chicago | Hamburg | Berlin |
|---|---|---|---|---|---|
| Track type | Welded rail, 100 lb/yd | Welded rail, 100 lb/yd | Welded rail, 100 lb/yd | Welded rail, 50 lb/yd | Welded rail, 83 lb/yd |
| Roadbed | Ballast | Concrete | Concrete | Ballast | Concrete |
| Track mounting | Rubber pad between rail and wood crosstie | Rubber pad between rail and concrete roadbed | Rubber pad between rail and roadbed | Wood pad between rail and wood crosstie | Rubber pad between rail and concrete crosstie, crosstie resiliently mounted in concrete roadbed |
| Track installed | 1949 | 1962 | 1951 | 1962 | 1961 |
| Vehicle model | 1962 | 1962 | 1958 | 1962 | 1962 |
| Wheel type | Solid steel, 34-in. dia | Solid steel, 28-in. dia | Solid steel, 26-in. dia | Steel resilient wheel, 35-in. dia | Solid steel, 36-in. dia |
| Suspension system | Rubber at axles, steel coil springs at bolster | Steel coil springs at axles, air cushion at bolster with internal coil spring | Rubber at axles, steel coil spring with rubber cone insert at bolsters | All rubber | All rubber |
| Truck type | Welded-steel frame, outside journals | Cast-steel frame, inside journals | Cast-steel frame, inside journals | Welded-steel frame, outside journals | Welded-steel frame, outside journals |

and concrete roadbed gave comparable results (for different systems). The type of track mounting also appears to be of secondary importance, so long as some form of vibration-damping mechanism is used between rail and roadbed. On the other hand, condition of roadbed (including track) would seem to be of primary significance. There is, admittedly, no quantitative indication of track and roadbed condition among these data. But the available information suggests that this is a primary reason why different systems featuring similar vehicles and track of approximately the same age produce rides varying greatly in smoothness. The data suggest that track condition can significantly downgrade the ranking given to a modern vehicle, but cannot significantly upgrade the ranking of an older, less modern vehicle. The New York, Lisbon, and Paris steel-wheeled test results indicate this point.

5.50 With regard to type of suspension system employed, Table 15 suggests that this also would appear to be of secondary importance, so long as it possesses the proper springing and damping characteristics. No attempt is made in this report to define "proper" suspension characteristics because this depends on many factors that differ according to the particular situation. However, it should be noted that there is a high degree of similarity among rapid transit vehicle suspension characteristics, primarily because of the vertical and horizontal movement constraints imposed by platform height and tunnel clearance requirements. These constraints in turn have an effect on the natural frequency of oscillation of the suspension system and thus on ride smoothness. Those systems on which suspension data could be obtained reported maximum static deflections (no load to full passenger load) from 1.5 to 3.4 in. and natural frequencies (vertical) from 1.7 to 2.6 cps.

## CONCLUSIONS — NOTES ON RIDE COMFORT

5.51 It was shown in this section that there exists much disagreement about the range of human response to vibrations encountered in vehicle riding, particularly in regard to the upper vibration limits associated with a "comfortable" ride. Because of this, it was decided to judge system ride characteristics on a comparison basis by conducting identical controlled tests and evaluating the results in a consistent manner.

5.52 The data collected have identified those systems having the best ride characteristics when measured on straight track at a controlled speed. It was found that five steel-wheeled systems produced the best ride characteristics of the various systems tested, on the basis of three different comparison techniques, and using two types of instrumentation. These steel-wheeled systems ranked better than the Paris rubber-tired vehicle operating on concrete roadway and better than a modern city bus operating on new suburban expressway.

5.53 Although these results are valid for comparing specific track-vehicle combinations, they are of limited use in making general system comparisons of overall comfort level. No comparison was made, for example, of vehicle performance on curves; nor were such factors as the amount and degree of system curvature considered. A passenger riding for a considerable distance on first the Chicago system and then the Paris rubber-tired system might judge the latter as more generally comfortable because of fewer curves, smoother acceleration, and lower noise levels. However, on the basis of measured vibration characteristics there is no justification for saying that the rubber-tired vehicle produces an inherently smoother ride than the steel-wheeled system; in fact, the opposite is indicated when the two are compared under equal conditions.

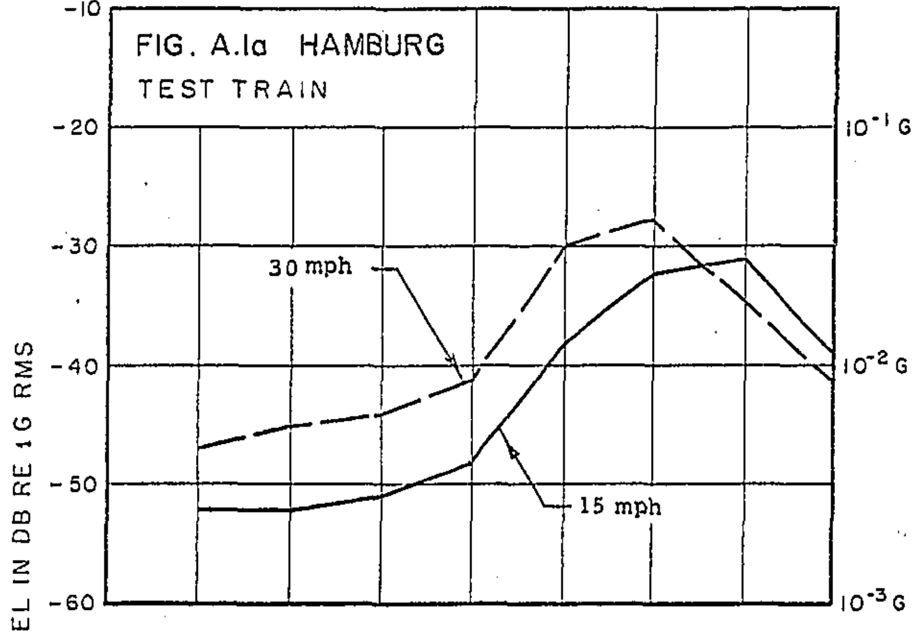
5.54 In regard to subjective opinions of ride quality, it was found during this study that noise contributes heavily to the general impression formed. In the case of Lisbon, for example, the exceptionally high noise levels encountered on certain portions of corrugated track produced a very poor opinion of overall ride quality. The vibration measurement results, however, showed the ride to be not so bad as believed. The same was also true in the case of Chicago, where high noise levels contributed heavily to the survey team's impression of a poorer ride than was indicated by the vibration measurement results.

5.55 It should be clear from these remarks and the data presented in this section that the judgment of vehicle ride quality is a complex problem. The establishment of criteria for evaluating vehicle comfort is likewise difficult and presently there exist no generally accepted criteria. If the effort to produce a system with superior ride and noise characteristics is made by employing the best designs, techniques, and materials that are available, a quieter and more comfortable car should result. It is still difficult to measure the quality of the result. A partial answer can be obtained by employing under similar test conditions the identical measurement and data evaluation techniques employed in this program. The data presented in this report should be useful in the establishment of ride comfort criteria, but they represent only a first step in that direction.

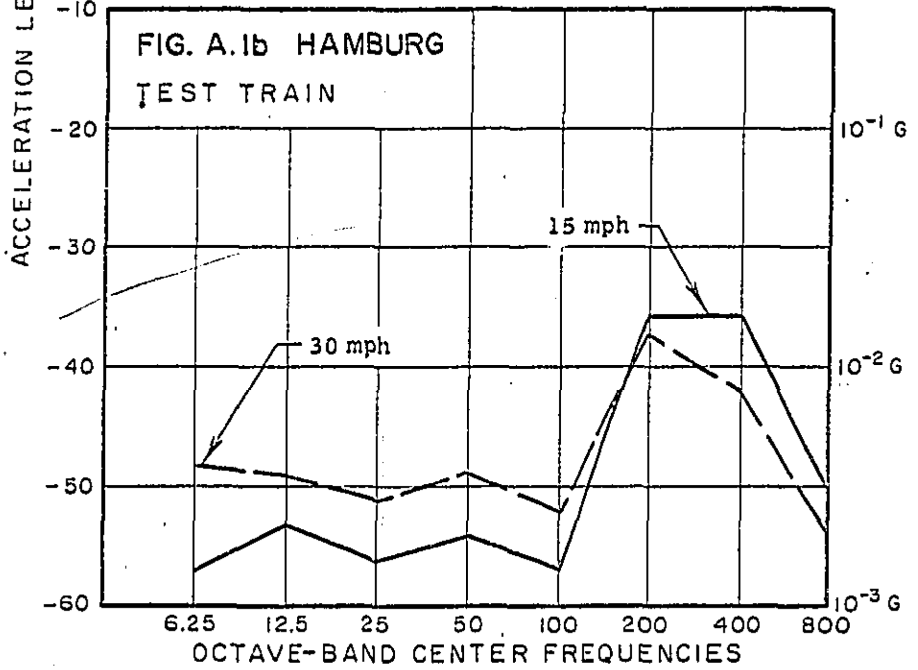
# APPENDIX A

# FREQUENCY-SPECTRUM GRAPHS OF VIBRATION DATA

VERTICAL VIBRATION LEVELS



HORIZONTAL VIBRATION LEVELS



Acceleration Level in DB re 1 G RMS

VERTICAL VIBRATION LEVELS

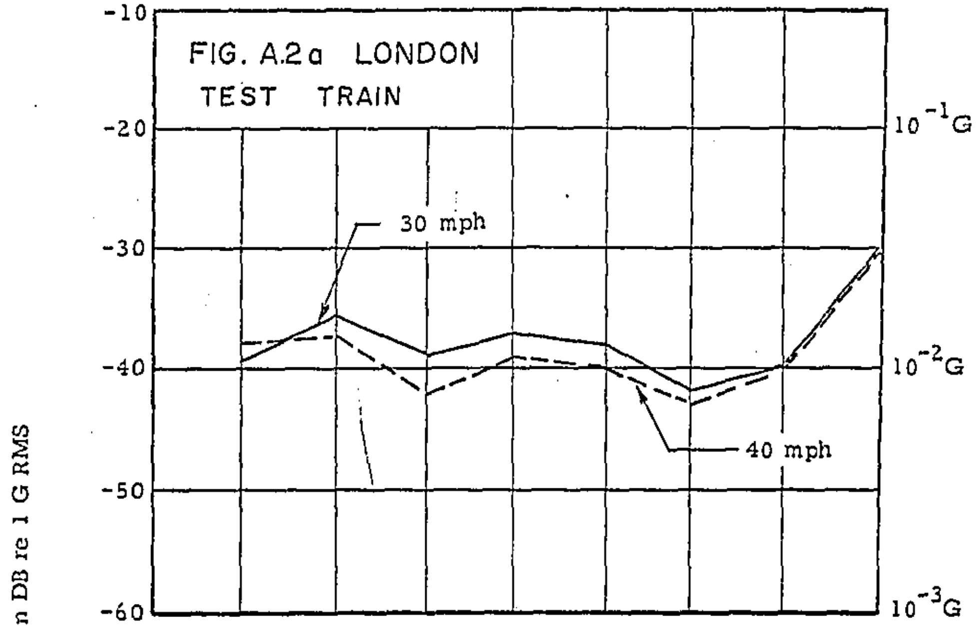


FIG. A.2a LONDON TEST TRAIN

HORIZONTAL VIBRATION LEVELS

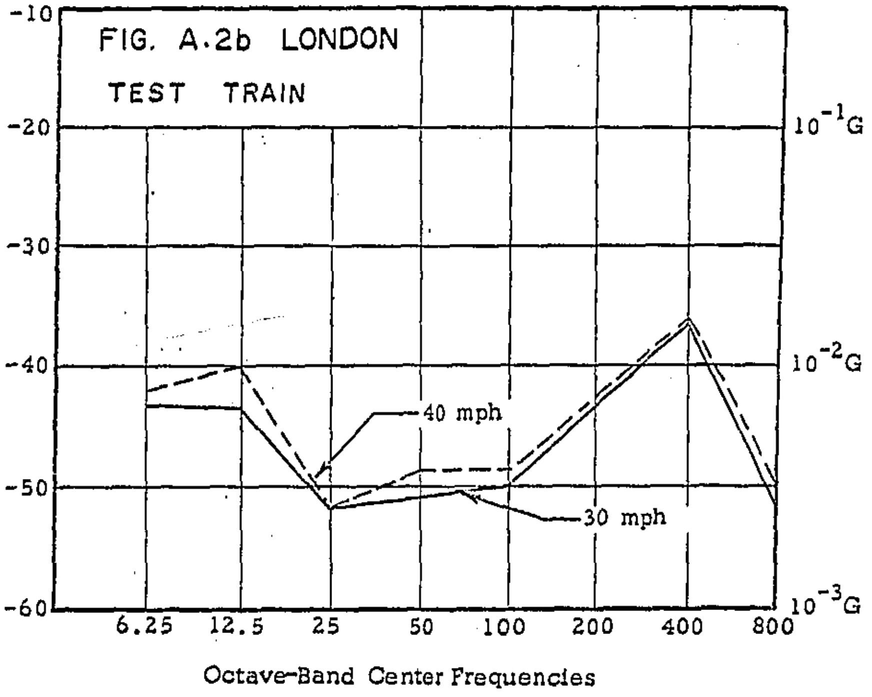


FIG. A.2b LONDON TEST TRAIN

VERTICAL VIBRATION LEVELS

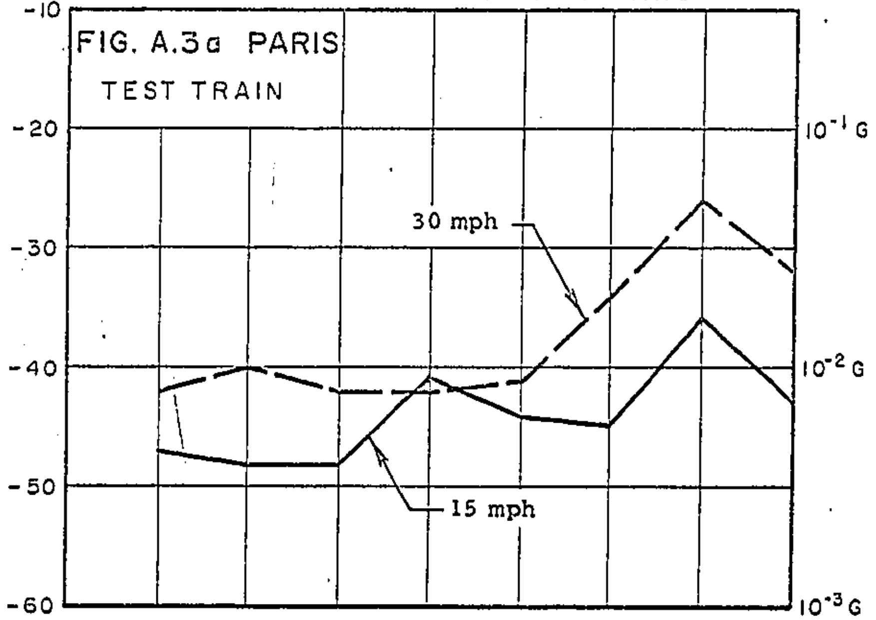


FIG. A.3a PARIS

TEST TRAIN

HORIZONTAL VIBRATION LEVELS

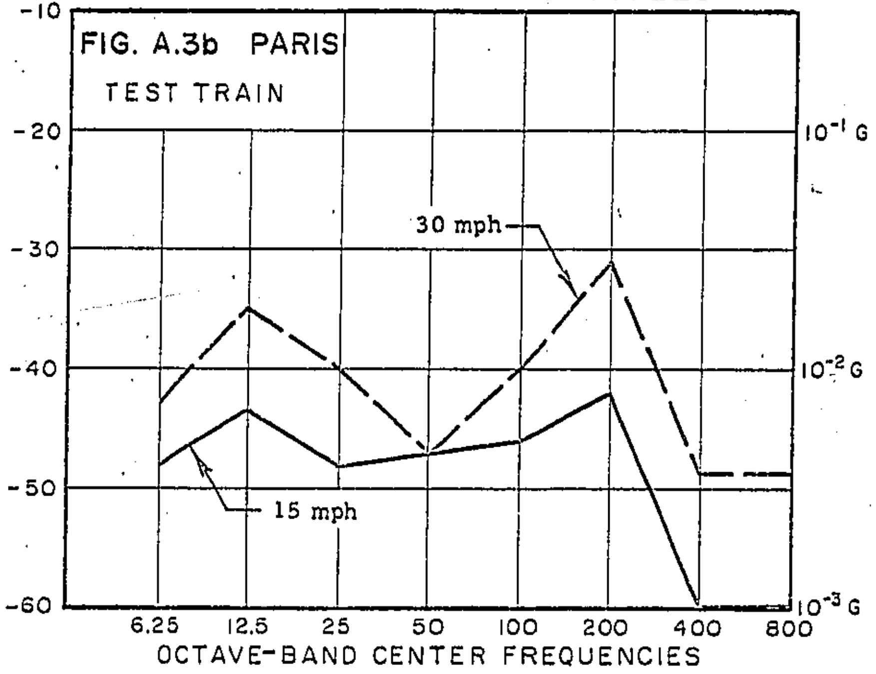


FIG. A.3b PARIS

TEST TRAIN

ACCELERATION LEVEL IN DB RE 1 G RMS

## VERTICAL VIBRATION LEVELS

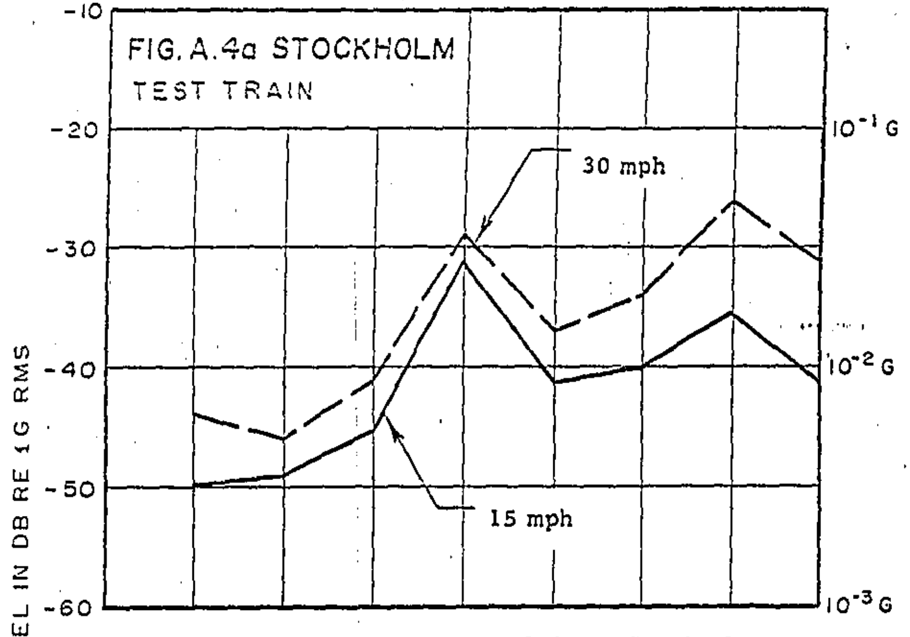


FIG. A.4a STOCKHOLM
TEST TRAIN

## HORIZONTAL VIBRATION LEVELS

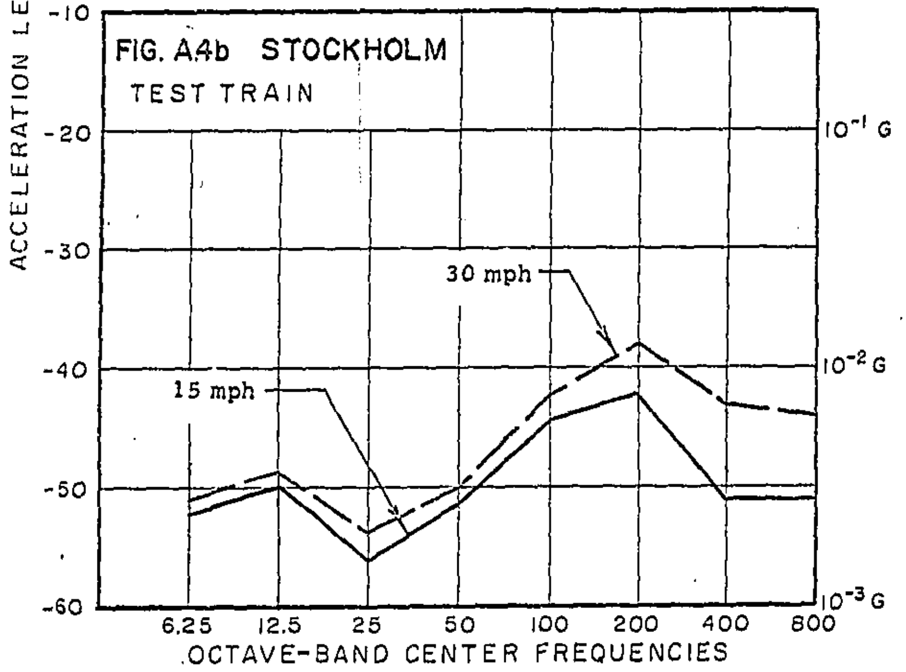


FIG. A4b STOCKHOLM
TEST TRAIN

VERTICAL VIBRATION LEVELS

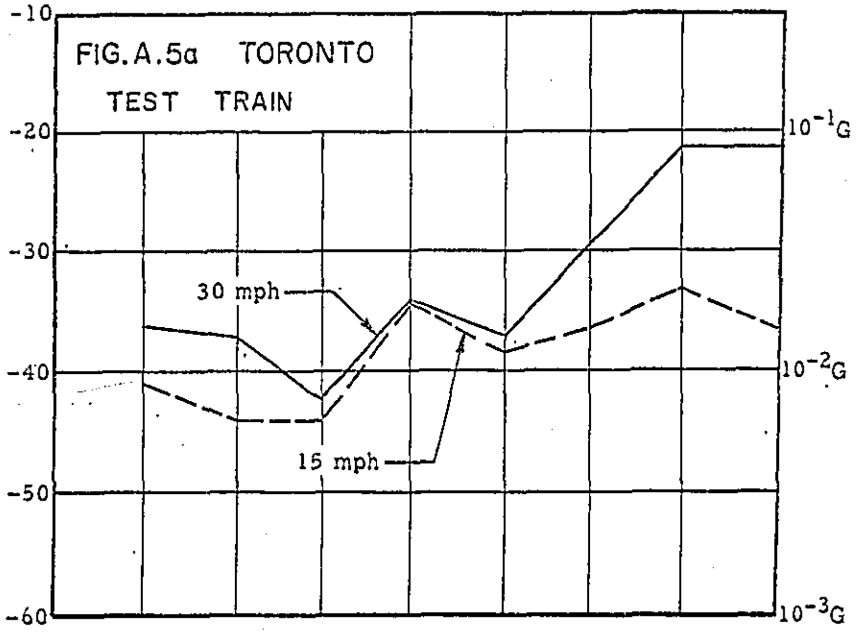


FIG. A.5a TORONTO TEST TRAIN

HORIZONTAL VIBRATION LEVELS

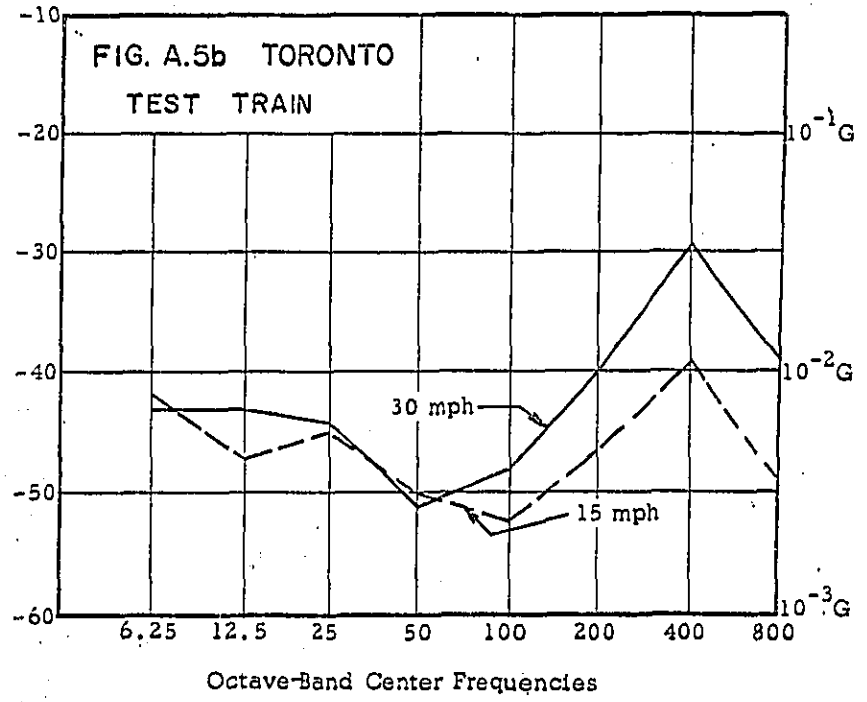


FIG. A.5b TORONTO TEST TRAIN

VERTICAL VIBRATION LEVELS

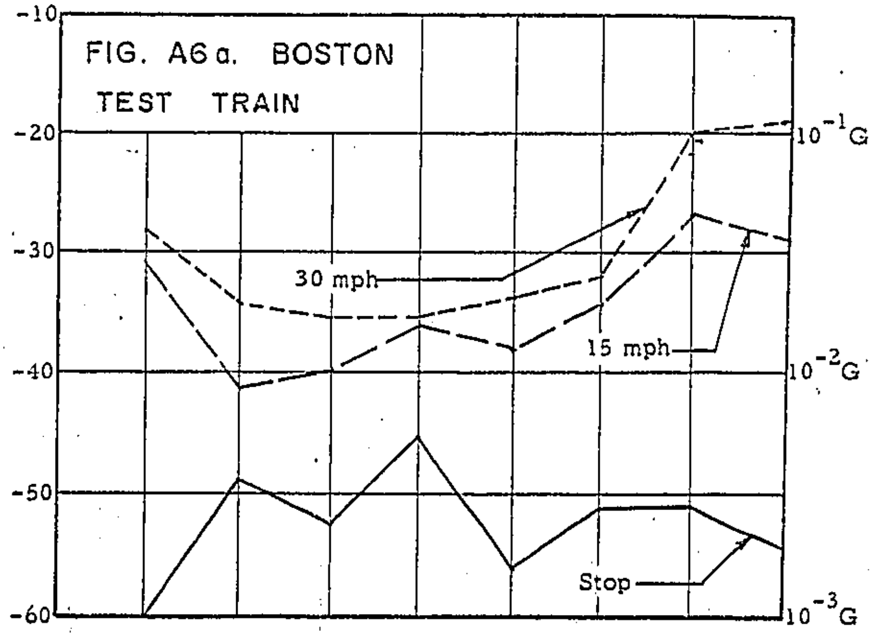


FIG. A6a. BOSTON TEST TRAIN

HORIZONTAL VIBRATION LEVELS

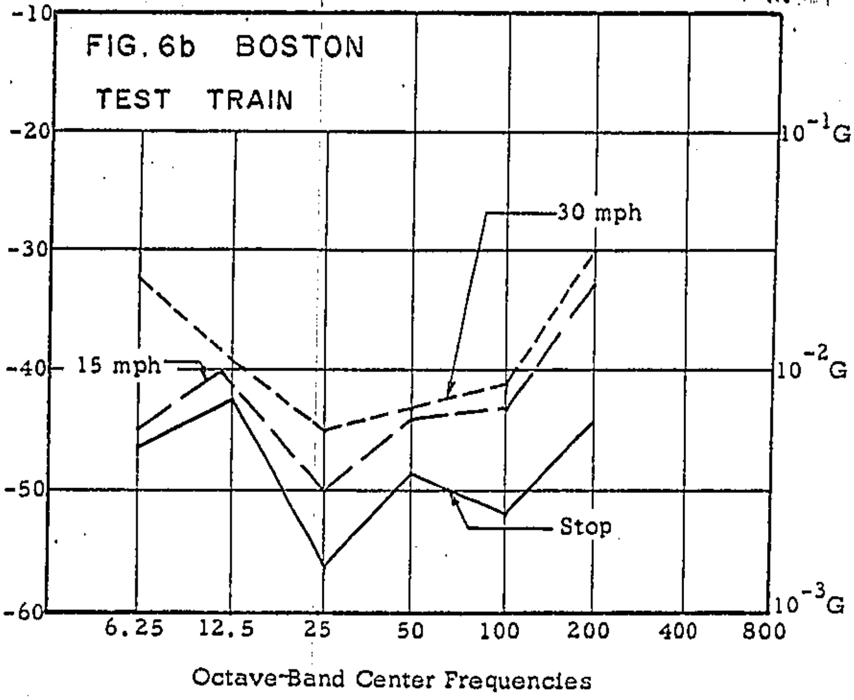
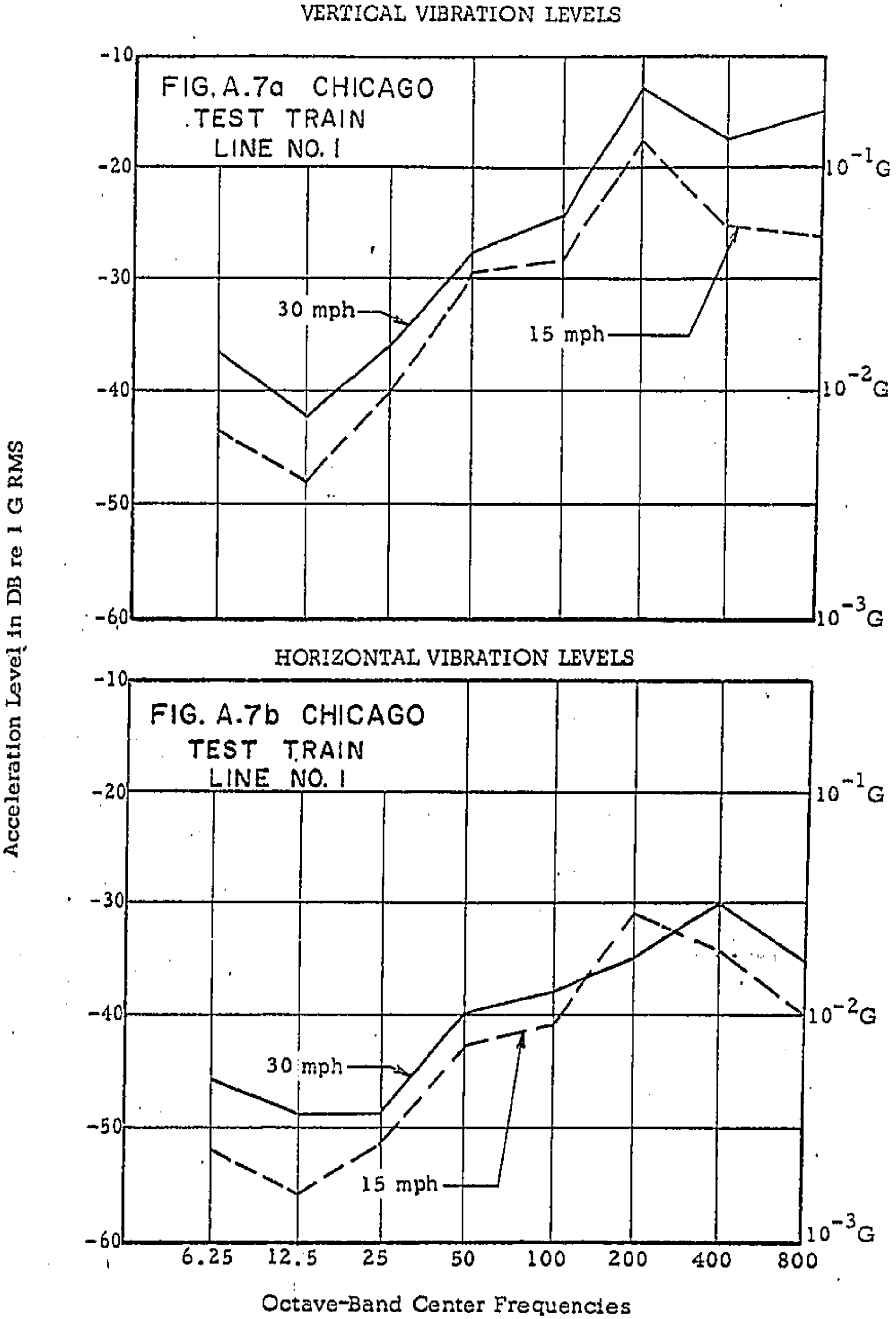
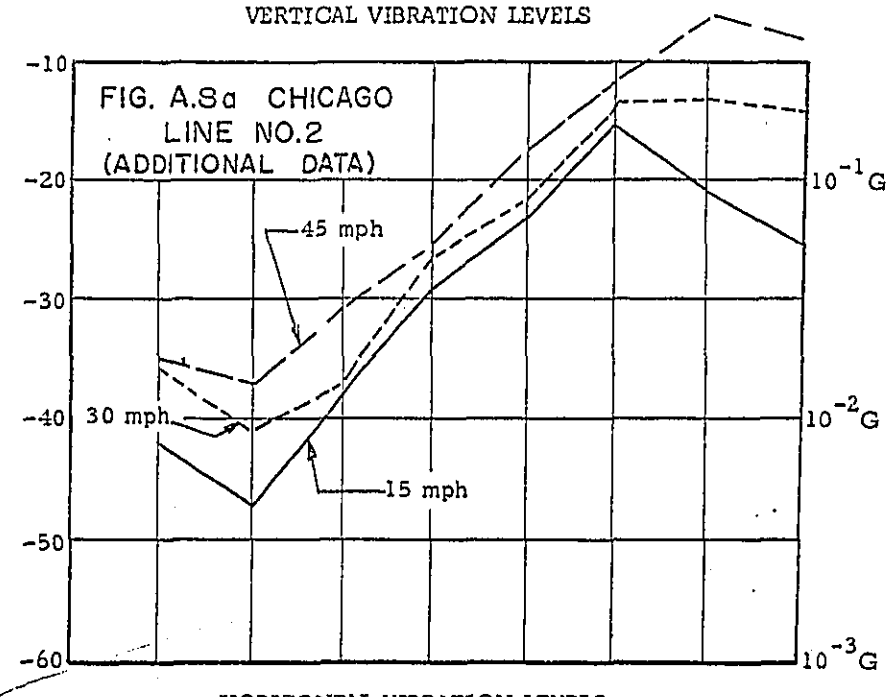
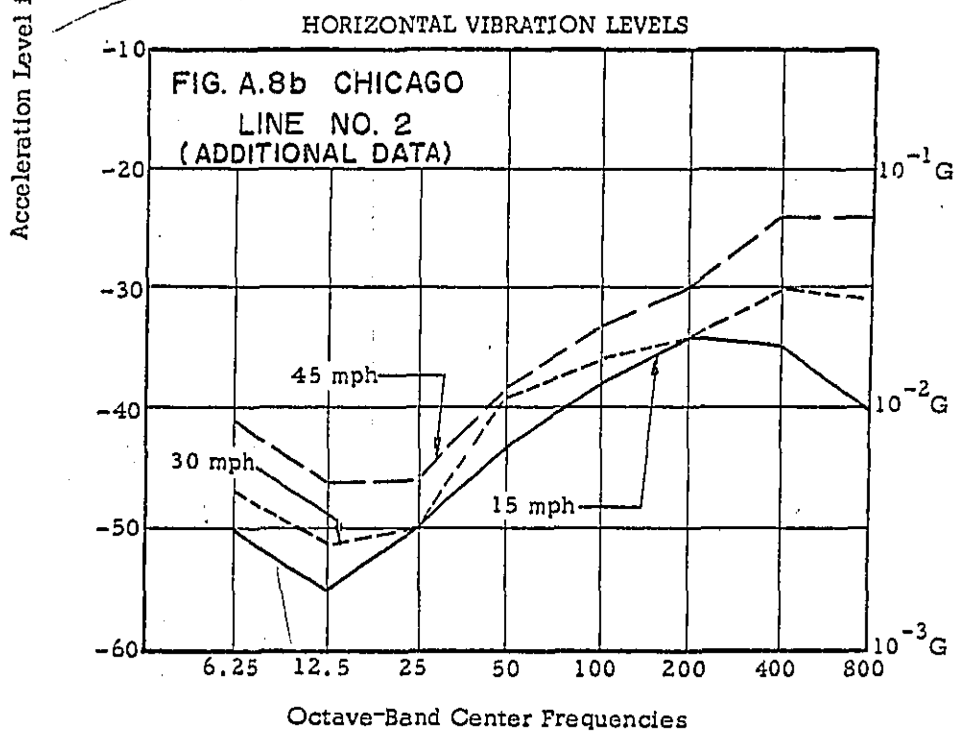


FIG. 6b BOSTON TEST TRAIN


VERTICAL VIBRATION LEVELS
FIG. A.7a CHICAGO
TEST TRAIN
LINE NO. I
30 mph
15 mph
-10
-20
-30
-40
-50
-60
10^-1 G
10^-2 G
10^-3 G
HORIZONTAL VIBRATION LEVELS
FIG. A.7b CHICAGO
TEST TRAIN
LINE NO. I
30 mph
15 mph
-10
-20
-30
-40
-50
-60
10^-1 G
10^-2 G
10^-3 G
Acceleration Level in DB re 1 G RMS
6.25
12.5
25
50
100
200
400
800
Octave-Band Center Frequencies


VERTICAL VIBRATION LEVELS
FIG. A.8a CHICAGO
LINE NO.2
(ADDITIONAL DATA)
45 mph
30 mph
15 mph
-10
-20
-30
-40
-50
-60
$10^{-1}$G
$10^{-2}$G
$10^{-3}$G


HORIZONTAL VIBRATION LEVELS
FIG. A.8b CHICAGO
LINE NO. 2
(ADDITIONAL DATA)
45 mph
30 mph
15 mph
-10
-20
-30
-40
-50
-60
$10^{-1}$G
$10^{-2}$G
$10^{-3}$G
Acceleration Level in DB re 1 G RMS
6.25
12.5
25
50
100
200
400
800
Octave-Band Center Frequencies

VERTICAL VIBRATION LEVELS

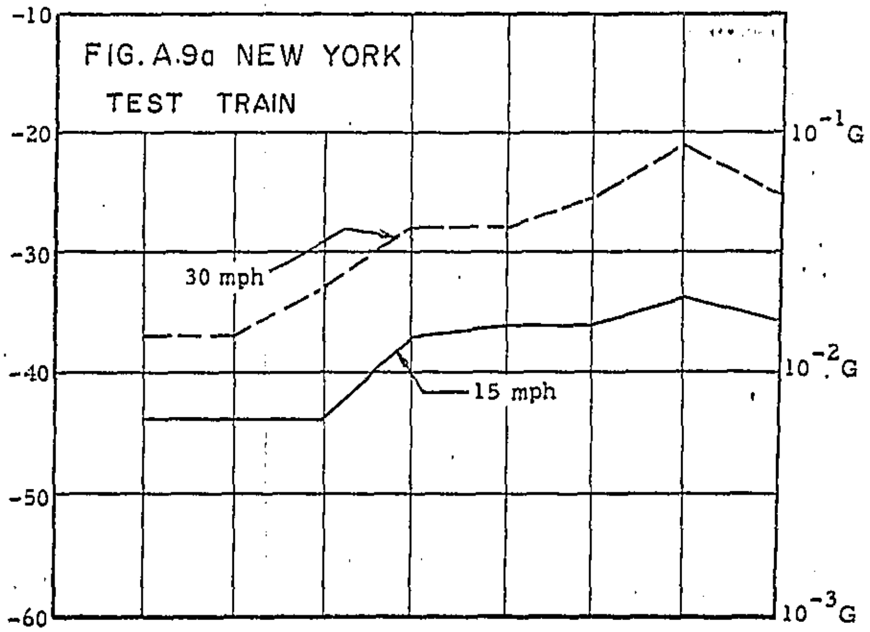


FIG. A.9a NEW YORK TEST TRAIN

HORIZONTAL VIBRATION LEVELS

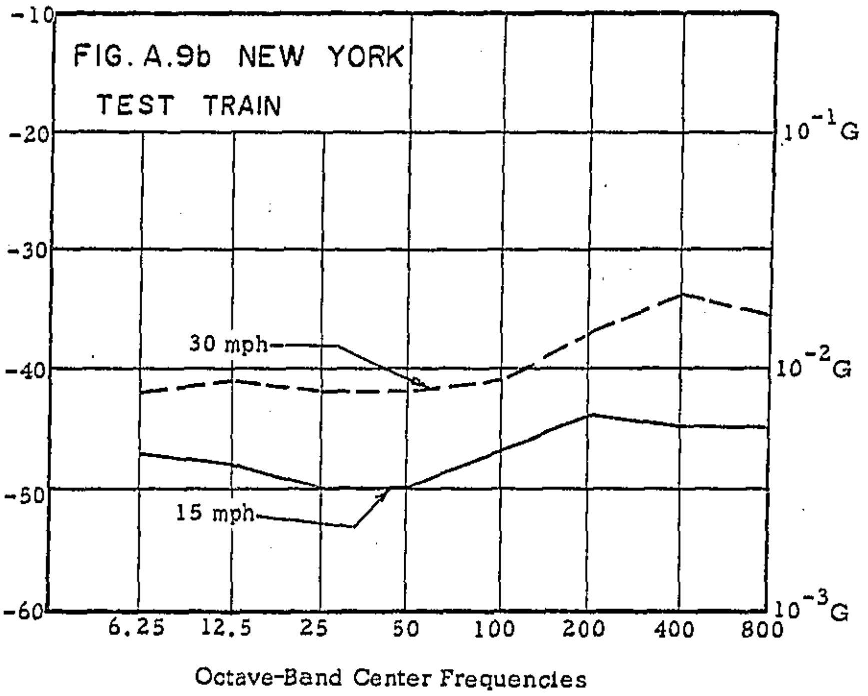


FIG. A.9b NEW YORK TEST TRAIN

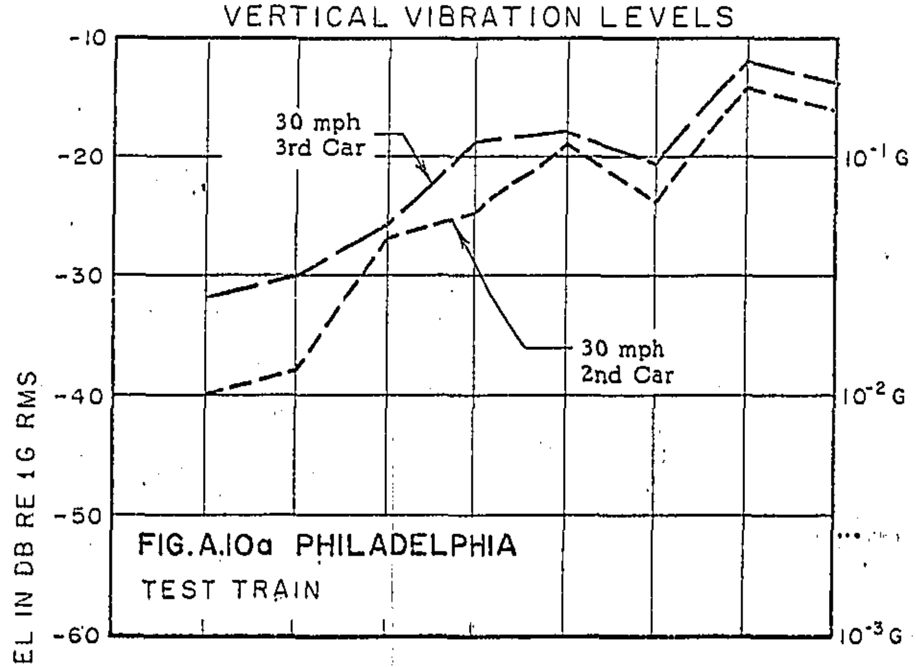


FIG. A.10a PHILADELPHIA
TEST TRAIN

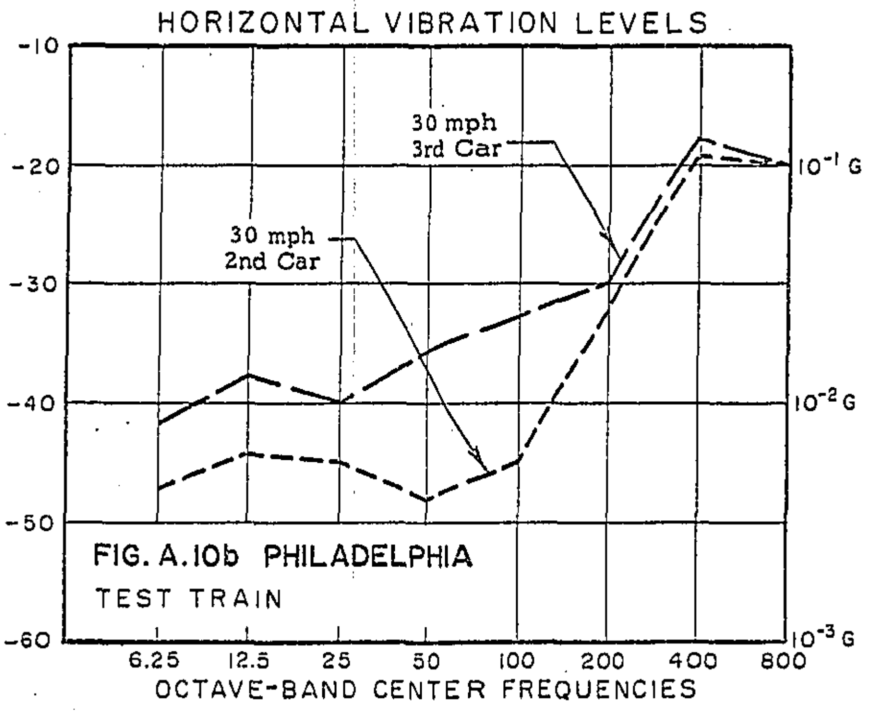


FIG. A.10b PHILADELPHIA
TEST TRAIN

VERTICAL VIBRATION LEVELS

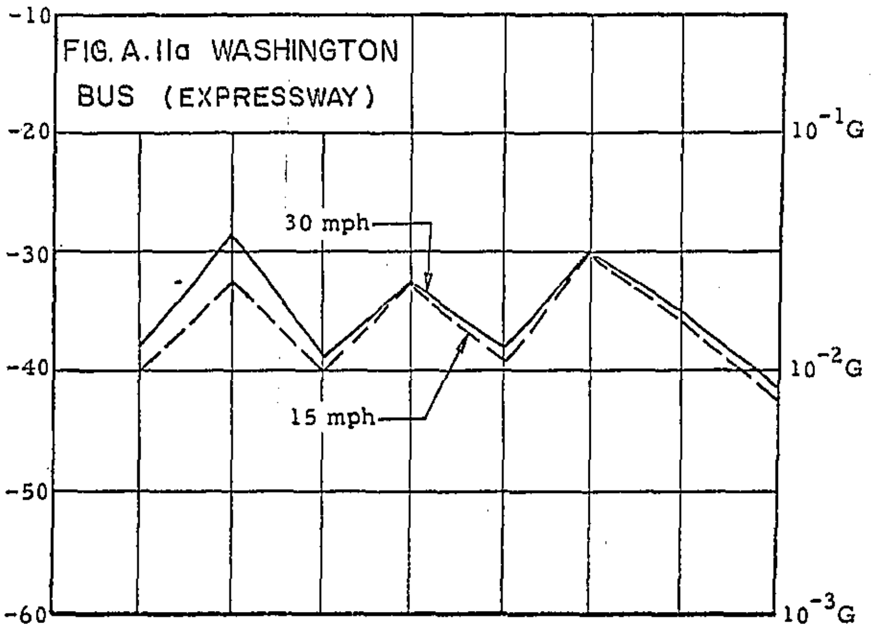


FIG. A.11a WASHINGTON BUS (EXPRESSWAY)

HORIZONTAL VIBRATION LEVELS

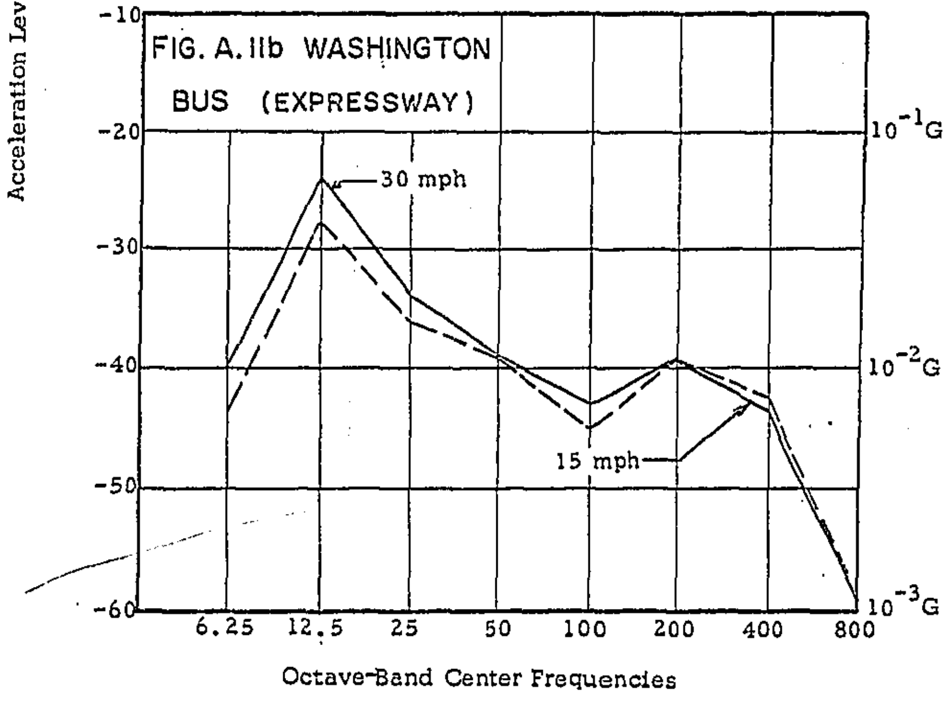


FIG. A.11b WASHINGTON BUS (EXPRESSWAY)

VERTICAL VIBRATION LEVELS

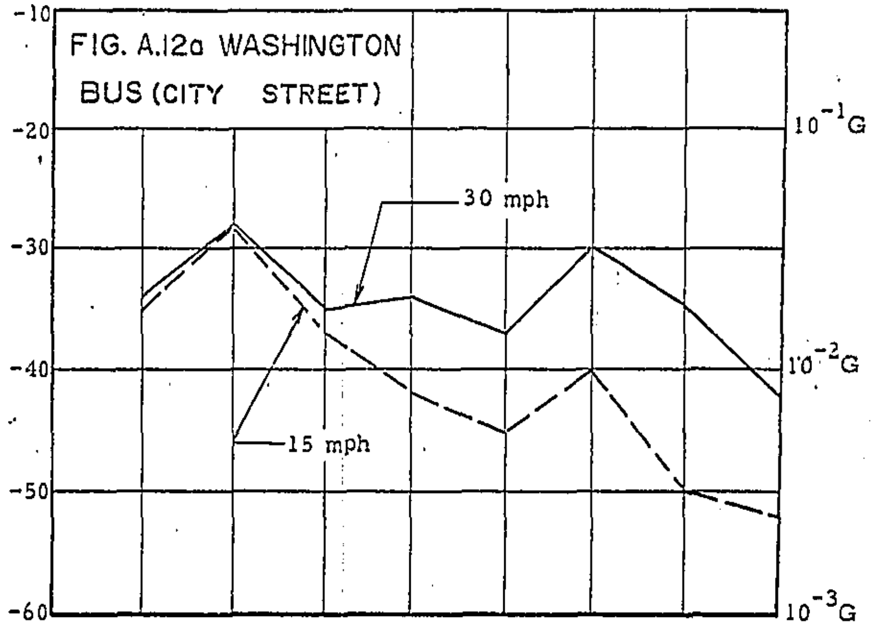


FIG. A.12a WASHINGTON BUS (CITY STREET)

HORIZONTAL VIBRATION LEVELS

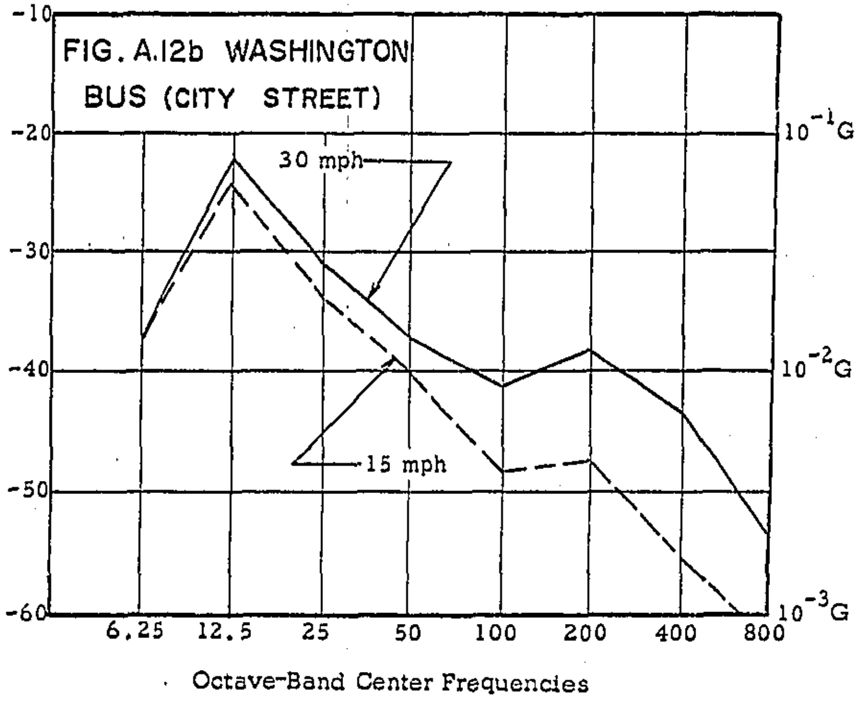


FIG. A.12b WASHINGTON BUS (CITY STREET)

# APPENDIX B

## CALCULATION OF OVERALL DECIBEL LEVEL

B.1 The overall sound pressure level (SPL) in decibels is commonly read as a single number on the scale of a sound-level meter while the noise of interest is occurring. This method has many disadvantages, however. Another way of obtaining the same number is to tape record the noise, obtain octave-band sound pressure levels later in the laboratory, and then use these octave-band levels to compute the overall level. This is done in a step-by-step process by successively combining the eight octave-band decibel levels. It should be noted that decibels cannot be added directly. They must be combined on an energy basis. This involves converting the number of decibels to relative powers, adding, and then converting back to the corresponding decibels. Figure B.1 provides an easy method for performing this operation.

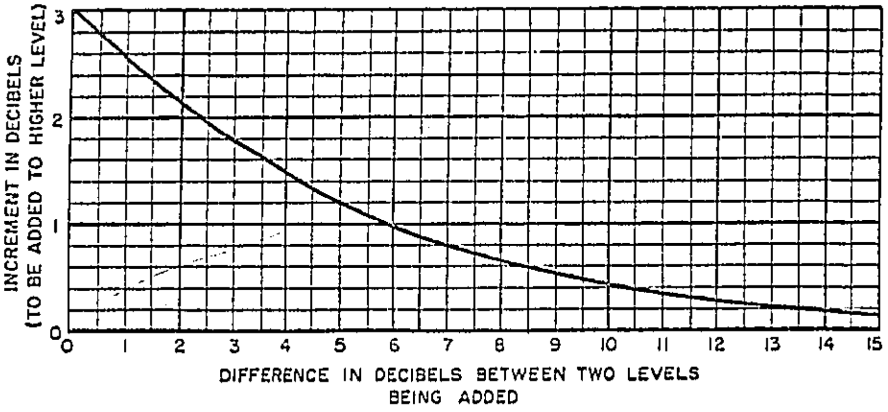


FIGURE B.1. METHOD OF OBTAINING TOTAL SOUND PRESSURE LEVEL FROM OCTAVE-BAND LEVELS

B.2 For example, consider the sound pressure levels inside the TALGO train, as shown in Figure 51 and Table B.1.

TABLE B.1

SOUND PRESSURE LEVELS IN THE TALGO TRAIN

| Octave-Band No. | Octave-Band Center Freq, cps | TALGO at 30 mph SPL, db |
|---|---|---|
| 1 | 50 | 90 |
| 2 | 100 | 78 |
| 3 | 200 | 79 |
| 4 | 400 | 74 |
| 5 | 800 | 66 |
| 6 | 1600 | 57 |
| 7 | 3200 | 52 |
| 8 | 6400 | 42 |

B.3 The first step in obtaining the overall decibel level is to combine the levels in bands 1 and 2: $L_1 = 90$, $L_2 = 78$; $L_1 - L_2 = 12$.

From Figure B.1, $L_i = 0.3$ db

$$L_{comb} = L_1 + L_i = 90.3 \text{ db} \quad .$$

This new value is then combined with the level in band 3 in the same manner: $L_1 = 90.3$, $L_2 = 79$; $L_1 - L_2 = 11.3$.

From Figure B.1, $L_i = 0.35$

$$L_{comb} = L_1 + L_i = 90.65 .$$

This value is then combined with the level of band 4 in a similar manner to obtain a value for combination with band 5, etc., for all eight bands. The computed overall decibel level is 92 db.

## CALCULATION OF LOUDNESS LEVEL

B.4 The loudness level (LL) in phons is a single number computed from octave-band sound pressure levels according to the procedure described in the following paragraphs. In this procedure, a quantity called the <u>sone</u> is used, which is also a unit of loudness similar to the phon.

B.5 To obtain the loudness level in phons, the sound pressure level in decibels in each octave band is converted to sones by means of the appropriate columns in Figure B.2. The total loudness in sones is then obtained by the following operations:

$$\Sigma S_i = S_1 + S_2 + \ldots + S_8 \text{ and}$$

$$S_t = S_m + 0.3\,(\Sigma S_i - S_m),$$

where $S_t$ = loudness of total noise

$S_m$ = loudness of loudest band.

The total loudness in sones is converted to loudness level in phons by means of the nomogram at the right of Figure B.2.

B.6 For example, consider the TALGO train octave-band sound pressure levels presented in Figure 51 and Figure C.14 (Appendix C). The SPL in each band and the corresponding value in sones is given in Table B.2.

TABLE B.2

LOUDNESS LEVEL IN SONES ON TALGO TRAIN

| Octave-Band Center Freq, cps | TALGO at 30 mph SPL, db | $S_i$ Sones |
|---|---|---|
| 50 | 90 | 17 |
| 100 | 78 | 10 |
| 200 | 79 | 15 |
| 400 | 74 | 11 |
| 800 | 66 | 7 |
| 1600 | 57 | 4 |
| 3200 | 56 | 4 |
| 6400 | 42 | 2 |
|  |  | $\sum S_i = 70$ |

From Table B.2, Column 3, the highest $S_i$ is 17. Therefore,

$$S_m = 17$$

$$S_t = 17 + 0.3\,(70 - 17)$$

$$= 33.$$

From Figure B.2, LL (phons) = 91.

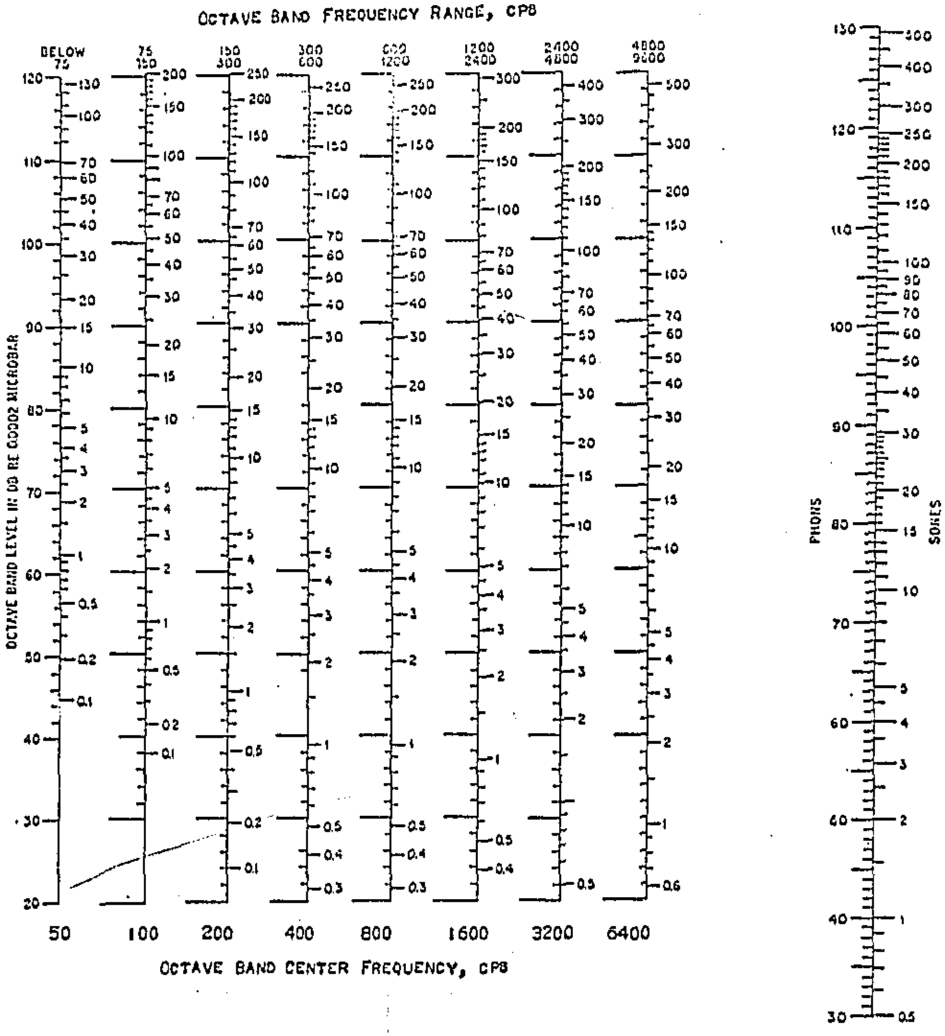


FIGURE B.2. NOMOGRAMS FOR CALCULATION OF LOUDNESS LEVEL IN SONES AND CONVERSION TO PHONS

## OCTAVE-BAND FREQUENCY RANGE

B.7 Throughout this report, the eight octave bands used in the sound data analysis are identified by their center-frequency value. Since this value is not the true arithmetic central value, some confusion could arise as to the frequency range of each octave band. To prevent such confusion, the frequency range of each band is indicated in Table B.3.

TABLE B.3

FREQUENCY RANGES FOR VARIOUS BANDS

| Band No. | Octave-Band Center Freq, cps | Octave-Band Frequency Range, cps |
|---|---|---|
| 1 | 50 | 20-75 |
| 2 | 100 | 75-150 |
| 3 | 200 | 150-300 |
| 4 | 400 | 300-600 |
| 5 | 800 | 600-1200 |
| 6 | 1600 | 1200-2400 |
| 7 | 3200 | 2400-4800 |
| 8 | 6400 | 4800-9600 |

# APPENDIX C

## OCTAVE-BAND GRAPHS OF VEHICLE AND STATION SOUND PRESSURE LEVEL

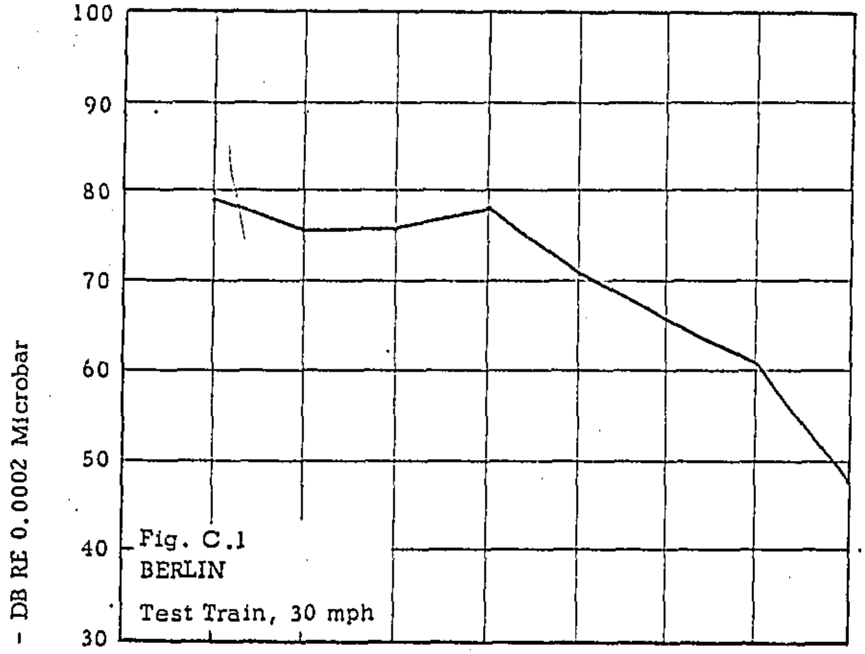


Fig. C.1
BERLIN
Test Train, 30 mph

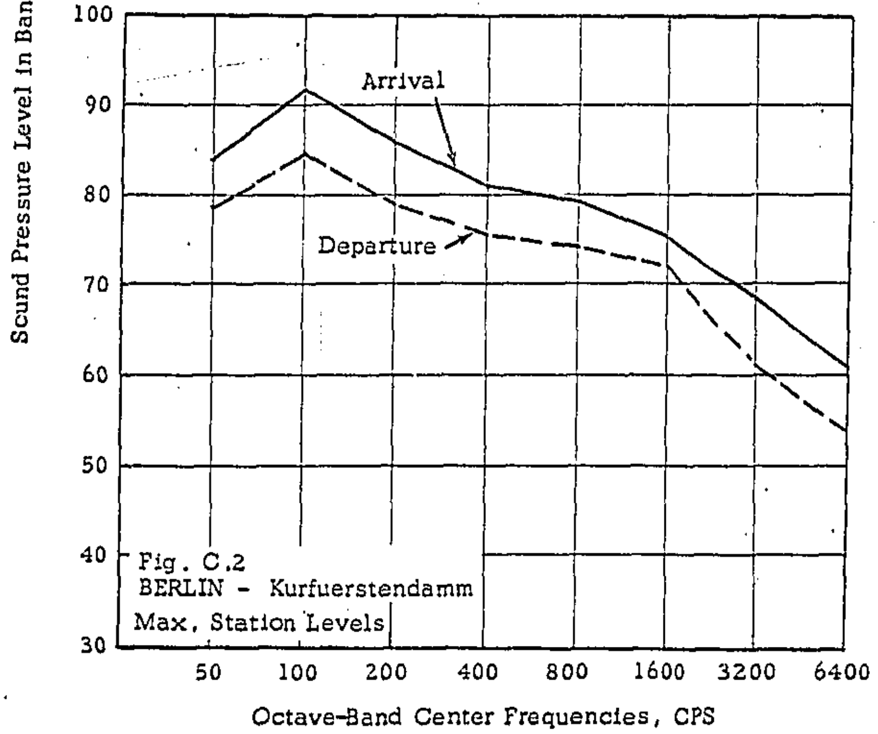


Fig. C.2
BERLIN - Kurfuerstendamm
Max. Station Levels

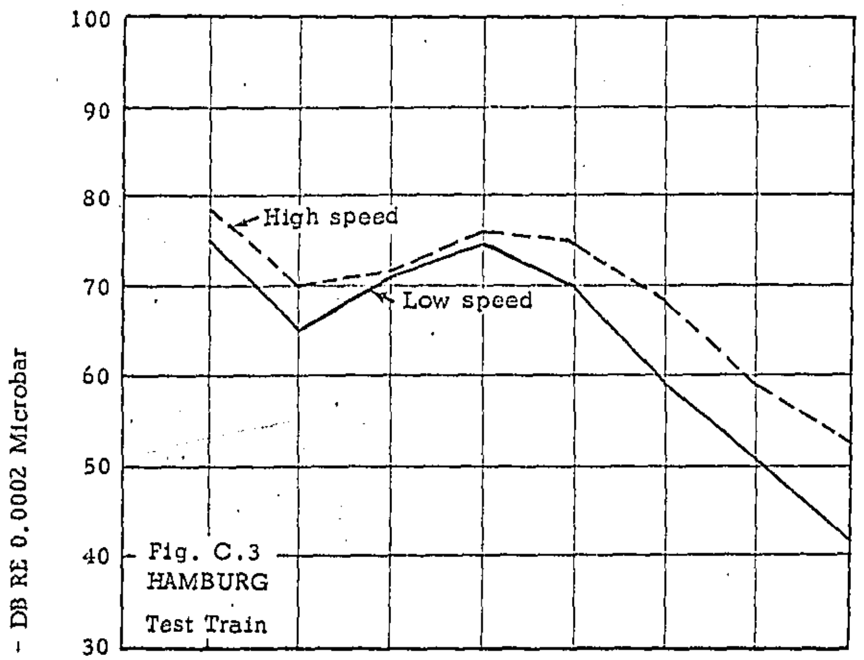


Fig. C.3
HAMBURG
Test Train

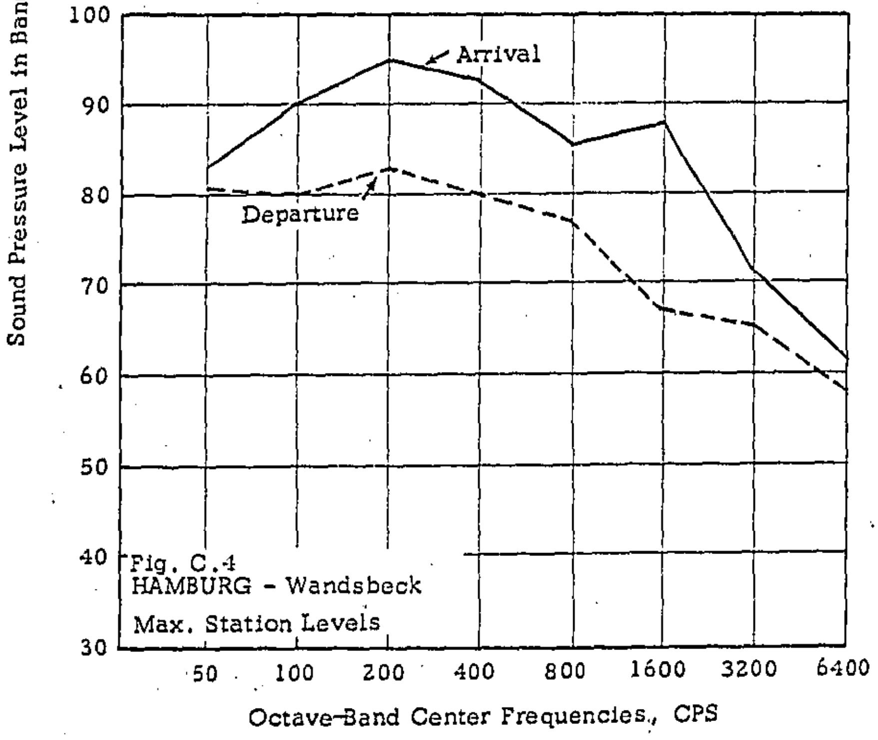


Fig. C.4
HAMBURG - Wandsbeck
Max. Station Levels

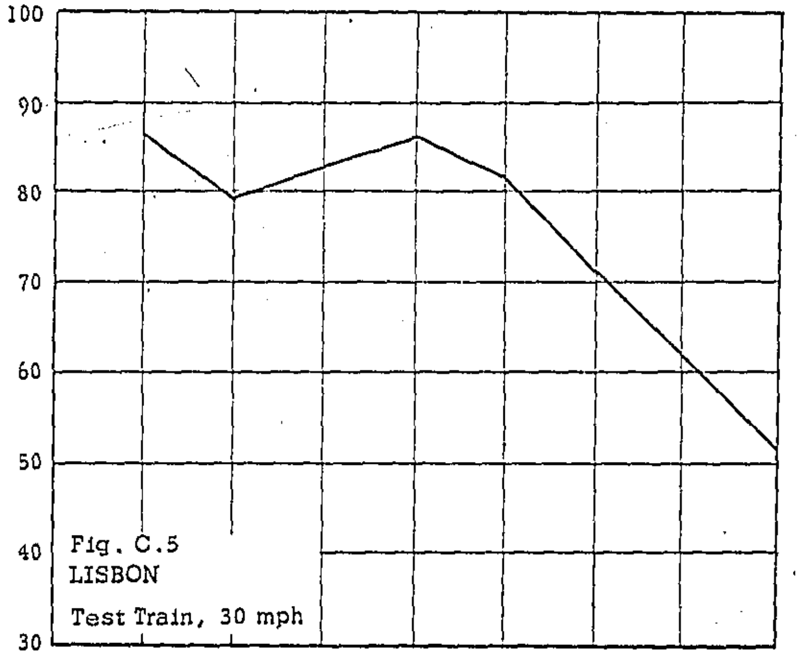


Fig. C.5
LISBON

Test Train, 30 mph

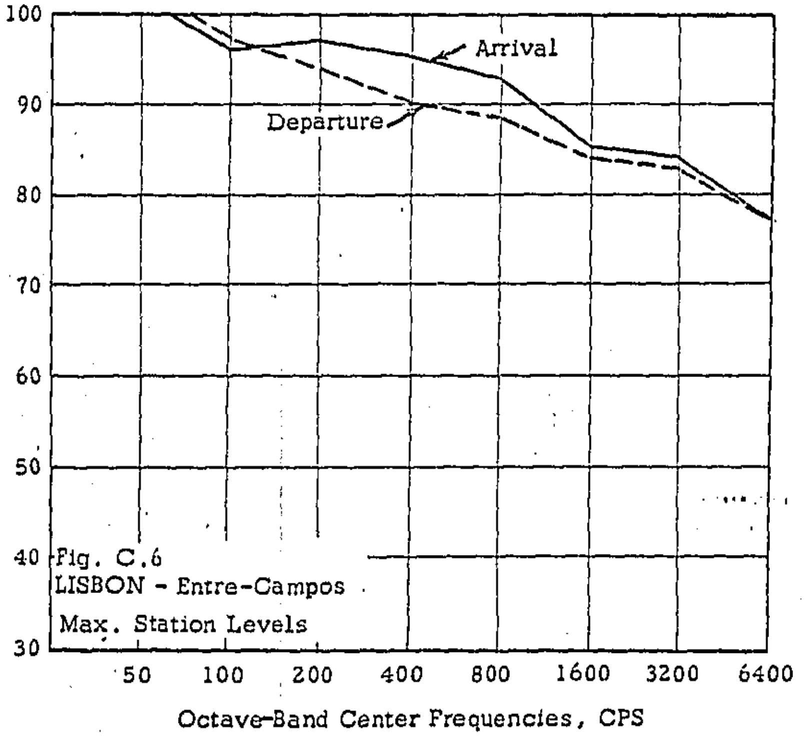


Fig. C.6
LISBON - Entre-Campos
Max. Station Levels

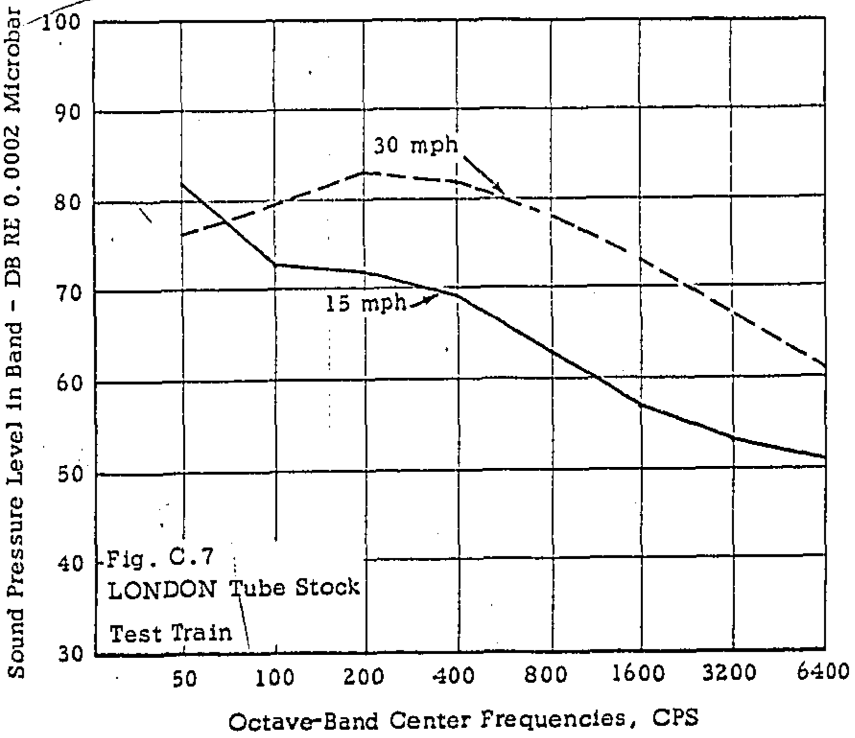


Fig. C.7
LONDON Tube Stock
Test Train

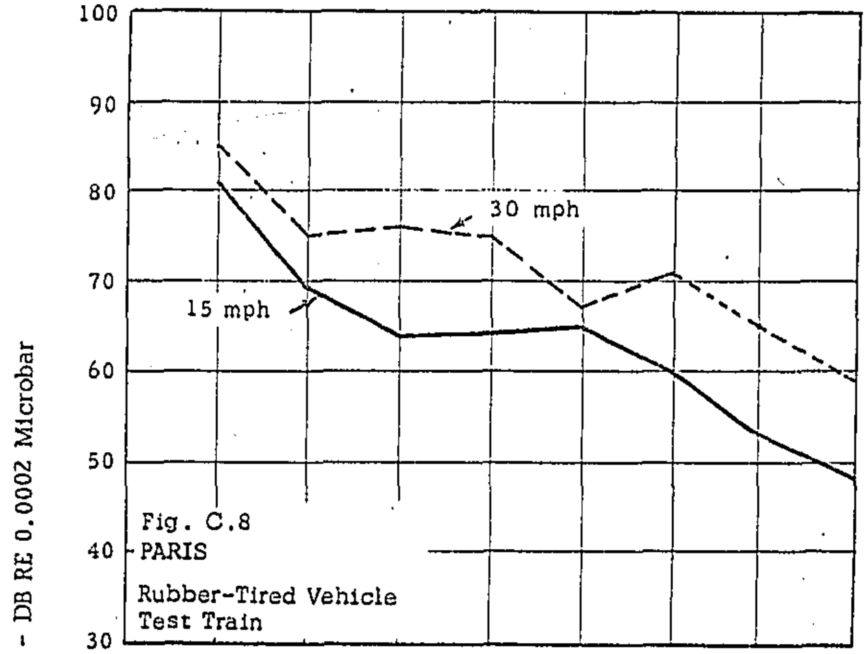


Fig. C.8
PARIS

Rubber-Tired Vehicle
Test Train

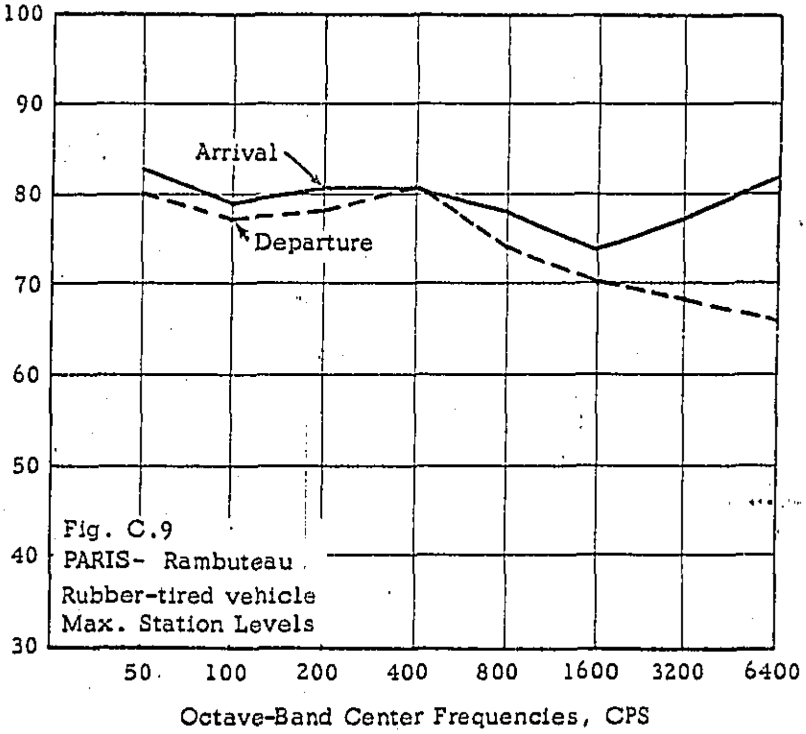


Fig. C.9
PARIS- Rambuteau
Rubber-tired vehicle
Max. Station Levels

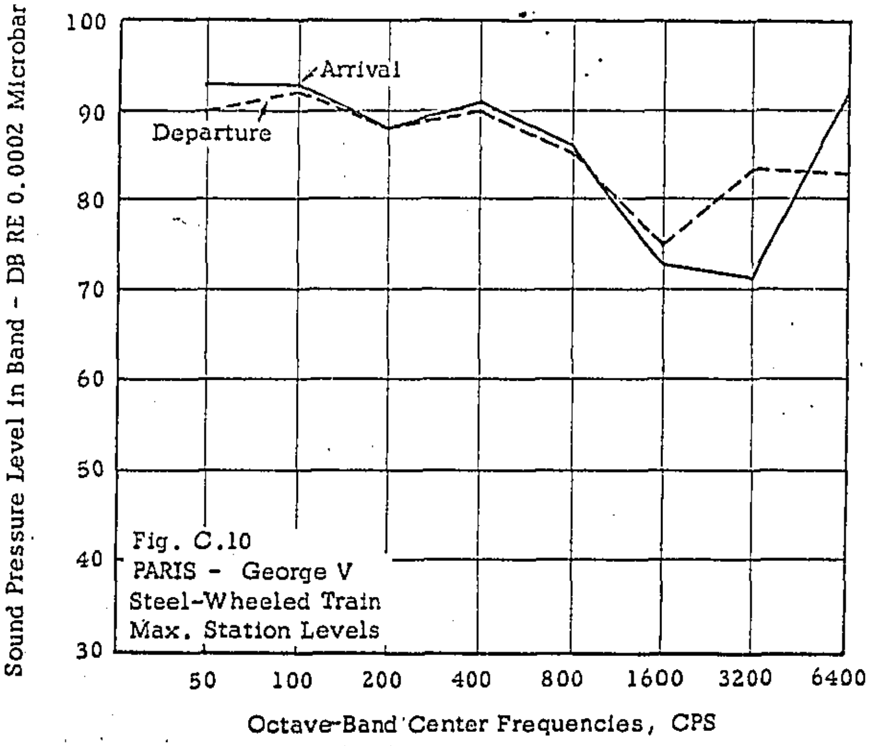


Fig. C.10
PARIS - George V
Steel-Wheeled Train
Max. Station Levels

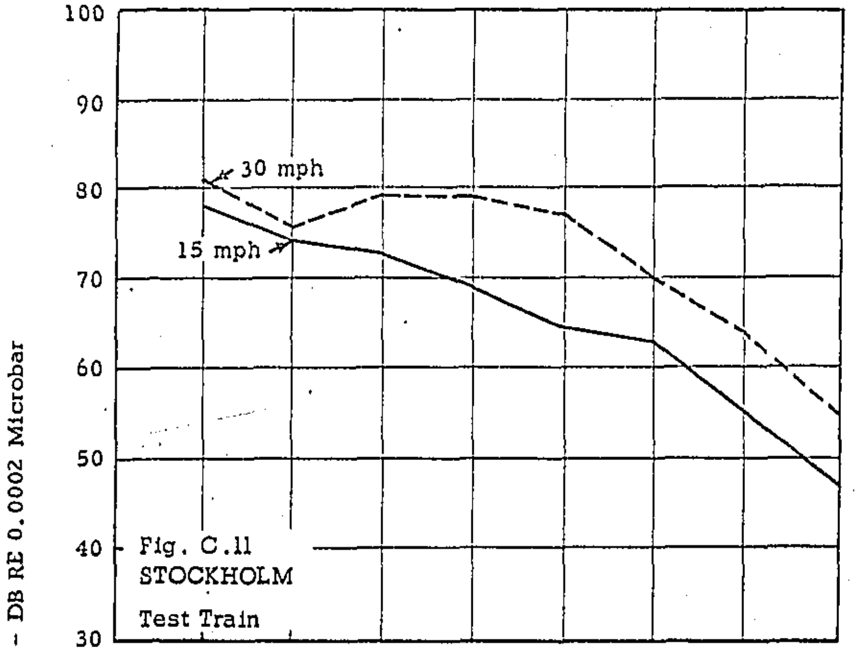


Fig. C.11
STOCKHOLM

Test Train

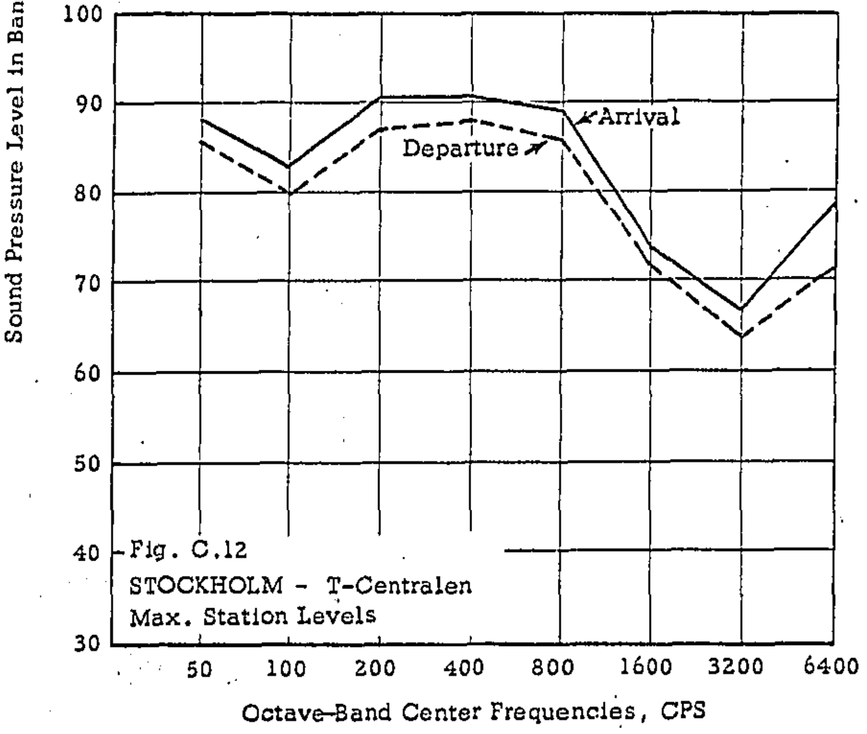


Fig. C.12
STOCKHOLM - T-Centralen
Max. Station Levels

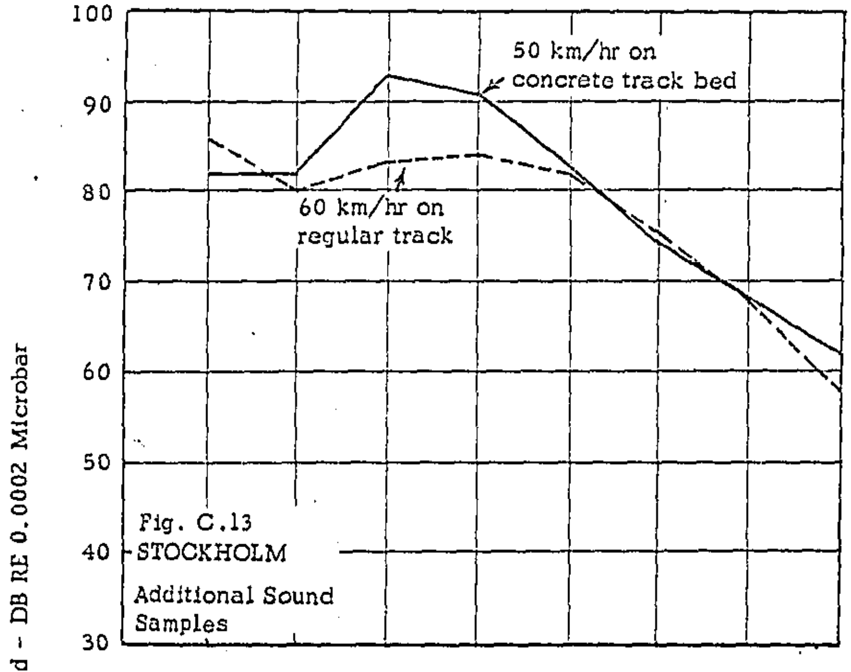


Fig. C.13
STOCKHOLM

Additional Sound
Samples

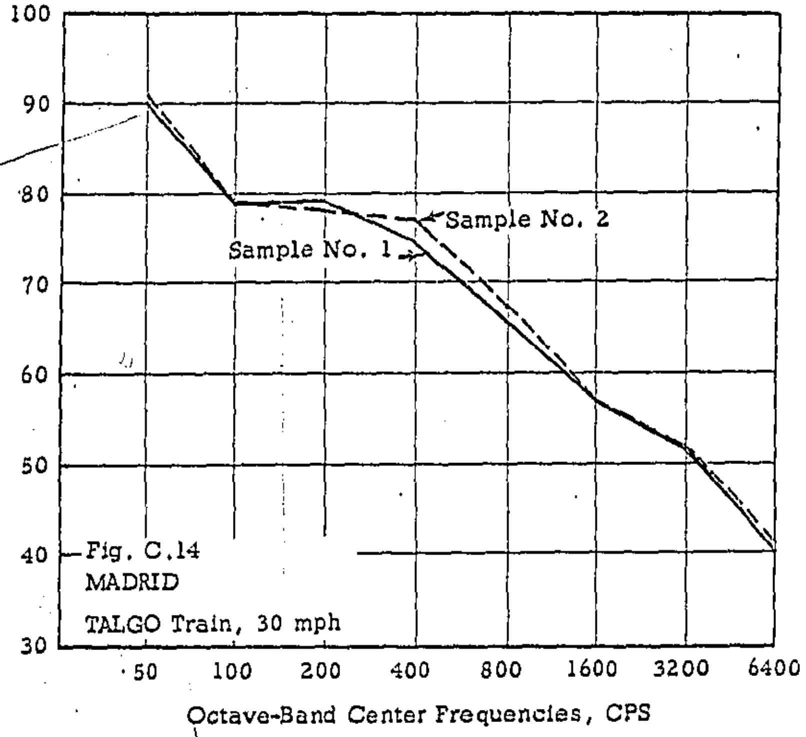


Fig. C.14
MADRID

TALGO Train, 30 mph

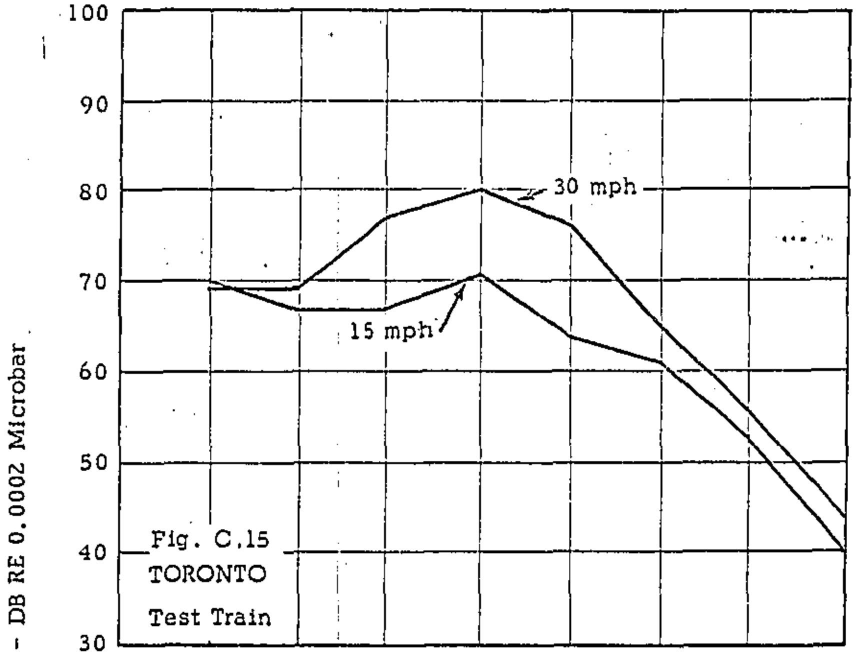


Fig. C.15
TORONTO
Test Train

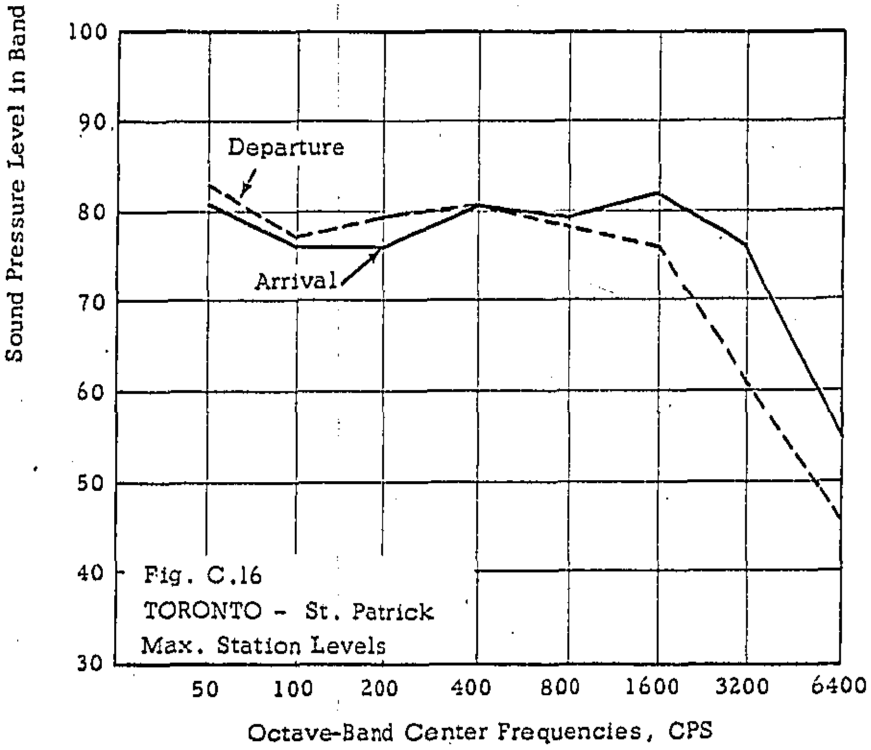


Fig. C.16
TORONTO - St. Patrick
Max. Station Levels

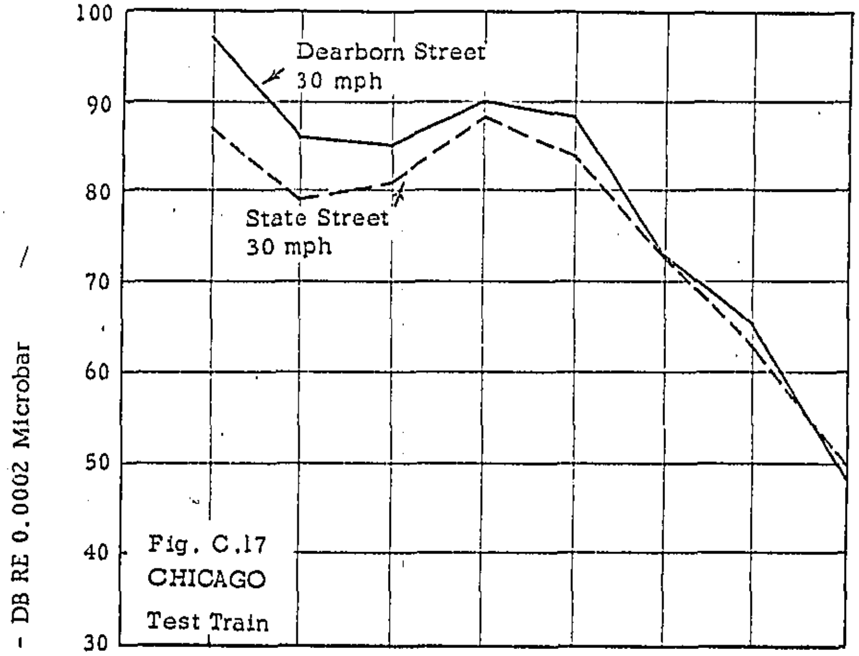


Fig. C.17
CHICAGO
Test Train

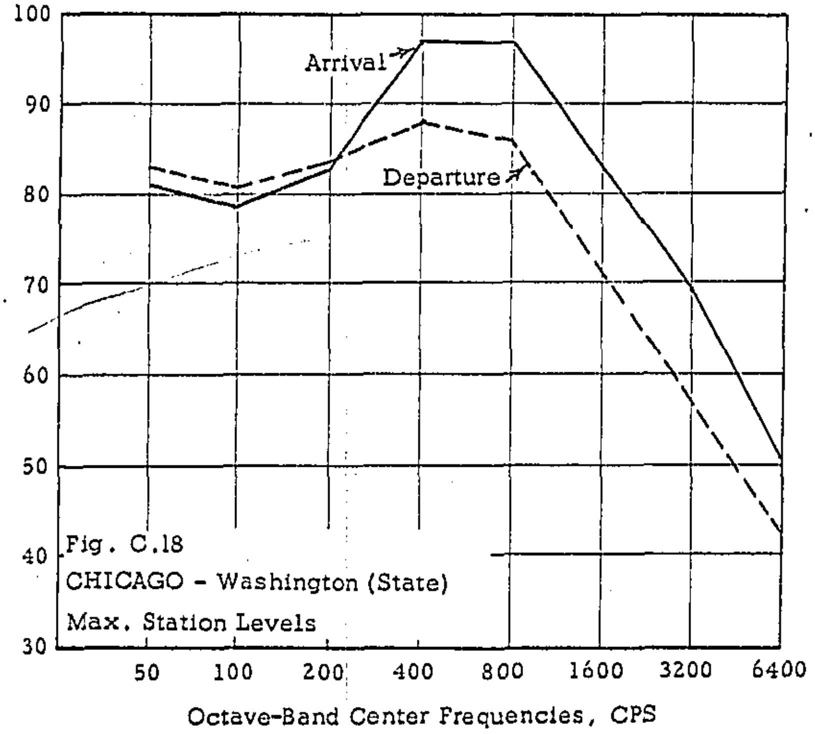


Fig. C.18
CHICAGO - Washington (State)
Max. Station Levels

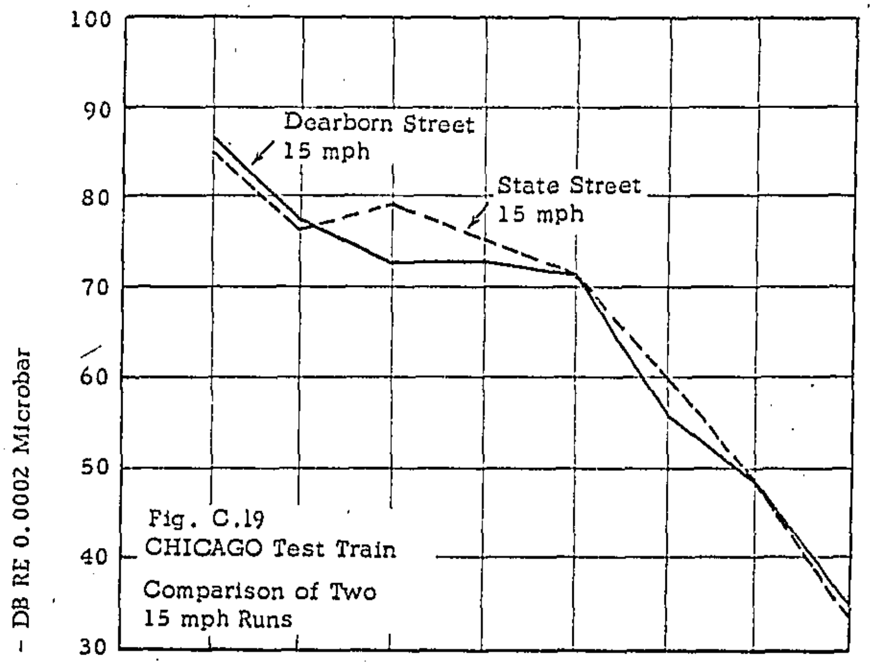


Fig. C.19
CHICAGO Test Train

Comparison of Two
15 mph Runs

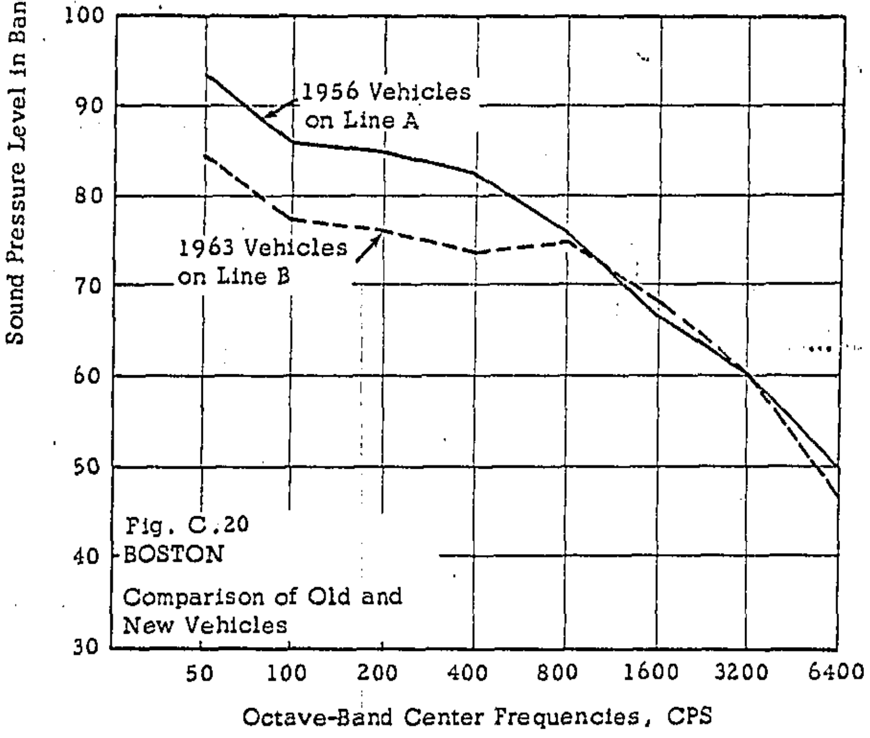


Fig. C.20
BOSTON

Comparison of Old and
New Vehicles

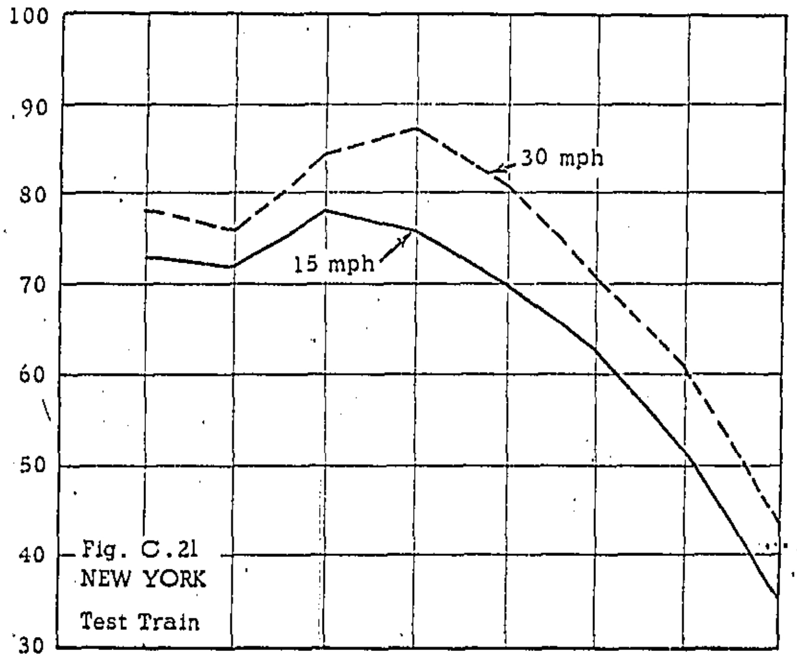


Fig. C.21
NEW YORK
Test Train

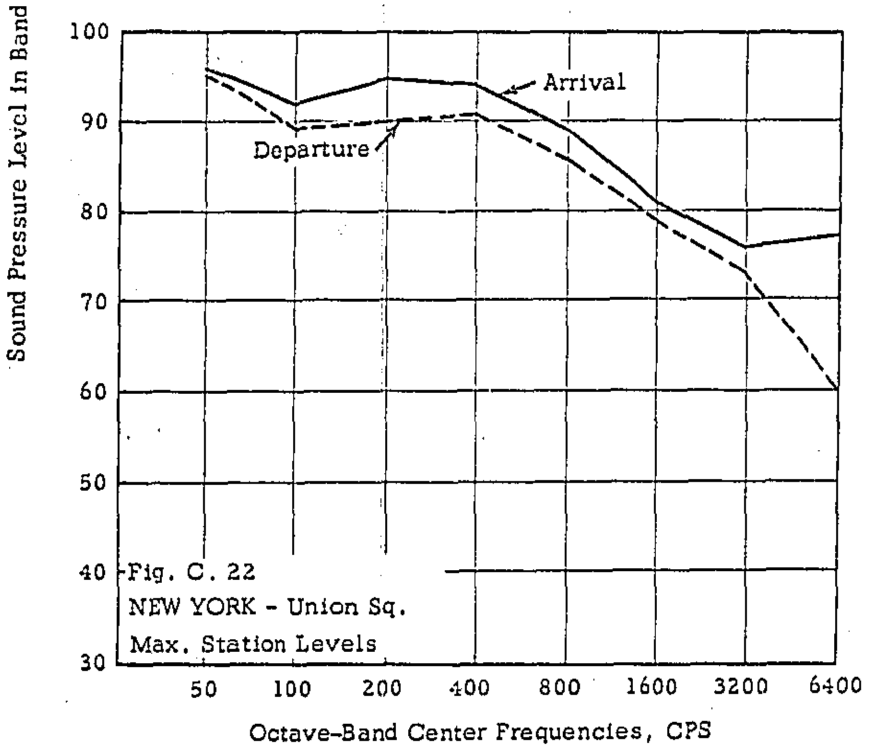


Fig. C. 22
NEW YORK - Union Sq.
Max. Station Levels

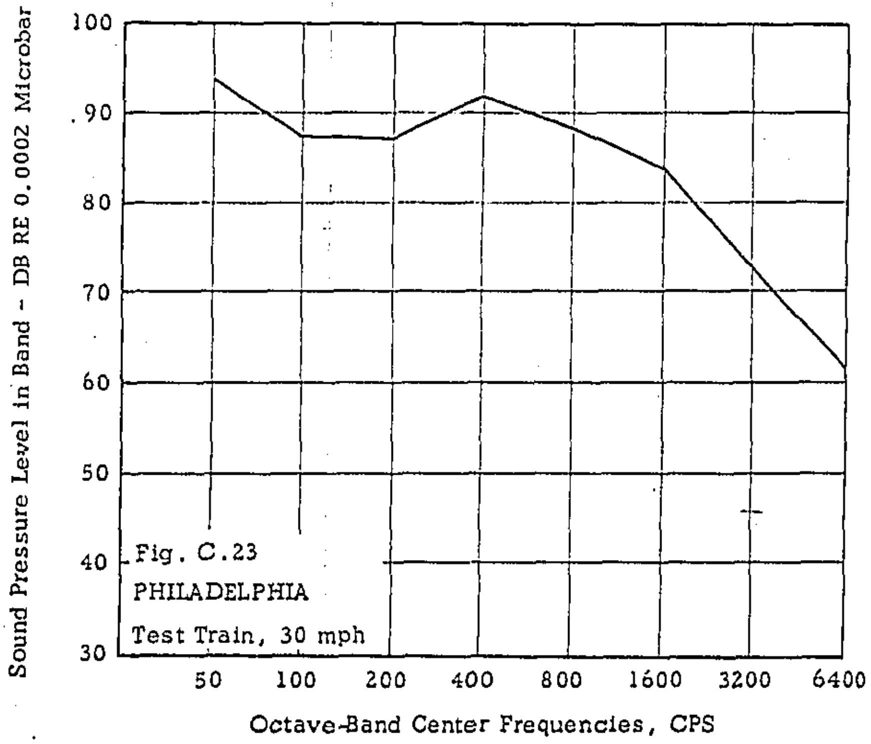


Fig. C.23
PHILADELPHIA
Test Train, 30 mph

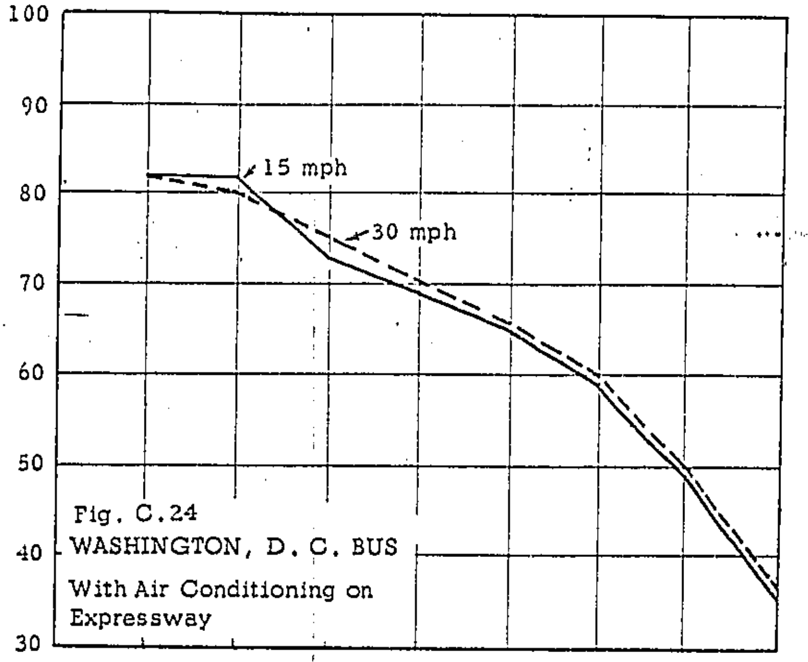


Fig. C.24
WASHINGTON, D. C. BUS
With Air Conditioning on Expressway

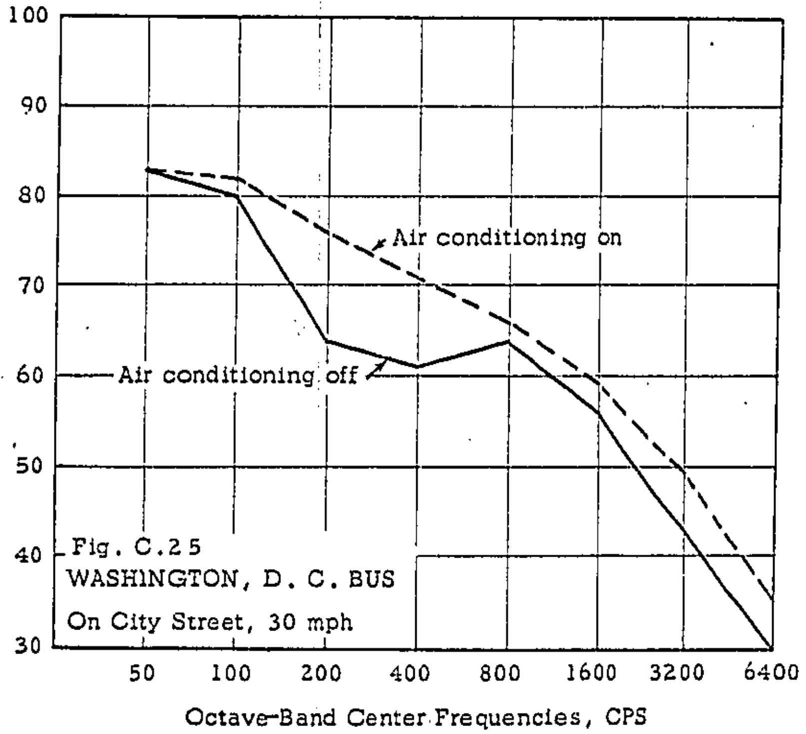


Fig. C.25
WASHINGTON, D. C. BUS
On City Street, 30 mph

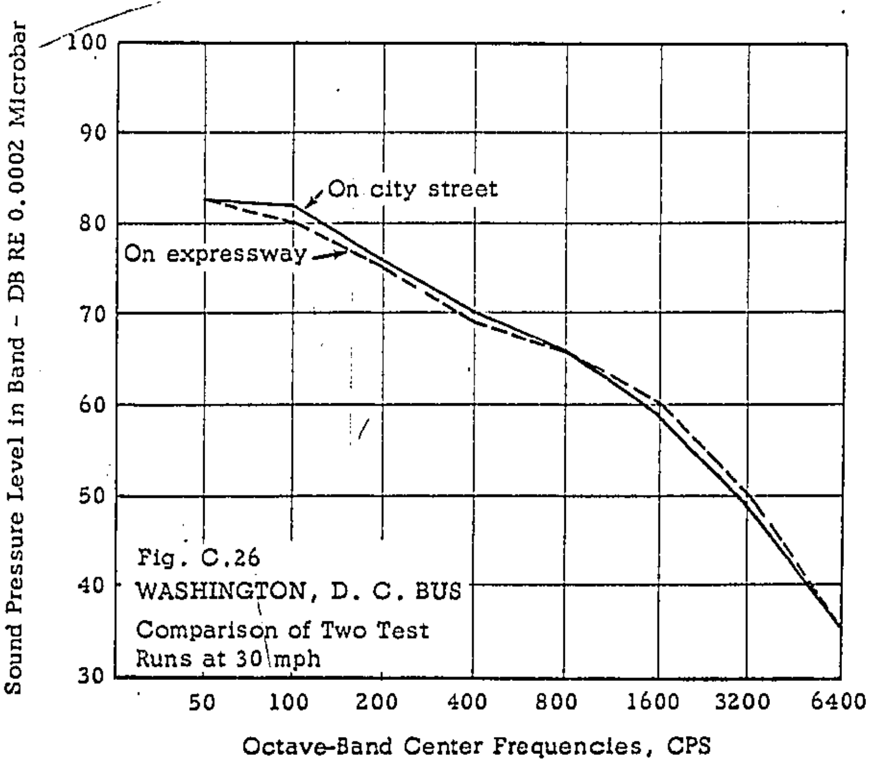
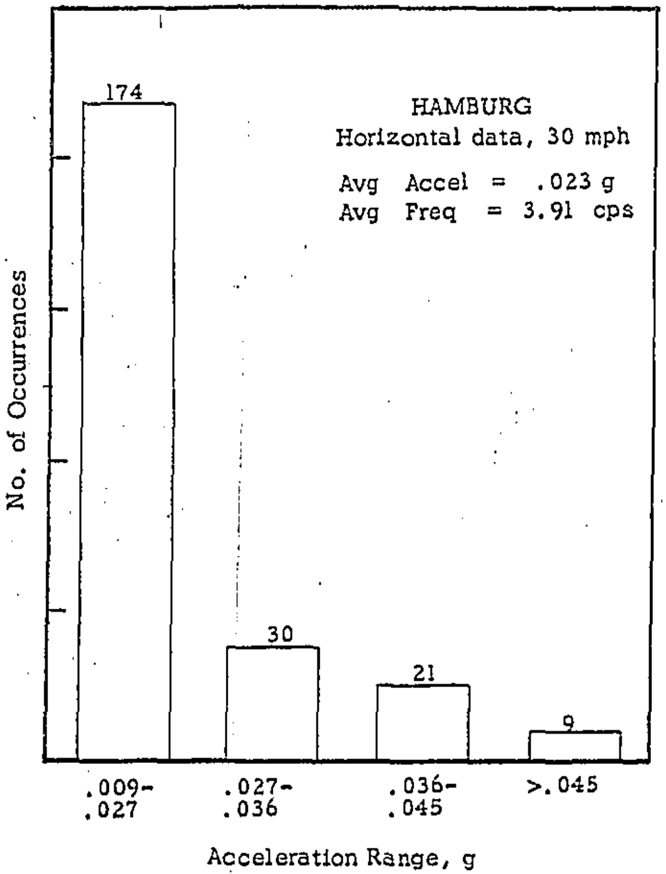


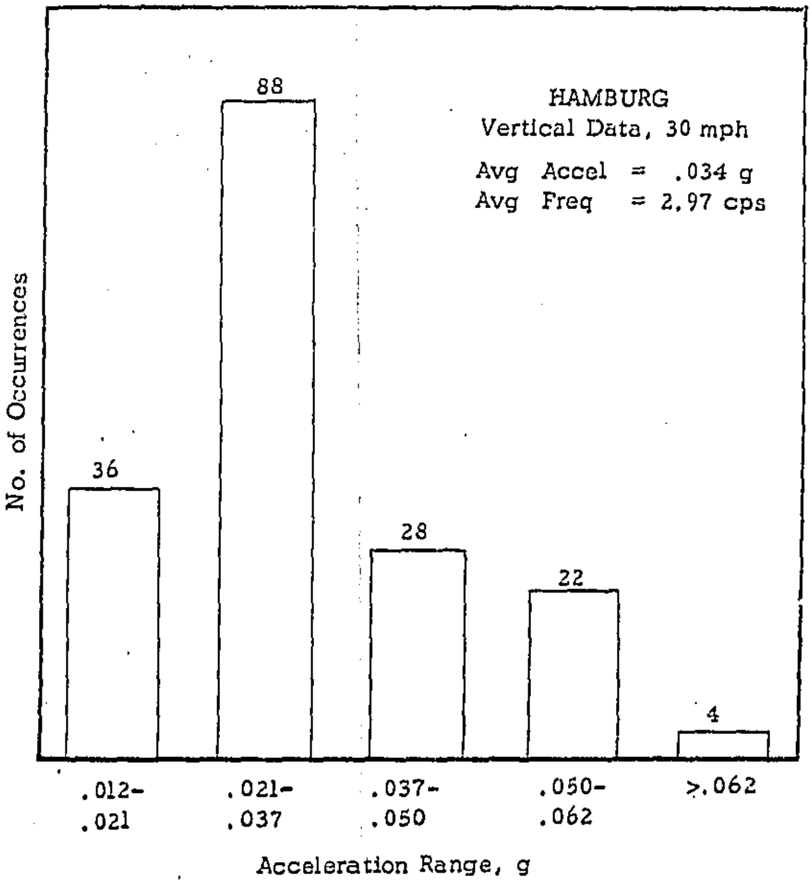
Fig. C.26
WASHINGTON, D. C. BUS
Comparison of Two Test
Runs at 30 mph

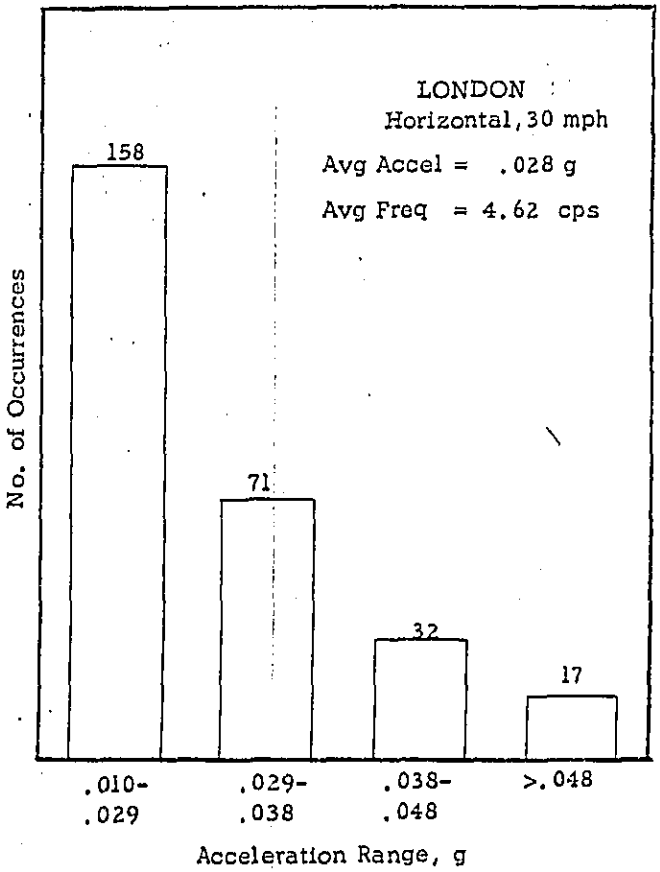
# APPENDIX D

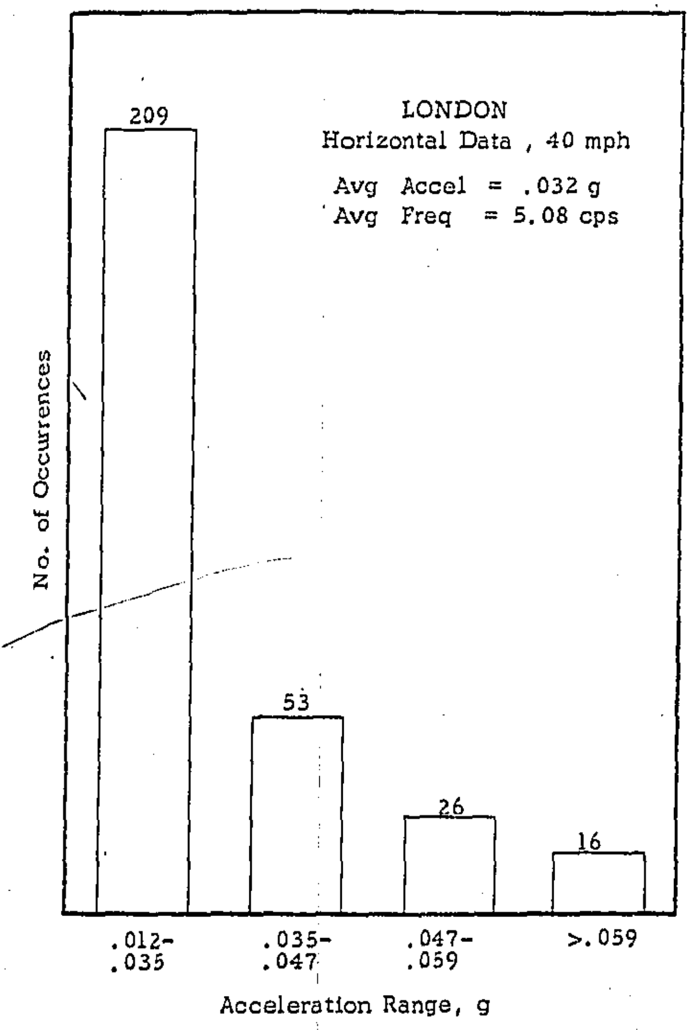
# FREQUENCY-AMPLITUDE CHARTS OF VIBRATION DATA

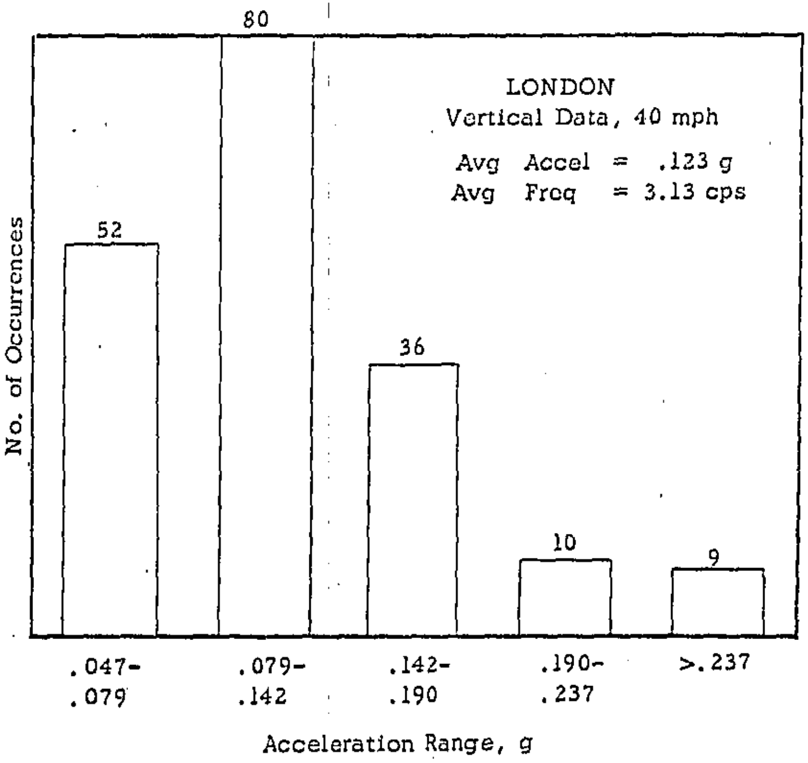
Frequency-amplitude data obtained in the low-frequency analysis of magnetic tape records are presented in this appendix. The charts show the relative frequency of occurrences of horizontal and vertical vibration forces in each of the indicated g ranges. In every case, the data refer to a 60-sec sample.

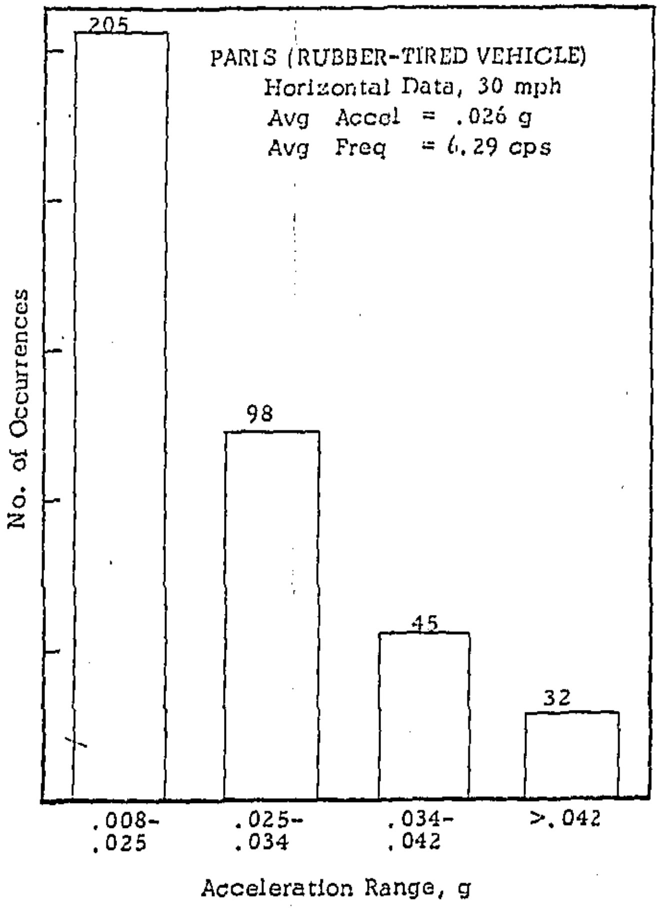

174
30
21
9
HAMBURG
Horizontal data, 30 mph
Avg Accel = .023 g
Avg Freq = 3.91 cps
No. of Occurrences
.009-.027
.027-.036
.036-.045
>.045
Acceleration Range, g

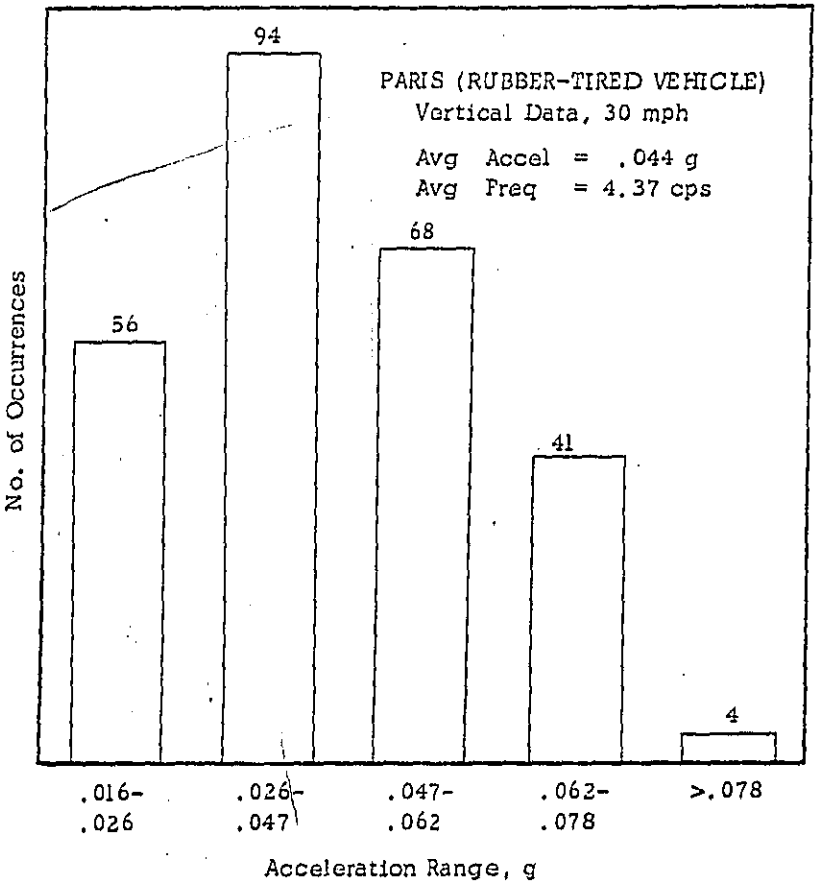

HAMBURG
Vertical Data, 30 mph
Avg Accel = .034 g
Avg Freq = 2.97 cps
No. of Occurrences
36
88
28
22
4
.012-.021
.021-.037
.037-.050
.050-.062
>.062
Acceleration Range, g

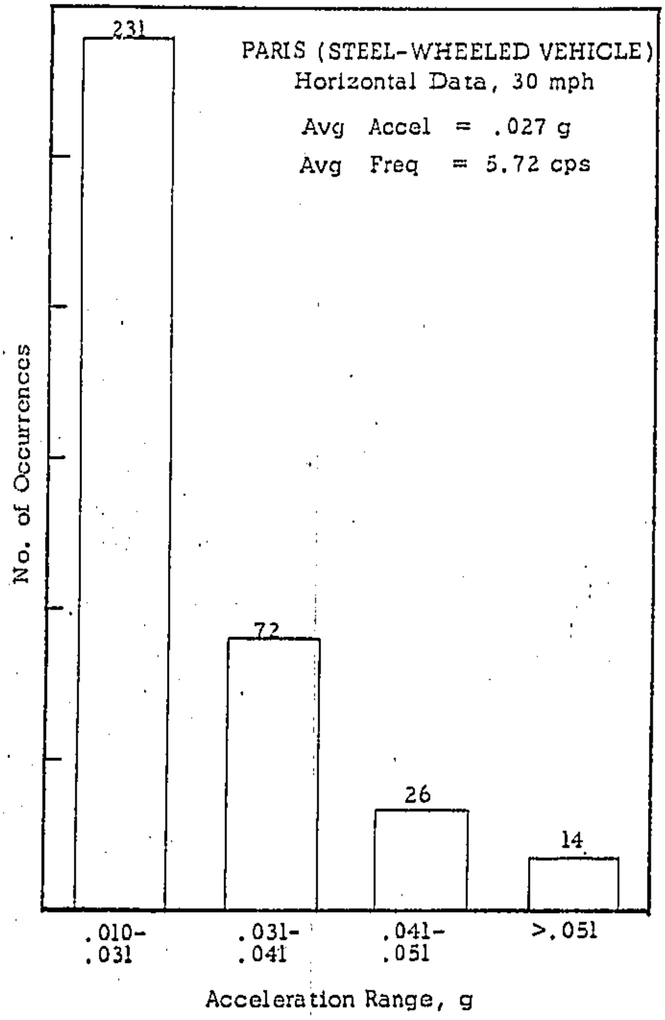

LONDON
Horizontal, 30 mph
Avg Accel = .028 g
Avg Freq = 4.62 cps
158
71
32
17
No. of Occurrences
.010-.029
.029-.038
.038-.048
>.048
Acceleration Range, g

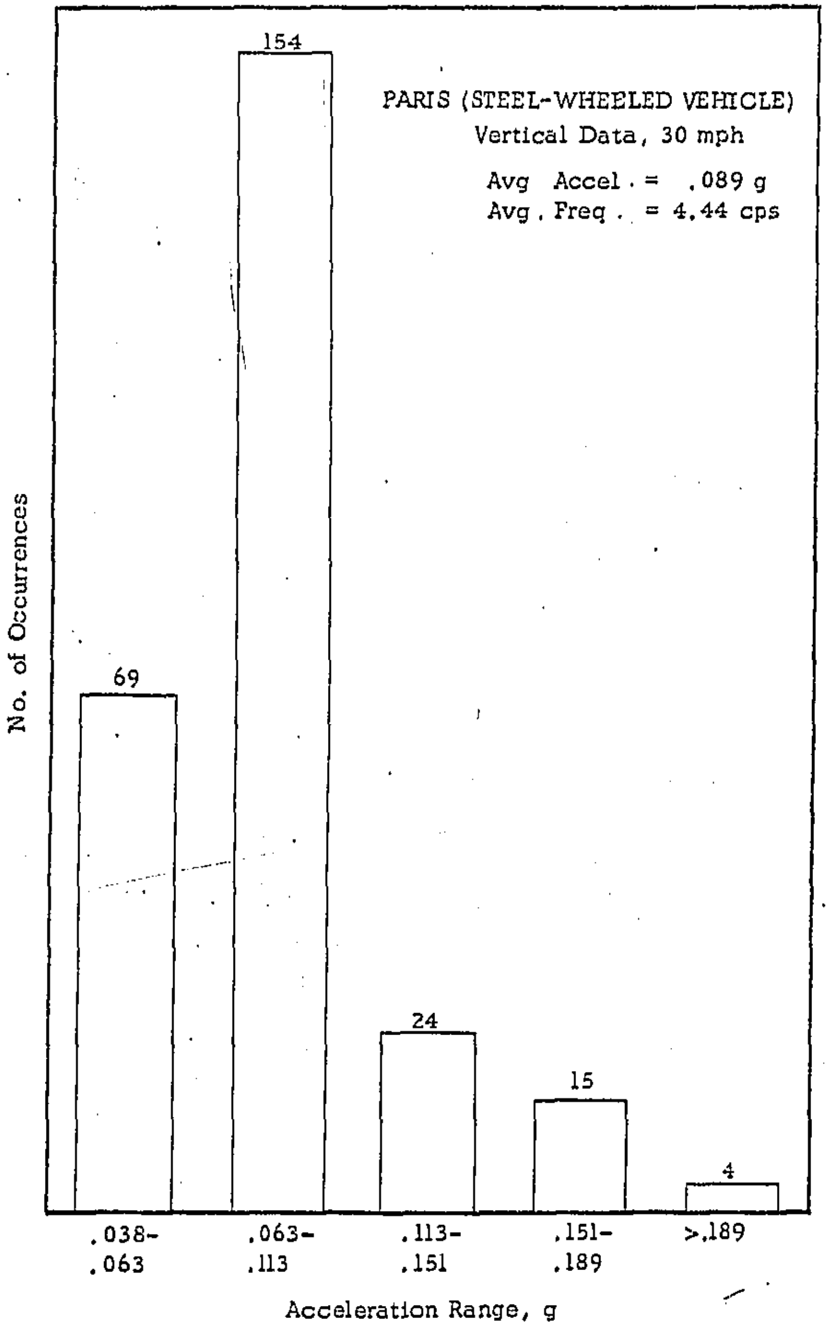

LONDON
Horizontal Data , 40 mph
Avg Accel = .032 g
Avg Freq = 5.08 cps
No. of Occurrences
209
53
26
16
.012-.035
.035-.047
.047-.059
>.059
Acceleration Range, g

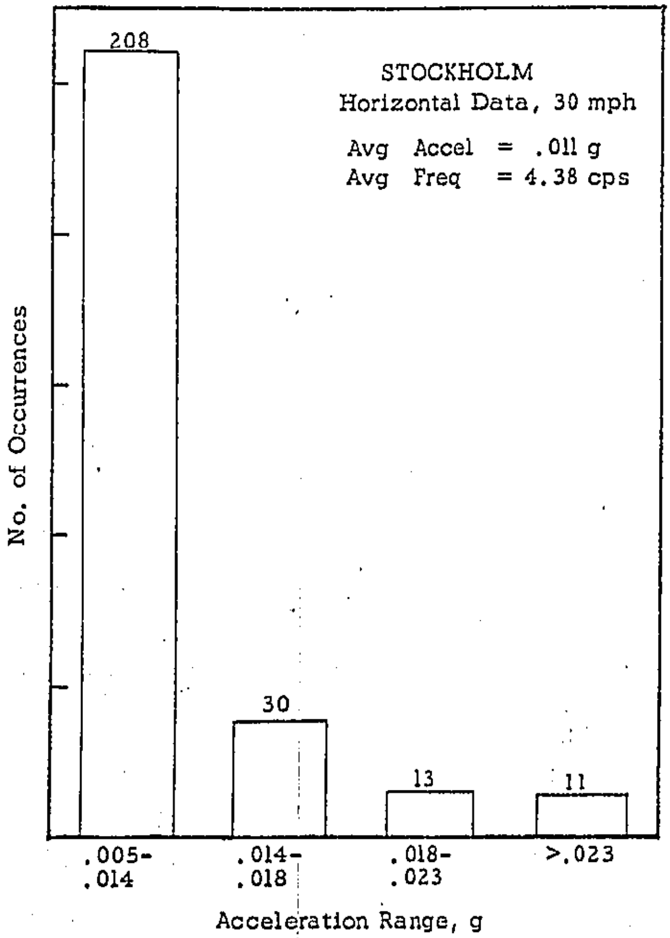

80
LONDON
Vertical Data, 40 mph
Avg Accel = .123 g
Avg Freq = 3.13 cps
52
36
10
9
No. of Occurrences
.047-
.079
.079-
.142
.142-
.190
.190-
.237
>.237
Acceleration Range, g

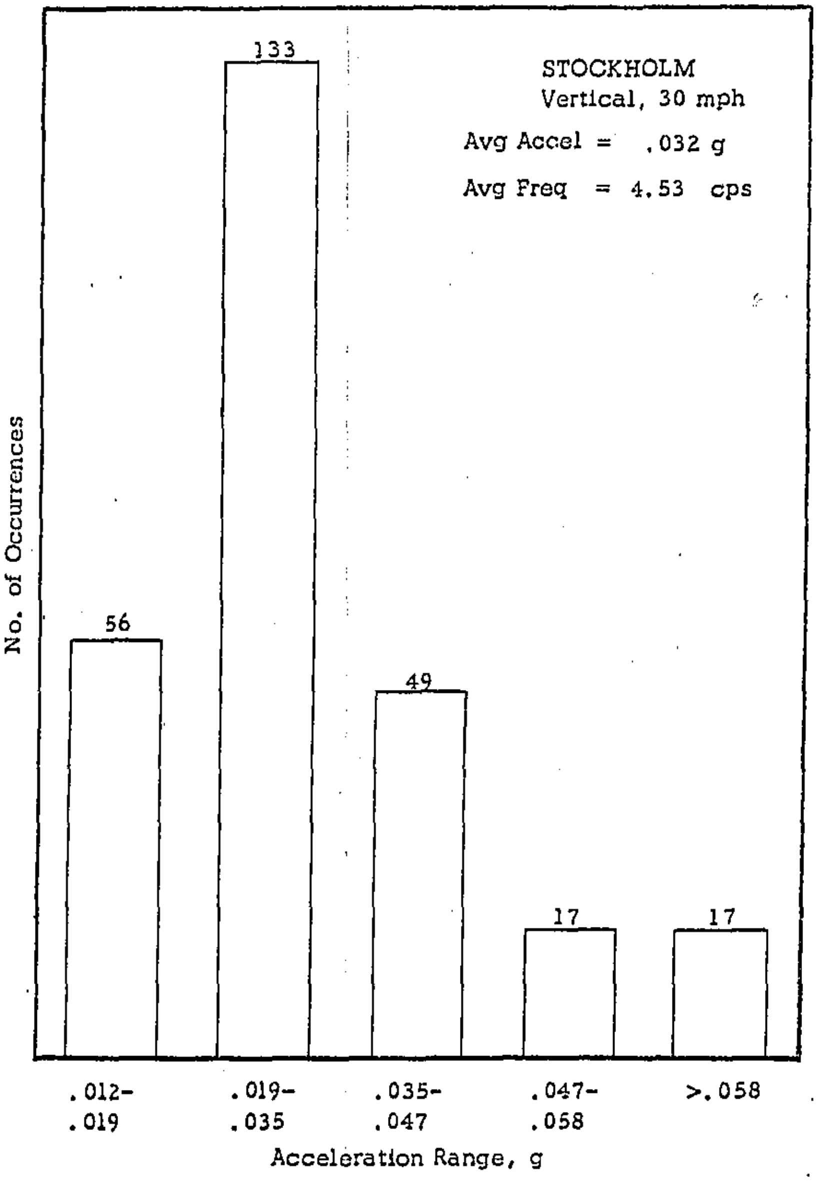

PARIS (RUBBER-TIRED VEHICLE)
Horizontal Data, 30 mph
Avg Accel = .026 g
Avg Freq = 6.29 cps
205
98
45
32
No. of Occurrences
.008-.025
.025-.034
.034-.042
>.042
Acceleration Range, g

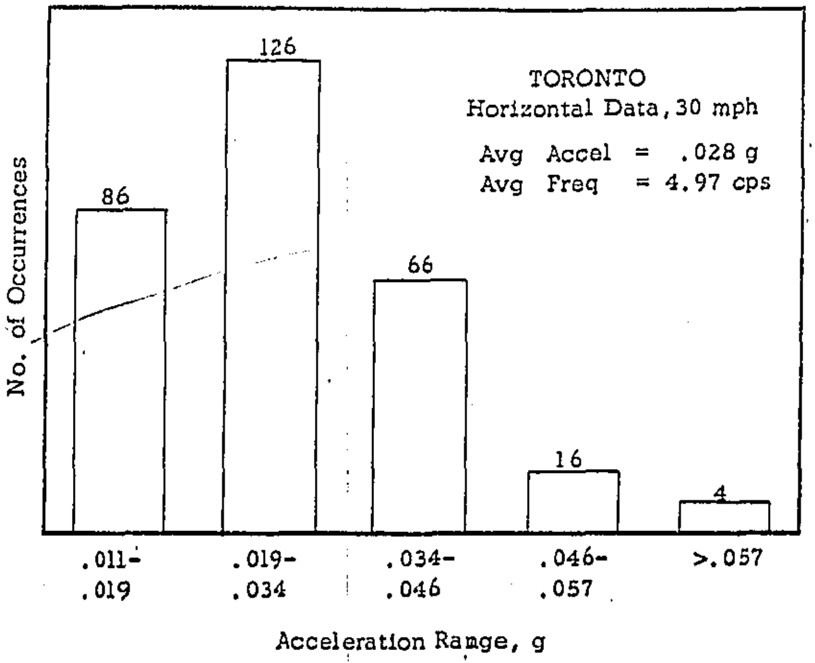

PARIS (RUBBER-TIRED VEHICLE)
Vertical Data, 30 mph
Avg Accel = .044 g
Avg Freq = 4.37 cps
No. of Occurrences
56
94
68
41
4
.016-
.026
.026-
.047
.047-
.062
.062-
.078
>.078
Acceleration Range, g

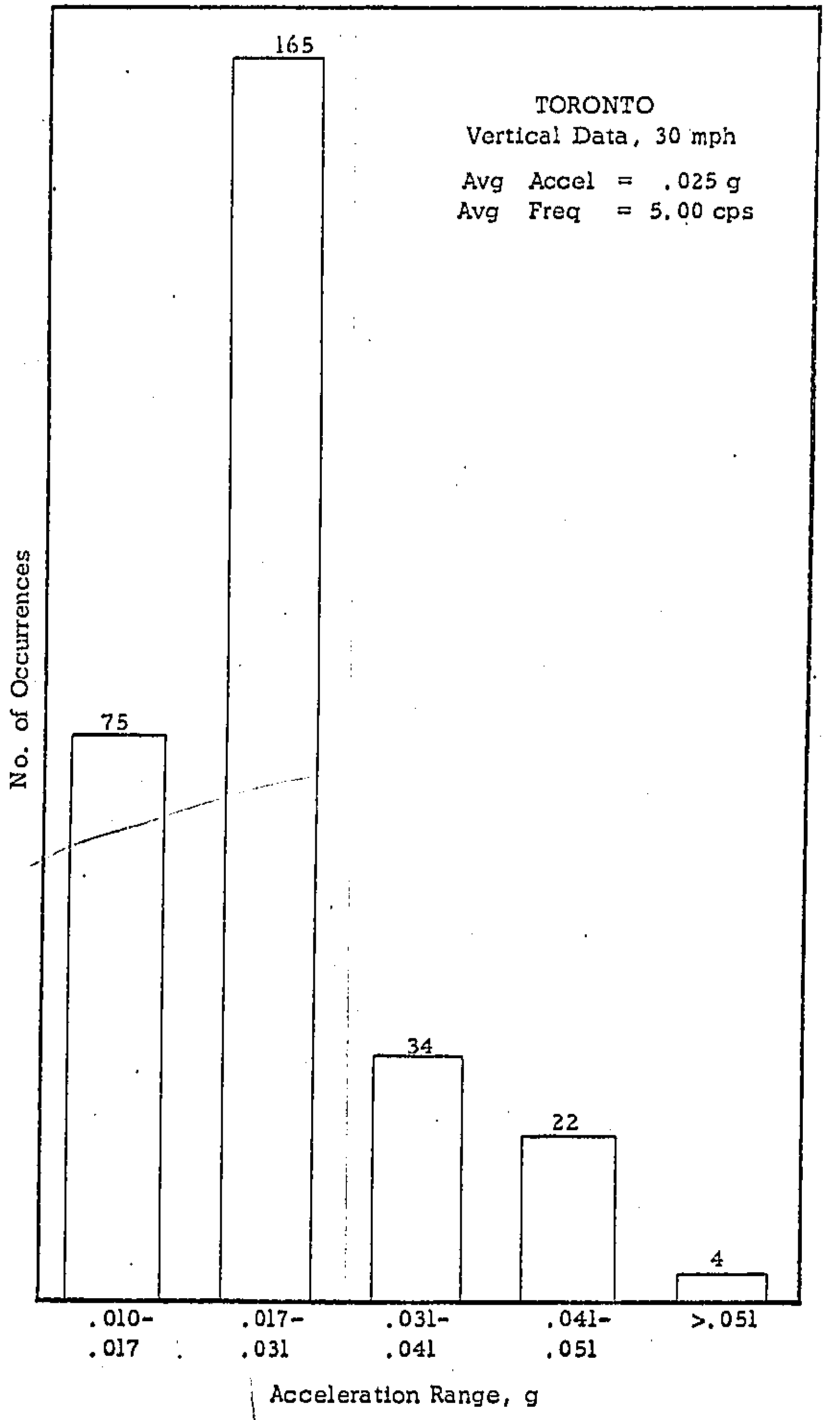
231
PARIS (STEEL-WHEELED VEHICLE)
Horizontal Data, 30 mph
Avg Accel = .027 g
Avg Freq = 5.72 cps
No. of Occurrences
72
26
14
.010-.031
.031-.041
.041-.051
>.051
Acceleration Range, g

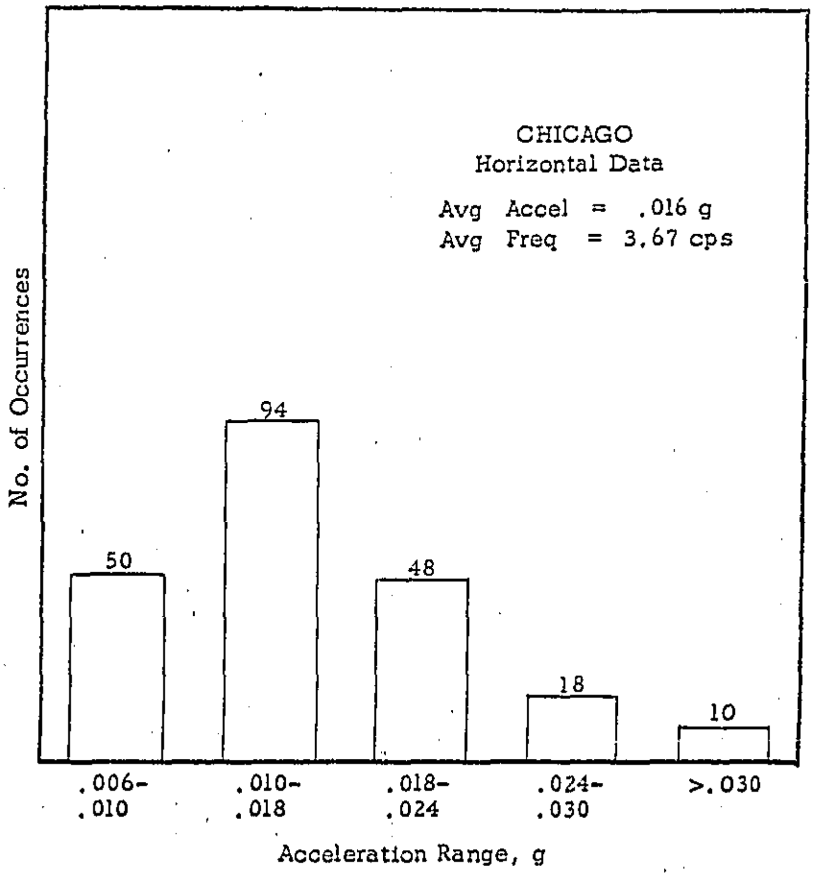

154
PARIS (STEEL-WHEELED VEHICLE)
Vertical Data, 30 mph
Avg Accel. = .089 g
Avg. Freq. = 4.44 cps
No. of Occurrences
69
24
15
4
.038-
.063
.063-
.113
.113-
.151
.151-
.189
>.189
Acceleration Range, g

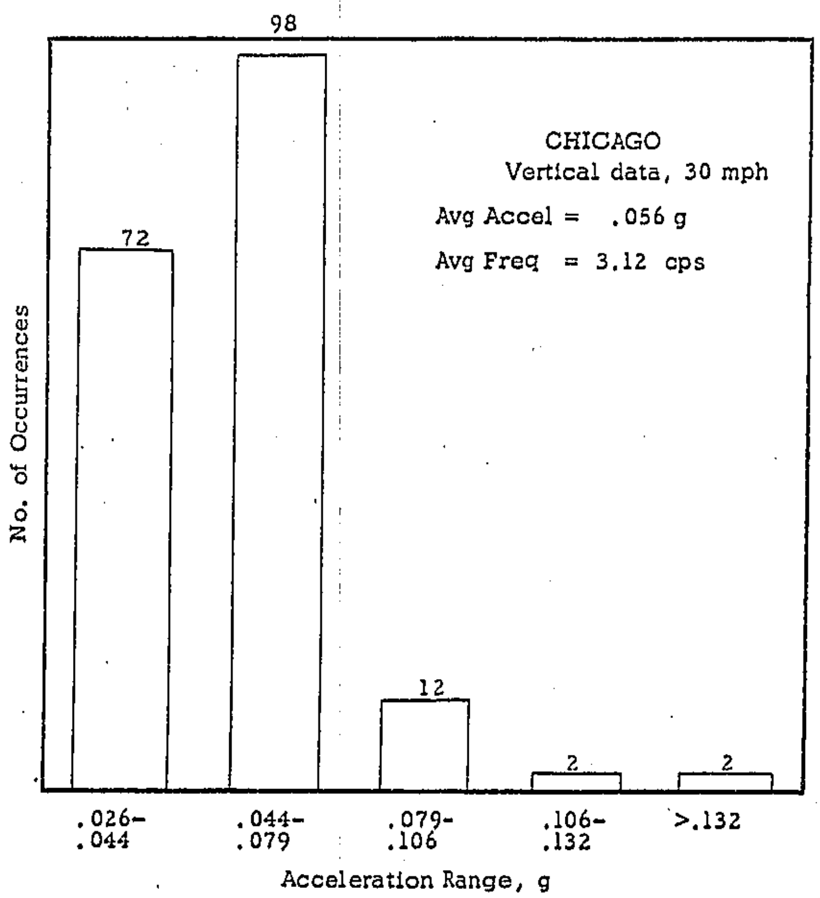

208
30
13
11
STOCKHOLM
Horizontal Data, 30 mph
Avg Accel = .011 g
Avg Freq = 4.38 cps
No. of Occurrences
.005-.014
.014-.018
.018-.023
>.023
Acceleration Range, g

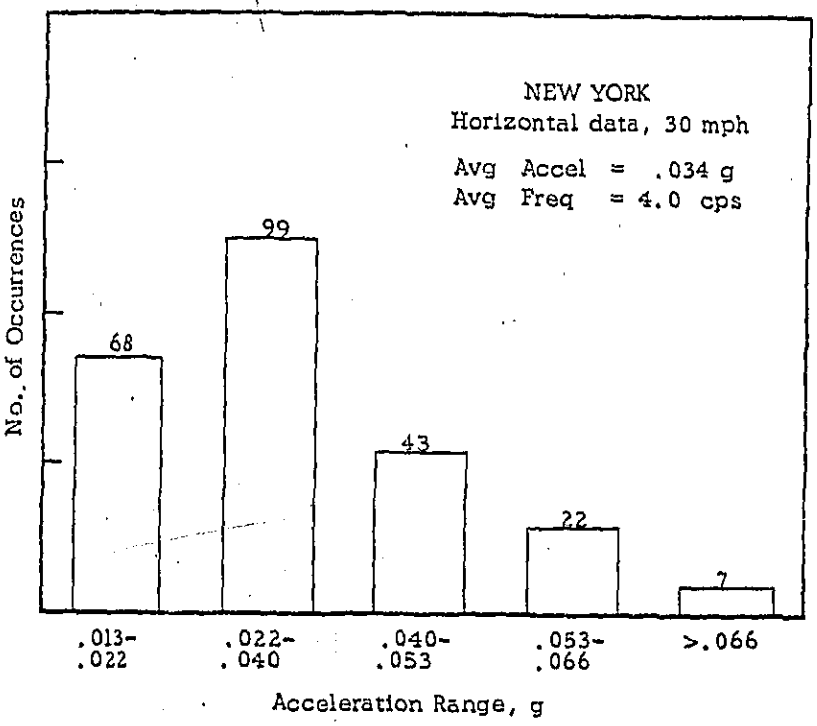

STOCKHOLM
Vertical, 30 mph
Avg Accel = .032 g
Avg Freq = 4.53 cps
No. of Occurrences
56
133
49
17
17
.012-.019
.019-.035
.035-.047
.047-.058
>.058
Acceleration Range, g

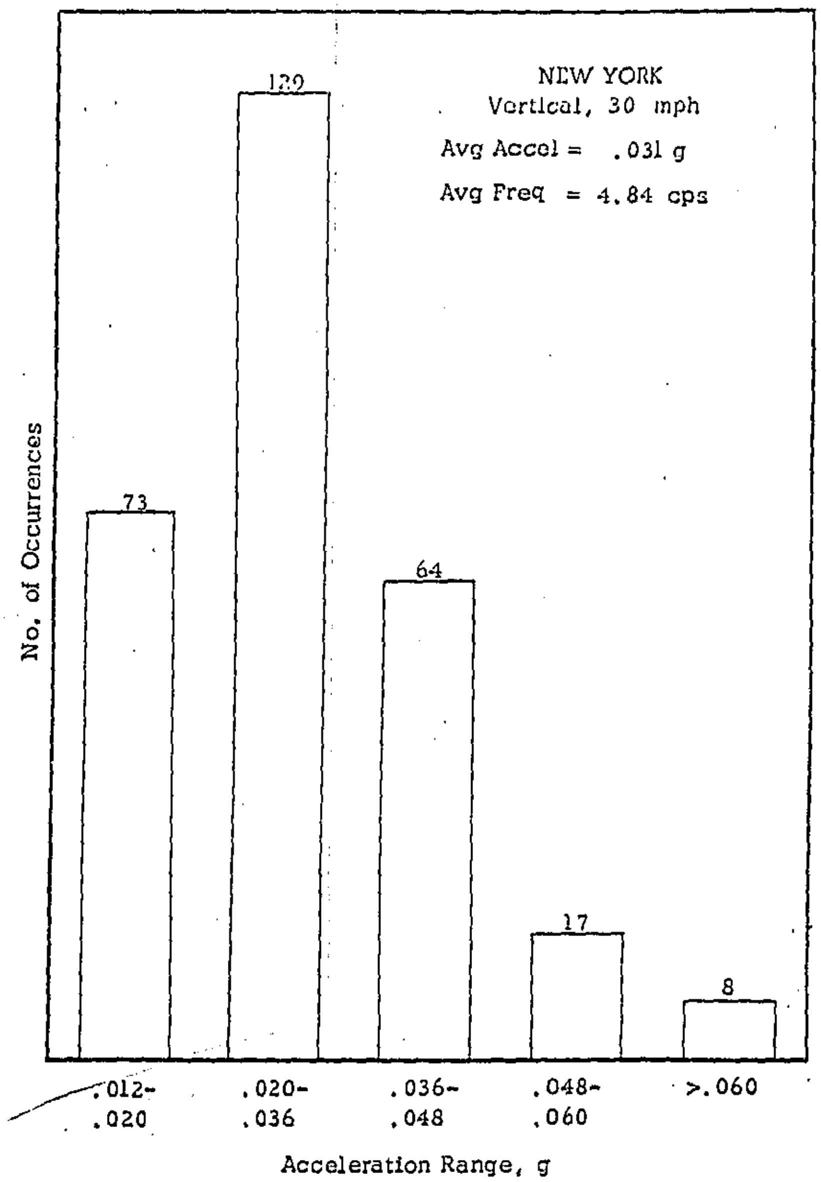

TORONTO
Horizontal Data, 30 mph
Avg Accel = .028 g
Avg Freq = 4.97 cps
No. of Occurrences
86
126
66
16
4
.011-.019
.019-.034
.034-.046
.046-.057
>.057
Acceleration Range, g

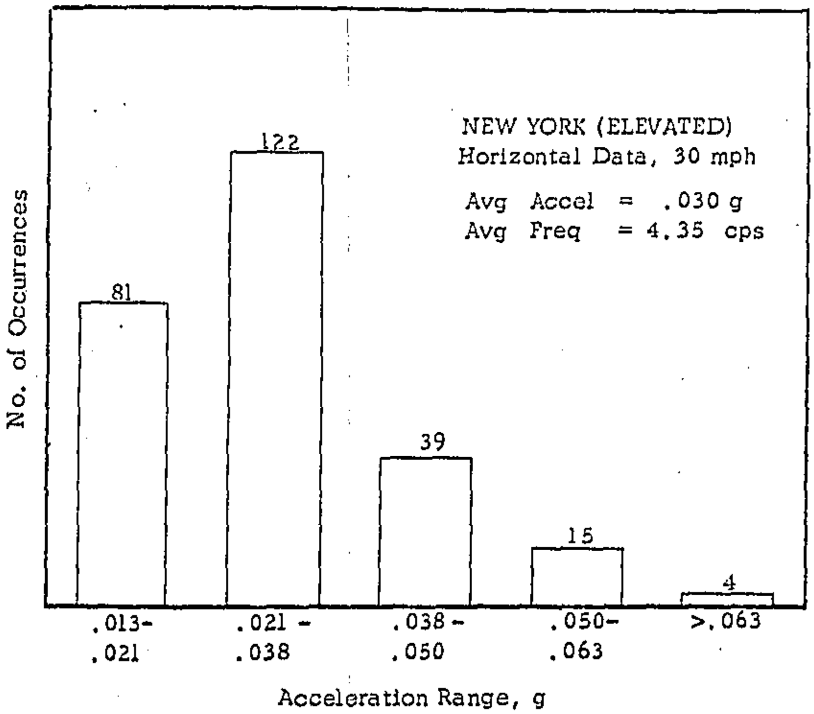
TORONTO
Vertical Data, 30 mph
Avg Accel = .025 g
Avg Freq = 5.00 cps
No. of Occurrences
165
75
34
22
4
.010-.017
.017-.031
.031-.041
.041-.051
>.051
Acceleration Range, g

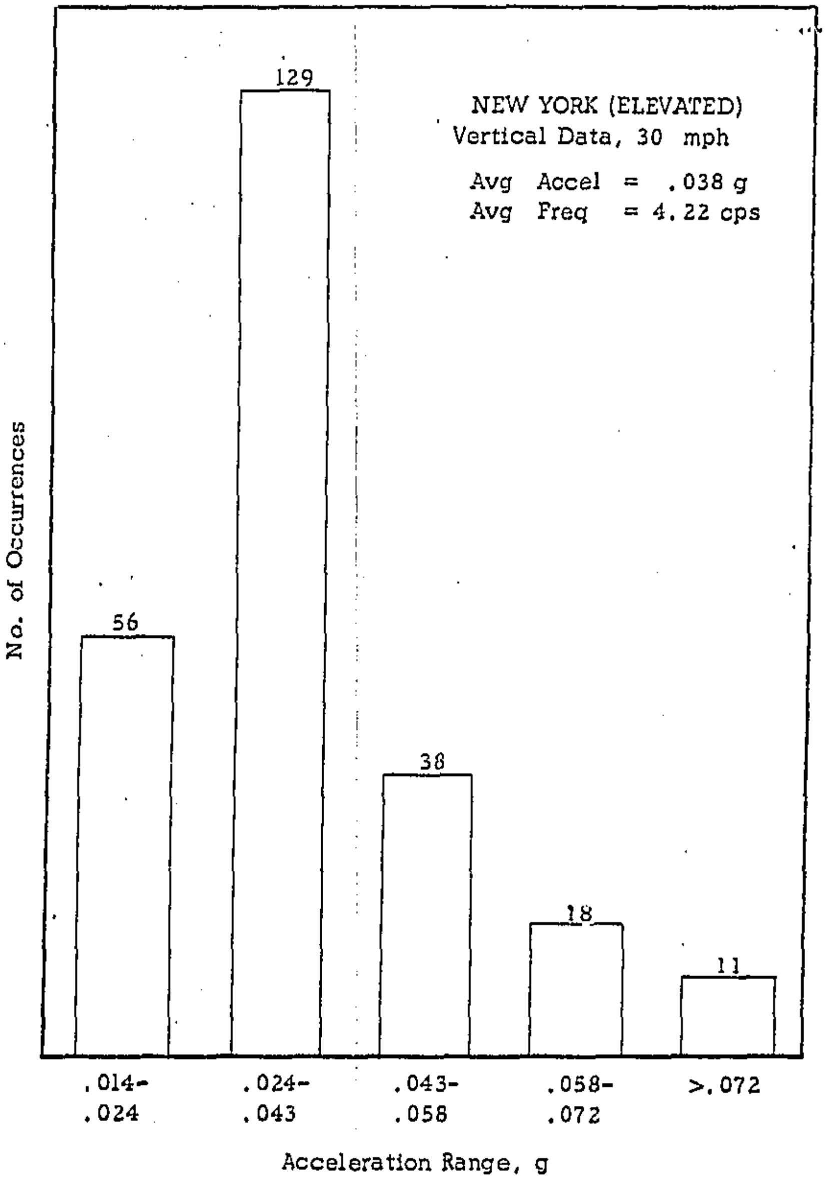

CHICAGO
Horizontal Data
Avg Accel = .016 g
Avg Freq = 3.67 cps
No. of Occurrences
50
94
48
18
10
.006-.010
.010-.018
.018-.024
.024-.030
>.030
Acceleration Range, g

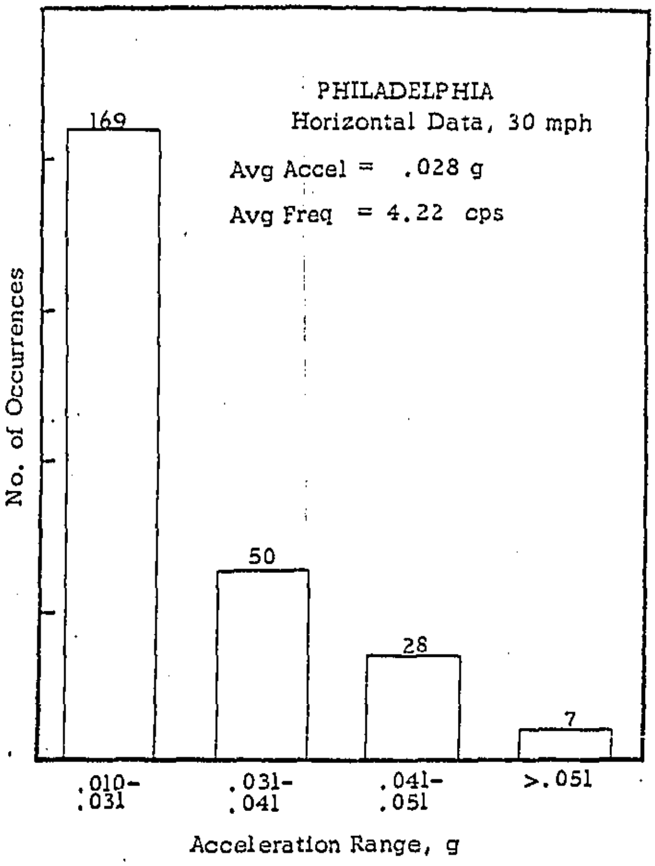

98
72
12
2
2
CHICAGO
Vertical data, 30 mph
Avg Accel = .056 g
Avg Freq = 3.12 cps
No. of Occurrences
.026-.044
.044-.079
.079-.106
.106-.132
>.132
Acceleration Range, g

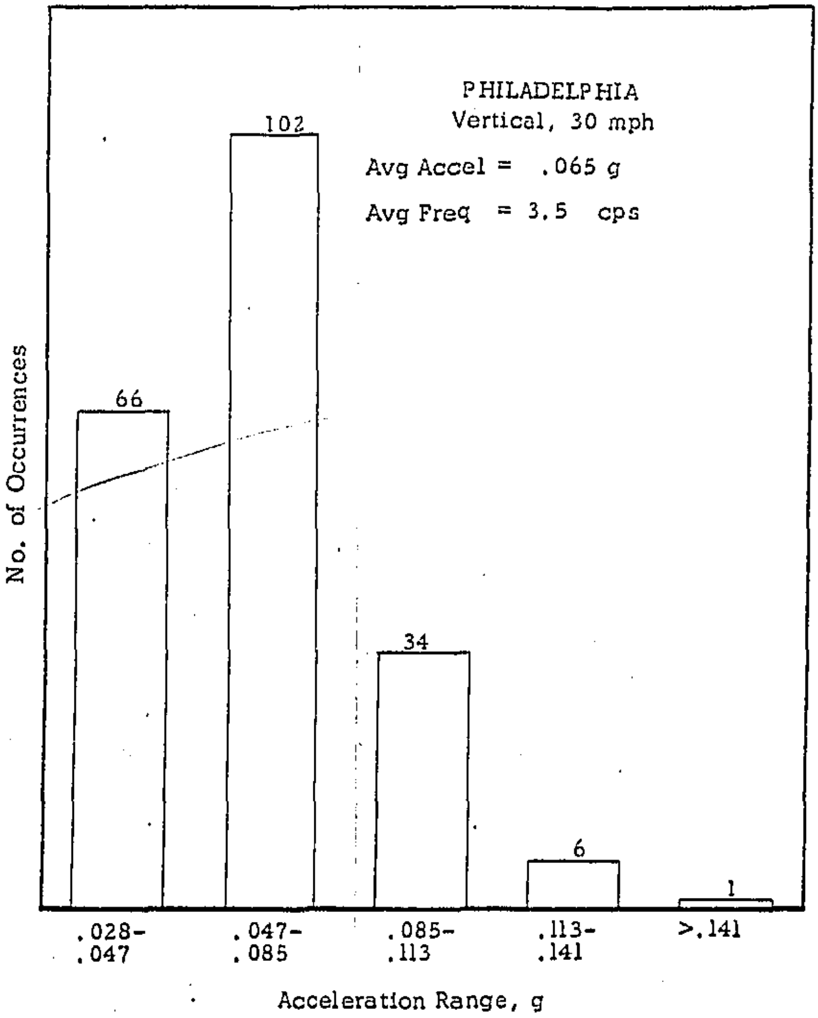

NEW YORK
Horizontal data, 30 mph
Avg Accel = .034 g
Avg Freq = 4.0 cps
No. of Occurrences
68
99
43
22
7
.013-.022
.022-.040
.040-.053
.053-.066
>.066
Acceleration Range, g

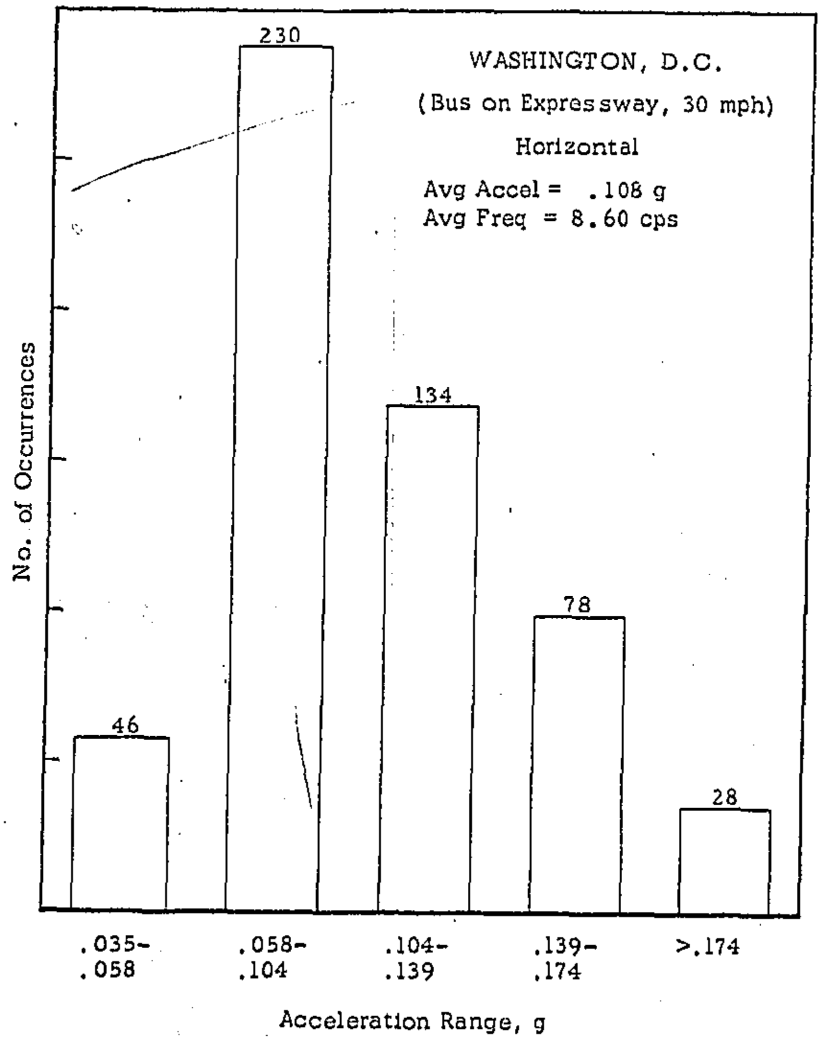

NEW YORK
Vertical, 30 mph
Avg Accel = .031 g
Avg Freq = 4.84 cps
No. of Occurrences
73
129
64
17
8
.012-.020
.020-.036
.036-.048
.048-.060
>.060
Acceleration Range, g

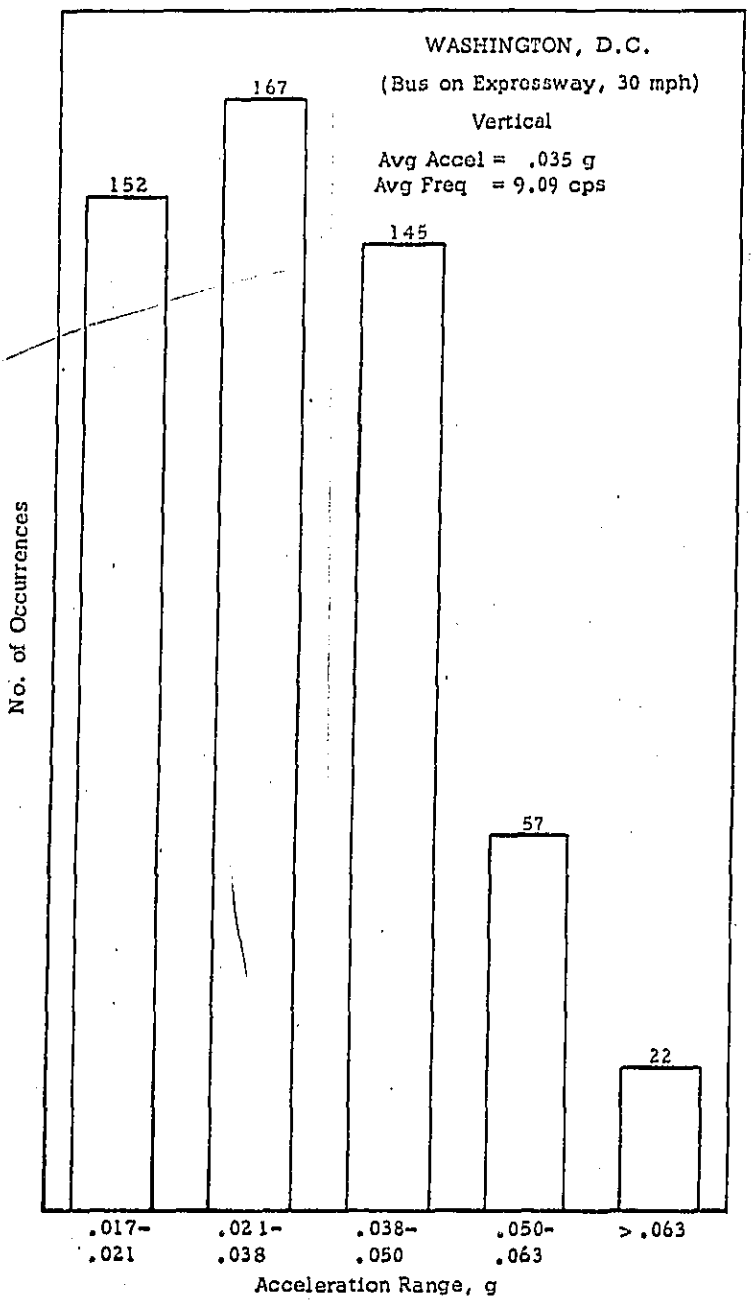

NEW YORK (ELEVATED)
Horizontal Data, 30 mph
Avg Accel = .030 g
Avg Freq = 4.35 cps
No. of Occurrences
81
122
39
15
4
.013-.021
.021-.038
.038-.050
.050-.063
>.063
Acceleration Range, g

NEW YORK (ELEVATED)
Vertical Data, 30 mph
Avg Accel = .038 g
Avg Freq = 4.22 cps
No. of Occurrences
56
129
38
18
11
.014-.024
.024-.043
.043-.058
.058-.072
>.072
Acceleration Range, g


PHILADELPHIA
Horizontal Data, 30 mph
Avg Accel = .028 g
Avg Freq = 4.22 cps
No. of Occurrences
169
50
28
7
.010-.031
.031-.041
.041-.051
>.051
Acceleration Range, g


PHILADELPHIA
Vertical, 30 mph
Avg Accel = .065 g
Avg Freq = 3.5 cps
No. of Occurrences
66
102
34
6
1
.028-.047
.047-.085
.085-.113
.113-.141
>.141
Acceleration Range, g


WASHINGTON, D.C.
(Bus on Expressway, 30 mph)
Horizontal
Avg Accel = .108 g
Avg Freq = 8.60 cps
No. of Occurrences
46
230
134
78
28
.035-.058
.058-.104
.104-.139
.139-.174
>.174
Acceleration Range, g

WASHINGTON, D.C.
(Bus on Expressway, 30 mph)
Vertical
Avg Accel = .035 g
Avg Freq = 9.09 cps
152
167
145
57
22
No. of Occurrences
.017-
.021
.021-
.038
.038-
.050
.050-
.063
> .063
Acceleration Range, g

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