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Earth-borne vibrations generated by highway traffic and construction activities are compiled from data acquired throughout most of California over a 17-year period. Review and reassessment of the compiled data, in light of recent information in the literature, reveals and reaffirms Caltrans' experience that architectural damages to buildings from such vibrations to be highly improbable. Vibration intrusion into buildings from such vibrations are also highly improbable.

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RESEARCH REPORT

SURVEY OF EARTH-BORNE VIBRATIONS DUE TO HIGHWAY CONSTRUCTION AND HIGHWAY TRAFFIC

76-20

FINAL REPORT

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DEPARTMENT OF TRANSPORTATION
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OFFICE OF TRANSPORTATION LABORATORY

April 1976

FHWA No. A-8-3
TL No. 636391

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

SURVEY OF EARTH-BORNE VIBRATIONS
DUE TO HIGHWAY CONSTRUCTION AND HIGHWAY TRAFFIC

Study made by . . . . General Services Branch

Under the Supervision of . . . . W. H. Ames, P.E.

Principal Investigator . . . . W. Chow, P.E.

Co-Investigator . . . . A. Sequeira, P.E.
R. Johnson

Report Prepared by . . . . W. Chow, P.E.

Very truly yours,

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

WC:lrb

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This work was accomplished in cooperation with the United States Department of Transportation, Federal Highway Administration, as Item A-8-3 of work program HPR-1 (13) Part 2, Research, and was titled "Survey of Earth-Borne Vibrations Due to Highway Construction and Highway Traffic." The contents of this report reflect the view of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. It should also be recognized that the opinions, findings, and conclusions expressed in this publication are not necessarily those of the Federal Highway Administration.

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I. INTRODUCTION

With today's increased environmental "conciousness", there followed an increased concern about construction and highway traffic induced earth-borne vibrations and their possible adverse effects on buildings and its occupants. Prior to the mid-1960's, there had been little data and information on such vibrations. However, since the early 1970's several publications (2,3,4,5) about such earth-borne vibrations and its effects on buildings and their occupants have been printed. In light of these new publications, and in relation to them, this report compiles and summarizes Caltrans' earth-borne vibration data acquired over 17 years. It provides an overview of vibration damage and intrusion within the range associated with traffic and construction activities and provides vibration levels which should not be exceeded to avoid damage and intrusion.

II. CONCLUSIONS

1. Architectural damage is probable when vertical ground vibrations generate soil particle vertical velocity that exceeds .1965 in./sec. within the normal frequency range (1-100 Hz) of soils. Intrusion is probable when such velocity exceeds .0984 in./sec.

2. Earth-borne vibrations created by normal highway vehicular traffic will not cause architectural damage to buildings, nor will earth-borne vibration intrusion occur. Such vibrations compiled for this report are well below architectural damage level of .1968 in./sec. and intrusion level of .0984 in./sec.

3. Earth-borne vibrations created by highway construction vehicular equipment are an improbable cause of architectural damage to buildings. In general, they are an order of magnitude below architectural damage level. However, with today's (1975) large construction vehicular equipment discretion or special care should be exercised when they are operated "near" buildings. "Near" is usually within a range of 10' to 25', depending on the specific equipment. At that distance, or closer, vibrations may approach the intrusion level.

4. Pavement breaking machines produce vibrations above architectural damage level and discretion should be applied in their use adjacent to buildings. Intrusion from such vibrations will occur.

5. Earth-borne vibrations created by train passages, in general, may approach the threshold of architectural damage level.

6. In-house activities often create larger building vibrations than those caused by adjacent vehicular traffic and construction activities.

III. IMPLEMENTATION

Earth-borne vibration levels determined in this study for various moving vehicular equipment and potential resultant damage and intrusion effects are used as the primary criteria in assessing transportation generated vibration concerns voiced by the public and industry.

IV. GENERAL DISCUSSION

A. Background

Vehicular traffic and highway construction activities create earth-borne vibrations which often "trigger" people's reaction resulting in complaints about vibration intrusion into buildings and/or building damages. This report is confined to such vibrations. Earth-borne ground surface vibrations are created by vehicular traffic and highway construction activities. They are created by interactions between the vehicle's tires or tracks and the road or ground surface. Pavement expansion joints, expansion cracks, and rough pavement are all causes of vehicle-pavement interactions causing ground surface vibrations. Earth-borne vibrations from construction activities are usually generated by pile drilling, pile driving, pavement breaking, and moving vehicular construction equipment.

Earth-borne vibrations are borne mainly by three waves: P-waves (compression), S-waves (shear) and Raleigh waves (surface). It is the Raleigh wave which is reported throughout this report and is generally the "culprit" in vibration complaints. This is reported by Miller and Pursey (1954) (1) and others (2,3).

It would seem to those who are familiar with the physical laws pertaining to dynamics that acceleration, or perhaps displacement, would be the primary factor influencing architectural damage and intrusion potential. Experience and studies by independent authorities (2,3,9), however, indicate consistently that peak particle velocity within the range of normal earth vibrations correlates best with damage and intrusion whereas acceleration and displacement do not. Therefore, it is peak particle velocity which is reported throughout this report.

Particle velocity is further defined to mean the vertical velocity at which the soil particles or other materials vibrate locally as opposed to the propagation velocity of vibrations. The latter being the speed which vibrations travel through the ground away from its source.

Messrs. Leonard and Whiffin (2) present a summary of the "reaction of people and damage to buildings at various vibration levels." It is reporduced herein as Figure 1 (1,2) with Caltrans' added notations of vibration levels "A", "B", "C", "D", "E", and "F" in in./sec. Furthermore, Messrs. Leonard and Whiffin (2) have proposed a peak particle velocity of 5 mm/sec. (.1968 in./sec.) as the "threshold at which there is a risk of architectural damage to normal dwelling-houses with plastered walls and ceilings." Architectural damage (2) is defined as cracking of plaster or other brittle materials as opposed to structural damage which impairs the structure's functioning. Architectural damage is shown as level "E" in Figure 1-1. It is the criteria used in this report to evaluate the effects of the compiled vibration data.

Considering earth-borne vibrations created by dynamite blasting, Messrs. Duvall, Johnson and Nicholls (4) classified 5.4 in./sec. particle velocity as a minor damage level and defines it as "formation of new fine cracks either in plaster or dry wall joints or the opening of old cracks." For no damage or safe blasting criteria, they classify its level as 2 in./sec. of particle velocity. It is of interest to note that they reported some normal in-house activities generated vibrations that were between the levels of 2 - 5.4 in./sec. That is, some in-house activities created vibrations at the minor damage level of 5.4 in./sec.

Consider that a ground dynamite blast sends forth a single vibration pulse, whereas traffic and construction vibrations are almost of a continuous nature. Because of its almost continuous nature, it is probable that smaller, continuous vibrations, over a single large vibration pulse, would be equally damaging over an extended period. Thus, Messrs. Duvall, Johnson and Nicholls (4) set a safe dynamite blast level of 2 in./sec., whereas Messrs. Leonard and Whiffin (2) set a safe traffic vibration level of .1968 in./sec. or an order of magnitude below safe blasting vibrations.

B. Caltrans' Experience

The compilation of these vibration data presented herein are the results of investigating specific complaints or concerns about earth-borne vibrations over a 17-year period. Caltrans conducted its first vibrations investigation in 1958. It involved a manufacturing plant making water pumps in El Cerrito. Since that initial complaint, it has conducted 22 additional vibration investigations to date. Figures 2-7 is a compilation of the data from these investigations. In the 23 vibration investigations, a large amount of data were collected. However, for brevity, only the data from a common series of the most severe vibration recordings or an unusual datum point from each investigation is tabulated in the compilation.

The 23 investigations covered almost all of California in several geographical areas:

1) Los Angeles Basin
2) San Francisco Bay Area
3) Sacramento Valley Area
4) Salinas Valley Area
5) Petaluma
6) San Jose

These vibration investigations involved:

1) Private Houses and Apartments
2) Manufacturing Plants
3) Aerospace Companies
4) Machine Shops
5) Art Gallery
6) Move Studio
7) Medical-Dental Building
8) Computer Data Processing Company
9) Grain Silo

Investigations involved measuring vibrations inside buildings and structures as well as outside ground vibrations caused by vehicular traffic, trains, and highway construction activities.

The usual concerns voiced were allegations that vehicle induced earth-borne vibrations would damage a building or structure. However, unusual concerns also included allegations such as:

1) Vibrations "electrified" the air in a bedroom "robbing" its occupants of sleep.
2) Earth-borne vibrations shook a dentist's drill.
3) Earth-borne vibrations may adversely affect "sophisticated" star-tracking space instruments.

Of the 23 vibration investigations, all except three have been resolved without litgation. One remains unresolved (1975) concerning a proposed freeway routing close to a major aerospace manufacturing facility.

The original research proposal stated that:

> "The proposed work will be in essence a survey of vibrations emanating from various types of highways, highway structures and vibrations emanating from in-progress highway construction. Soil samples or conditions and geological formations will be obtained for each test location. On finished highways a test vehicle of known axles and axle loads will be used at various speeds to induce vibrations into the surrounding earth. Three seismometers will be located at various distances normal to the pavement edge to record the induced vibrations from the passing test vehicle. The three (3) seismometers will also show the attenuation distances from the pavement. This test procedure will be carried out at different highway sections, i.e., cuts, fills, level sections, undercrossings, overcrossings and elevated structures."

> "Essentially, the same test method will be used to record in-progress highway construction vibrations. Vibrations emanating from pile driving, slope cutting, scraping, filling or any highway construction producing large vibration vs. distances with different highway configurations will be studied."

In light of the architectural damage level proposed by Leonard and Whiffin (2), and Caltrans' compiled vibration data being below it in practically all cases, it would be superfluous to conduct a series of vibration investigations to reaffirm what has been revealed over the past 17 years. Rather than conduct a series of repetitive investigations, the intent of the original proposal was accomplished by utilizing these vibration test data compiled over 17 years as listed in Figures 2-7. The apparent typicality of the low levels of vibrations found are further confirmed by other workers in the field such as References 3, 4, and 5.

Furthermore, additional work in an attempt to correlate vibration data with all variables (highway structures, geological formations, traffic speed, distances, axle weights, construction equipment, soil saturation, seasonal changes, etc.) would also be superfluous because of the low-level vibrations revealed in the studies which would be improbable of producing damages or intrusions into buildings or structures.

V. DISCUSSION OF THE COMPILED TEST DATA

As previously stated, only the most severe vibration data from a particular series or vibration data of special interest from each of the 23 vibration investigations are compiled in Figures 2-7. These compiled data are further grouped and plotted in 4 graphs (Figures 8, 9, 10, and 11).

A. Vehicular Traffic Vibration Level

Figure 8 is a plot of the compiled highway and street-traffic induced ground vibrations at various distances from its source. It represents a portion of the 17 years of accumulated vibration data, specifically of vehicular traffic vibrations.

These data points represent a broad spectrum of vehicular equipment and their vibration manifestation upon a broad spectrum of highway structures and ground formations. The broad spectrum range of highway strucutres includes elevated fills, elevated structures, depressed highways and level sections of highways. The range of vehicular equipment includes a Caltrans lowboy (see Figure 12), trucks, buses, and typical street and highway vehicles.

The Caltrans lowboy was loaded to its legal maximum axle weight limits, as annotated in Figure 12, to record the amount of ground vibrations it would generate with its legal load. It was used in several investigations at various speeds both on city streets and highways. Earth-borne vibrations created by it and its attenuation with distances are plotted in Figure 8. It shows that maximum legal axle load, such as the lowboy, produced earth-borne vibrations well below the criteria of level "E" (Figure 1-1) for architectural damage. That is, the lowboy generated earth-borne vibrations about 1/10th of level "E".

Considering the wide spectrum of vehicular traffic, geologic formations and highway structures that data in Figure 8 represents, it is of interest to note that not a single vibration data point approached the architectural damage level "E" of .1968 in./sec. (5 mm/sec.). The largest vibration, .056 in./sec., ploted in Figure 8 appeared on the ground 17 feet from the passage of a fill haul truck. It was recorded in a San Mateo area, composed of San Francisco Bay fill, and was especially conducive to vibration emanations because of its mud-like character resulting in low frequency (3 cps) of vibrations. This then was the largest ground vibration caused by vehicular traffic recorded in 17 years of vibration investigations. In relation to the architectural damage level of .1968 in./sec. it is about 1/3rd of the architectural damage level.

It would seem that large vibration levels would occur on the ground closest to highway structures. Indeed, a relatively large level (.043 in./sec.) was recorded on the ground directly beneath a causeway. Directly on a concrete viaduct, the vibration level was .021 in./sec. and directly on the ground beaneath it, it was .010 to .013 in./sec. The smallest recorded vibration beneath a freeway structure was .006 in./sec. Recalling that .1968 in./sec. is the criteria for architectural damage, the "ratio" tabulation below shows that vibrations closest to its source were still only a fraction of the architectural damage criteria level "E"

	Vibration in./sec.(V)	Ratio = V / .1968(level "E")
Beneath Yolo Causeway	.043	.218
On Santa Monica Viaduct	.021	.106
Beneath Santa Monica Viaduct	.013-.010	.066-.05
Beneath Foothill Fwy Structure	.006	.030

Beyond 50 feet from its vibration source, ground vibrations had attenuated to a range of .023 in./sec. to zero. From these compiled data, all highway and street traffic vibrations were below the architectural damage level "E" of .1968 in./sec. The paragraph below is quoted from Leonard and Whiffin (2):

> "Vibrations are mainly generated by fluctuations of wheel contact loads as vehicles travel over road surface irregularities. Irregularities of the order of 20 mm in amplitude can cause peak particle velocities in the ground of up to 5 mm/s. At this level "architectural damage" may occur in buildings. However, before this level is reached, vibrations become intrusive and even annoying to occupants of buildings (at about 2.5 mm/s) and complaints may result."

The 20 mm amplitude road surface irregularities equates to .7872 inches and the 5 mm/s peak particle velocity equates to the frequently stated .1968 in./sec. California's highways are generally built and maintained with less than .3 inch irregularities which is reflected by the generally low earth-borne vibration levels found emanating from highway traffic. In the case of newly placed concrete pavements, all pavement surface irregularities .3 inch or higher, over a fixed distance, are summarized into a Profile Index. Exceeding the Profile Index requires the pavement contractor to grind down the bumps that are above .3 inch to meet the specified maximum Profile Index. Locating high pavement irregularities in excess of .3 inch and Profile Index calculation methodology is described in Test Method No. Calif. 526-E. It is part of Caltrans' Standard Specifications for constructing smooth riding concrete pavements.

B. Highway Construction Vibration Level

Figure 9 plots the ground vibrations at various distances caused by highway construction equipment. The largest vibrations were caused by an EMSCO pavement breaking machine: 2.88 in./sec. and

.275 in./sec. at respective distances of 10 and 38 feet from it. They were the highest velocities recorded in the 23 vibration investigations to date. Other than the EMSCO vibrations, all the other construction ground vibrations were well below the .1968 in./sec. velocity damage threshhold criteria "E". For example, a Catepillar D-9 produced .091 in./sec. of vibration velocity at a distance of 10 to 25 feet. Other than the EMSCO created vibrations, it was the largest but still less than 1/2 the architectural damage level "E". Excluding the two EMSCO pavement breaking vibration data points, the wide range of construction equipment creating vibrations emanating over distances of 5 to 200 feet and over a wide range of ground conditions shows these vibrations to be less than 1/2 the architectural damage level "E". Thus, these data show it is highly improbable that construction equipment, other than pavement breakers, would create sufficient vibrations to approach the architectural damage level. In general, it can be stated that the vibration level from highway construction is approximately .02 in./sec. or 1/10th the architectural damage criteria level.

Nondamaging earth-borne vibrations from construction equipment were also reported by L. M. Brown (5). His report states in the conclusion:

> "Although the principal conclusion of the vibration measurements undertaken by O. R. F. from 1964 to 1968 is the negative one, that the measured vibrations from construction equipment did not cause damage, it is felt that the data obtained can serve a wider purpose."

This further supports Caltrans' finding that earth-borne vibrations from construction equipment are generally nondamaging.

C. Train Vibration Level

Vibration effects of railroad trains were the concern on three investigations and are herein compared with vibrations emanating from highway activities.

Ground vibrations caused by trains are plotted in Figure 10. In general, almost all of the vibrations are above .02 in./sec. but below the architectural damage level of .1968 in./sec. In examining Figures 9 and 10 together, it is quite apparent that train vibrations are generally considerably larger than those created by construction equipment. Considering the compiled data which include results of only three train vibration studies, it appears, however, that vibrations from trains would generally be below the architectural damage level "E". From the data, it cannot be concluded that train vibrations will not reach or exceed the threshold of architectural damage and intrusion levels.

D. In-House Activities Vibration Level

In-house activities with its resultant building vibrations are plotted in Figure 11. These are vibrations caused solely by activities within buildings and not by any external vibration sources. These "in-house" source building vibrations appear to be much more significant factors in the creation of architectural damage when compared to vibration levels created by external vibration sources. If the in-house created vibrations in comparison are equal or larger than those created by outside sources, then the "damaging" effects of earth-borne ground vibrations are very questionable.

Figure 11 shows that two vibration data points plot above the architectural damage level. These were both roof vibrations of commercial buildings and were found to be many times greater than those emanating from vehicular traffic or construction activities.

Floor vibrations caused by kitchen disposals and footsteps were also many times larger than those created by vehicular traffic and construction activity ground vibrations. As indicated, in-house activities generally created equal or larger vibrations than those caused by vehicular traffic and construction activities. It is, however, generally accepted that vibrations from normal in-house activities are improbable causes of architectural damage. This lends further credence to our conclusion that vibrations created by vehicular traffic and construction activities, being of a lower magnitude are a highly improbable cause of architectural damage.

The following three paragraphs are quoted from the report "Blasting Vibrations and Their Effects on Structures" by Messrs. Nicholls, Johnson, and Duvall (4) of the United States Department of Interior, Bureau of Mines, Report #656, 1975, Page 21:

> "The normal activities associated with living in and maintaining a home give rise to vibrations that are, in some instances, capable of causing minor damage to plaster walls and ceilings in localized sections of the structure. To complete the study of vibrations from quarry blasting and their effects on structures, instrumentation was placed in several homes to record the vibrations from walking, door closing, jumping, and operating mechanical devices, such as an automatic washing machine and a clothes dryer. The vibration levels of some of these activities are listed in Table 3.1.
>
> "The data in Table 3.1 indicate that walking, door closing and the operation of an automatic clothes washing machine and dryer do not normally generate vibrations that approach a damaging level. It is interesting to note that the vibrations from these sources are approximately the same as those generated by a quarry blast and felt at a scaled distance of 100 ft-lb$^{\frac{1}{2}}$ (see Sections 4.3 and 6.4).

"Jumping in a room generates vibrations that are potentially damaging. "Heel drops", made by standing on the toes and suddenly dropping full weight on the heels, can also be potentially damaging. However, the large amplitude vibrations resulting from these more violent activities are localized and do not affect the entire structure as do ground vibrations. Thus, although the potential for causing damage is present, it is confined to a small specific area within the structure, and the probability of damage is thereby reduced."

These data in Table 3.1, stated in the above quote, shows the following range of vibrations from normal activities in a room:

Activity	Particle Velocity in Room (Vertical, in./sec.)
Walking	.00770 - 0.187
Door Closing	.0100 - 0.0558
Jumping	.219 - 5.00
Automatic Washer	.00400
Clothes Dryer	.00500
Heel Drops	.0100 - 3.500

Note that the first paragraph quoted above states that normal activities are "capable of causing minor (architectural) damage to plaster walls, ceilings...". The above listed activities of walking, jumping, and heel drops created larger vibrations than ground vibrations created by vehicular traffic and construction activities. Thus, Duvall's report further supports Caltrans' findings that vehicular traffic and construction activities are an improbable cause of architectural building damage.

If earth-borne vibrations are an improbable cause of architectural building damage, what are the probable causes? For residential construction the cracking of plaster walls and ceilings are generally caused by settling of foundations, drying out of "green" lumber, alternate shrinkage and expansion of lumber as the atmospheric humidity fluctuates. Forty potential causes of cracks in walls and ceilings, other than from vibrations, are listed in Bulletin 442 "Seismic Effects of Quarry Blasting" of the United States Department of the Interior, Bureau of Mines. They are:

1. Building a house on a fill.
2. Failure to make the footings wide enough.
3. Failure to carry the footings below the frost line.
4. Width of footings not made proportional to the loads they carry.
5. The posts in the basement not provided with separate footings.
6. Failure to provide a base raised above the basement floor line for the setting of wooden posts.
7. Not enough cement used in the concrete.
8. Failure to protect beams and sills from rotting through dampness.
9. Setting floor joists with one end on masonry and the other on wood.
10. Wooden beams used to support masonry over openings.
11. Mortar, plaster or concrete work allowed to freeze before setting.
12. Braces omitted in wooden walls.
13. Sheathing omitted in wooden walls (except in "back-plastered" construction).
14. Drainage water from roof not carried away from the foundations.
15. Floor joists too light.
16. Floor joists not bridged.
17. Supporting posts too small.
18. Cross beams too light.
19. Subflooring omitted.
20. Wooden walls not framed so as to equalize shrinkage.
21. Poor materials used in plaster.

22. Plaster applied too thin.
23. Laths placed too close together.
24. Laths run behind studs at corners.
25. Metal reinforcement omitted where wooden walls join masonry.
27. Metal lath omitted on wide expanses of ceiling.
28. Plaster applied directly on masonry at chimney stack.
29. Plaster applied on laths that are too dry.
30. Too much cement in the stucco.
31. Stucco not kept wet until set.
32. Subsoil drainage not carried away from walls.
33. First coat of plaster not properly keyed to backing.
34. Wood beams spanned too long between posts.
35. Failure to use double joists under unsupported partitions.
36. Floor joists placed too far apart.
37. Too few nails used.
38. Rafters too light or too far apart.
39. Failure to erect trusses over wide wooden openings.

E. <u>Earth-borne Vibration Intrusion Level</u>

A criteria for vibration intrusion level is difficult to formulate for it involves a subjective response rather than an objective measurement. For a given vibration, it involves people's psychological response to it which may vary from stoical acceptance to violent objectiion. The following paragraph is quoted from "Vibration and Acoustic Measurement Handbook" by Blake and Mitchell, page 504, Spartan Books, 1972:

> "The standards arise from physical considerations, such as soil stress or the malfunction of a particular, sensitive machine. Measurement and experience are our guides. Standards also arise from the complaints of persons. This is a far more difficult category because in practice the reaction of the person is psychological rather than physiological and, therefore, unpredictable. The eminent Scottish engineer, Nasmyth, made engines in

> the same building in which wineglasses were made. Nasmyth, as the transmitter, felt no nuisance; but his neighbor did. The severity of the vibration then depends on the point of view. The receiver, unless he identifies himself with the interest of the transmitter, may be supersensitive and beyond placation, particularly as he will tend to expect and seek out and tune his receptive apparatus to its utmost, at which it may easily detect motions in the range 0.00005 in peak-to-peak, depending on frequency. The receiver tends to be more tolerant and to identify himself with the transmitter if he considers the source activity to be justified rather than arbitrary."

Nevertheless, Leonard and Whiffin (2) state, "....., vibrations become intrusive and even annoying to occupants of buildings (at about 2.5 mm/s) and complaints may result." Other workers in the field have proposed similar levels. Therefore, this report uses 2.5 mm/s as the criteria for vibration intrusion.

The intrusive level of 2.5 mm/s equates to .0984 in./sec. and is shown as level "D" in Figure 1-1. In examining these compiled data for our studies (Figures 2-7), there are only seven data points which exceed the intrusion level "D" of .0984 in./sec. They are:

1. .243 in./sec., air conditioning equipment mounted on rooftop.
2. .942 in./sec., rooftop vibration from exhaust fan.
3. .126 in./sec., on ground directly beneath railroad bridge.
4. .153 in./sec., 6' from diesel locomotive.
5. 2.88 in./sec,, 10' from Emsco pavement breaker.
6. .275 in./sec., 3'-2" from Emsco pavement breaker.
7. .125 in./sec., vibrations on bedway of a mill.

Numbers 1, 2, and 7 are self-induced in-house activity vibrations, larger than level "D", and not attributable to highway activities.

Train vibrations 3 and 4 are intrusive but attenuate to 6 feet and beyond to below that level.

Pavement breaking is an "earth-shaking" affair and its vibration data 5 and 6 shows it to be so.

For the above, assuming the criteria is correct, there were no vehicular traffic vibrations that were intrusive. Pavement breaking, while generating vibrations that are intrusive, is a special construction activity and should be given special consideration to minimize its adverse effects. In general, highway construction activities do not produce "intrusive" vibration levels. Of the equipment studied, Caterpillar Models D-9 and 727 approached most closely to the intrusion level.

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9. "Review of Criteria for Estimating Damage to Residences From Blasting Vibrations" by W. I. Duvall and D. E. Fogelson, United States Bureau of Mines, RI 5968, 1961.

10. "Human Sensitivity to Vibration" by D. T. Wright and R. Green, Queen's University, Kingston, Ontario, Ontario Joint Highway Research Programme Report No. 7, February 1959.

11. "Vibration Studies" by G. S. Meadors, Jr., Virginia Department of Highways, Proceedings of the 27th Annual Convention of the Southeastern Association of State Highway Officials, October 6-9, 1968, Richmond, Virginia.

12. "Damage Effects of Pile Driving Vibrations" by J. F. Wiss, 45th Annual Highway Research Board Meeting, 1966.

13. "Traffic-Induced Vibration" by F. Chilton, T. Friesz and E. Chen, First Annual Meeting of the Transportation Research Board, 1975.

14. "A Study of the Vibration Produced in Structures by Heavy Vehicles" by H. B. Sutherland, Highway Research Board Proceedings, Vol. 30, 1951.

VII. LIST OF FIGURES

Figure 1-1

Vibration Level *Summary: Reaction of people and damage to buildings at various vibration levels

Peak Particle Velocity in/sec	Peak Particle Velocity** mm/s	Human Reaction	Effect on Buildings
A (0- .0059)	0 to 0.15	Imperceptible by people no intrusion.	Vibrations unlikely to cause damage of any type.
B (.0059- .0188)	0.15 to 0.3	Threshold of perception-possibility of intrusion	Vibrations unlikely to cause damage of any type.
C (.0787)	2.0	Vibrations perceptible	Recommended upper level of the vibration to which ruins and ancient monuments should be subjected
D (.0984)	2.5	Level at which continuous vibrations begin to annoy people	Virtually no risk of "architectural" damage to normal buildings
E (.1968)	5	Vibrations annoying to people in buildings (this agrees with the levels established for people standing on bridges and subjected to relatively short periods of vibrations)	Threshold at which there is a risk of "architectural" damage to normal dwelling - houses with plastered walls and ceilings. Special types of finish such as lining of walls, flexible ceiling treatment, etc., would minimize "architectural" damage.

Figure 1-2

Vibration Level *Summary: Reaction of people and damage to buildings at various vibration levels

Peak Particle Velocity in/sec	Peak Particle Velocity** mm/s	Human Reaction	Effect on Buildings
F (.3937- .5905)	10 - 15	Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges.	Vibrations at a greater level than normally expected from traffic, but would cause "architectural" damage and possibly minor structural damage.

* Extracted from Page 21 of "A Survey of Traffic-induced Vibrations" by Whiffin and Leonard, TRRL, RRL Report LR418 Crowthorne, Berkshire, England, 1971.

** The numbers in this column are based on the peak particle velocity in the vertical direction. Where human reactions are concerned, the value is that at the point at which the person is situated. For buildings, the value refers to the ground motion but no allowance is included for the amplifying effect of structural components.

Figure 2

COMPILATION OF SELECTED VIBRATION DATA
1958 - 1975

Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations Peak Velocity in/sec	Vibrations Hz	Symbols of Plotted Points
Jan. 1958 Mfg. plant 04-Ala-80		--	--	
Oct. 1959 Art Gallery 03-Sac-5, 03-Sac-80	Vibrations on ground directly beneath Yolo Causeway	.043	17	⊙
	Vibration attenuation 65' normal from causeway	.023	12	⊙
	" " 115' " " "	.000	00	
	25' away from (normal) elevated fill section of Yolo Causeway	.016	17	⊙
	100' away from (normal) elevated fill section of Yolo Causeway	.011	17	⊙
Jan. 1962 Pharmaceutical plant and instrument mfg. plant 07-LA-210	Vibrations on Santa Monica viaduct	.021	10	⊙
	" on ground directly beneath viaduct	.010	16	⊙
	" 18' normal from viaduct	.007	17	⊙
	" 36' " " "	.000	00	
	" 3.5' " " Golden St. Fwy. pavement edge	.027	16	⊙
	Vibrations 55' normal from Golden St. Fwy. pavement edge	.008	28	⊙
	Vibrations 95' normal from Golden St. Fwy. pavement edge	.000	00	
	Vibrations 4' normal from lowboy on Foothill Blvd., Los Angeles	.014	18	⊙
	Vibrations 29' normal from lowboy on Foothill Blvd., Los Angeles	.004	20	⊙

Figure 3

COMPILATION OF SELECTED VIBRATION DATA
1958 - 1975

Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations Peak Velocity in/sec	Vibrations Hz	Symbols of Plotted Points
Jan. 1962 Pharmaceutical plant and instrument mfg. plant 07-LA-210	Vibrations 40' from drilling 22" diameter pile hole	.011	36	△
	Vibrations 80' from drilling 22" diameter pile hole	.005	50	△
	Vibrations 20' from D-8 Caterpillar	.015	22	●
	Vibrations 100' from D-8 Caterpillar	.019	22	●
	Vibrations on pharmaceutical's pill making machine	.086	60	▲
May 1962 Private Home 07-LA-405	3 axle van exiting Sepulveda Blvd. offramp from San Diego Freeway 8' from sensor	.005	25	⊙
Oct. 1963 Aerospace Co. 07-LA-105	15' from lowboy going 43 mph on Van Ness St.	.014	20	⊙
	31' " " " 53 " on level section of Harbor Freeway	.005	20	⊙
	12' from lowboy going 43 mph on depressed section of Harbor Freeway	.010	20	⊙
	92' from lowboy going 40 mph on elevated section of Harbor Freeway	.000	00	
	15' from local Flower Street traffic	.025	14	⊙
	Traffic vibrations directly beneath Santa Monica viaduct	.012	19	⊙
	7' from drilling 22" diameter pile hole	.009	50	△
	6' from diesel locomotive	.153	33	◒
	56' from diesel locomotive	.019	22	◒
	On rooftop parking lot with 2 cars in motion	.009	9	▲
	Air conditioning equipment mounted on rooftop	.243	31	▲

COMPILATION OF SELECTED VIBRATION DATA
1958 - 1975

Figure 4

Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations: Peak Velocity in/sec	Vibrations: Hz	Symbols of Plotted Points
March 1964 Aerospace Machine shop 07-Ven-101	Vibrations 8' from lowboy going 50 mph on Ventura Freeway	.021	20	⊙
	Vibrations on machine shop's Universal grinder	.063	59	▲
July 1966 Private Home 07-LA-405	5 axle rock hopper with vibration sensor located 3' from pavement edge. Truck on outside lane	.035	25	⊙
Sept. 1967 Major movie studio 07-LA-2	50' from rock hopper and trailer on elevated fill section of Pomona Freeway	.006	33	⊙
	On ground 3' normal from elevated San Diego Freeway structure with passage of tanker & trailer	.007	40	⊙
	5' normal from Caterpillar earthmovers (621,631 and 641's)	.003	1.5	●
	100' normal from Caterpillar earthmovers (621, 631 and 641's)	.005	20	●
	140' normal from Caterpillar D-9's	.003	13	•
	213' " " " "	.002	13	•
	Vibrations on floor from studio's machine shop punch press	.024	27	▲
Oct. 1967 Medical-Dental Building 04-SM-92	17' from fill haul truck	.056	3	⊙
	77' from fill haul truck	.015	3	⊙
	35' " " " "	.025	3	⊙
	150' " " " "	.012	4	⊙
	Walking on floor of the medical-dental building	.053	3	▲

Figure 5

COMPILATION OF SELECTED VIBRATION DATA
1958 - 1975

Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations: Peak Velocity in/sec	Vibrations: Hz	Symbols of Plotted Points
Nov. 1968 Apartment 04-SF-280	On top of Protrero Hill with trains going through tunnel	.000	00	
	Trolley bus passage on city street with sensor 18' from bus	.000	00	
March 1969 Aerospace Co. 07-LA-105	5' from curb on Imperial Hwy. with car traffic Corner of Ardis Ave. and Imperial Hwy.	.001	1	
	55' from above curb line	.003	10	⊙
	Directly beneath elevated section of Santa Monica Freeway	.013	3	⊙
	64' normal to outside column of Santa Monica Fwy.	.001	3	⊙
	150' from Caterpillar earthmover 651 loaded & going full speed	.013	15	●
	140' from pile drilling with 18" auger bit	.006	9	△
	150' from Euclid E-50 40 yards earthmover	.001	2	□
	Vibrations on mezzanine floor from air conditioners on it	.068	8	▲
Oct. 1969 Cosmetic Mfg. Plant 07-LA-210	On ground directly beneath railroad bridge	.126	50	◒
	100' from above train passage	.055	50	◒
	By curb of Foothill Blvd. and transit mixer passage 3.5' from sensor.	.008	3	⊙
	Vibrations beneath Foothill Freeway structure	.006	5	⊙
	100' normal to above freeway structure	.003	5	⊙
	Rooftop vibrations from exhaust fan	.942	50	▲

Figure 6

COMPILATION OF SELECTED VIBRATION DATA 1958 - 1975

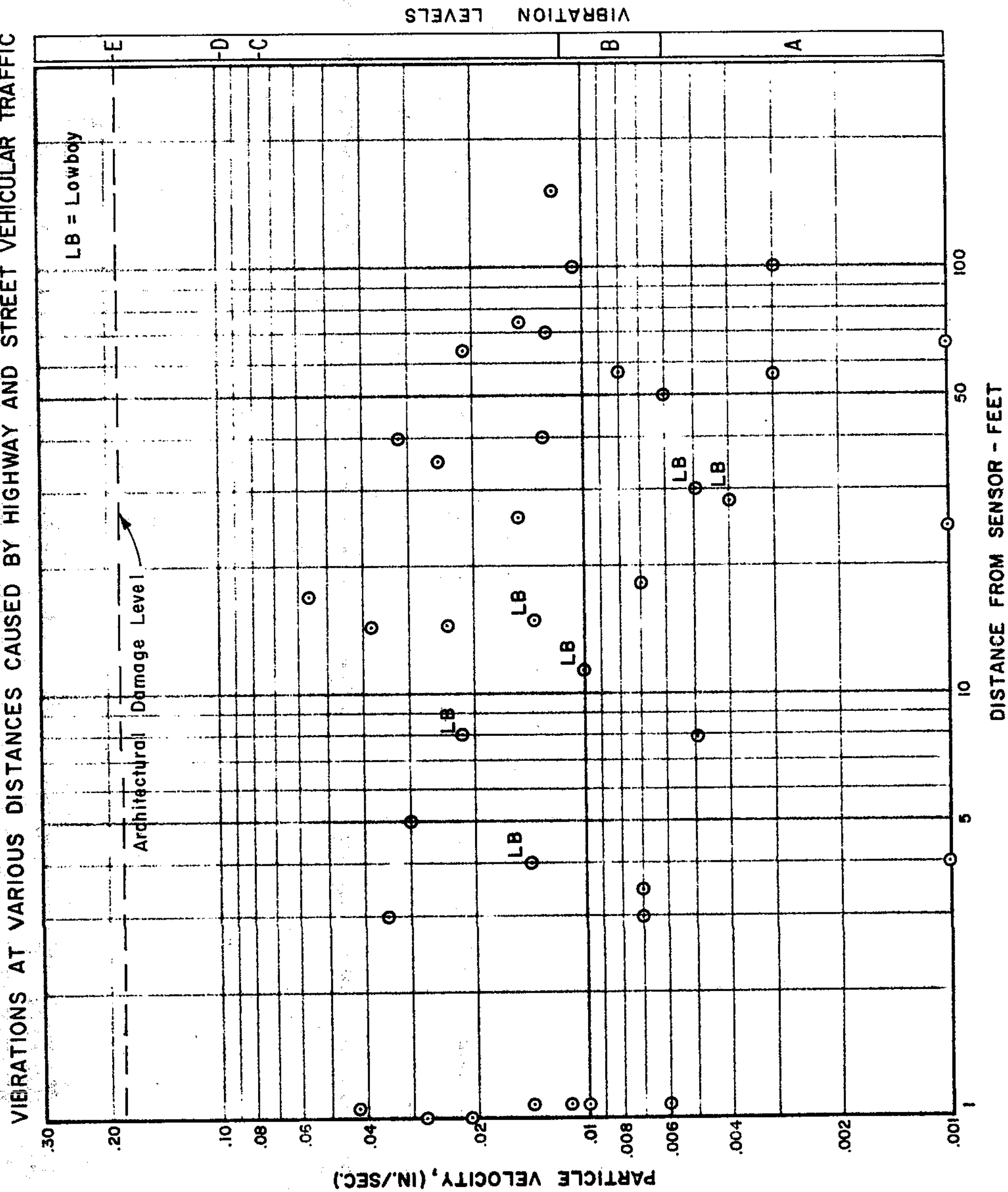
Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations: Peak Velocity in/sec	Vibrations: Hz	Symbols of Plotted Points
Nov. 1970 Private home 07-Ven-118	8' from SR118 pavement edge on shoulder with passage of cement hopper and trailer	.005	5	⊙
	Heavy footsteps	.002	4	▲
Feb. 1971 Private Homes 04-SM-1/35	10' from drilling 18" pile hole	.006	12	△
	110' " " " " "	.007	12	△
	Vibrations 15' from Caterpillar earthmover on St. Francis St.	.025	10	●
	Vibrations 44' from Caterpillar earthmover on St. Francis St.	.004	10	●
	Vibrations from walking on house floor	.010	5	▲
Nov. 1971 Concrete grain silo 05-Mon-101/198	7.5' from freight train (110± freight cars) going 40 - 50 mph	.026	1	◒
	10' from passenger train (9 cars) going 80± mph	.051	1	◒
July 1972 Apartment house 04-SF-480	On Richardson Ave. curb with trucks and bus traffic. 5' from sensor.	.030	14	⊙
	40' normal from above location	.013	14	⊙
	Vibrations from walking on 2nd floor	.009	1	▲
Aug. 1972 Private homes 07-LA-5	40' normal from outside lane of Santa Ana Fwy.	.031	14	⊙
	70' " " " " " " " "	.013	14	⊙
	Walking on kitchen floor	.018	1	▲
	Kitchen floor vibrations from sink disposal running	.094	60	▲

Figure 7

COMPILATION OF SELECTED VIBRATION DATA
1958 - 1975

Vibration Study Conducted for:	Vibration Source and/or Measurement Locations	Vibrations Peak Velocity in/sec	Vibrations Hz	Symbols of Plotted Points
Nov. 1972 Computer data processing co. 07-LA-1	Vibration level at Sepulveda Street curb 4' to sensor	.001	1	⊙
	10' from Emsco stumper breaking concrete pavement	2.88	25	■
	38' " " " " " "	.275	25	■
Jan. 1973 Machine shop 04-SF-280	- -	- -	- -	
Dec. 1973 Private home 04-SCl-280	25'± from off ramp (truck with load of carpets)	.001	1	⊙
Dec. 1973 Private home 04-SM-82	15'± from El Camino Real Hwy.	.039	12	⊙
May 1975 Machine shop 04-SCl-87	Floor vibration with shop in operation	.014	--	
	Vibration on bedway of Cincinnati mill	.125	--	
May 1975 Private home 05-Mon-1	Vibrations 10-25' away from Caterpillars D-9's and 727's	.091	--	●
July 1975 Two story private home 04-Son-101	Floor vibrations from footsteps on 2nd floor	.003	--	
	Vibrations on curb 1' - 4" from pavement edge	.004	--	

Figure 8


VIBRATIONS AT VARIOUS DISTANCES CAUSED BY HIGHWAY AND STREET VEHICULAR TRAFFIC
VIBRATION LEVELS
A
B
C
D
E
LB = Lowboy
LB
Architectural Damage Level
DISTANCE FROM SENSOR - FEET
1
5
10
50
100
PARTICLE VELOCITY, (IN./SEC.)
.30
.20
.10
.08
.06
.04
.02
.01
.008
.006
.004
.002
.001

VIBRATIONS AT VARIOUS DISTANCES CAUSED BY CONSTRUCTION EQUIPMENT

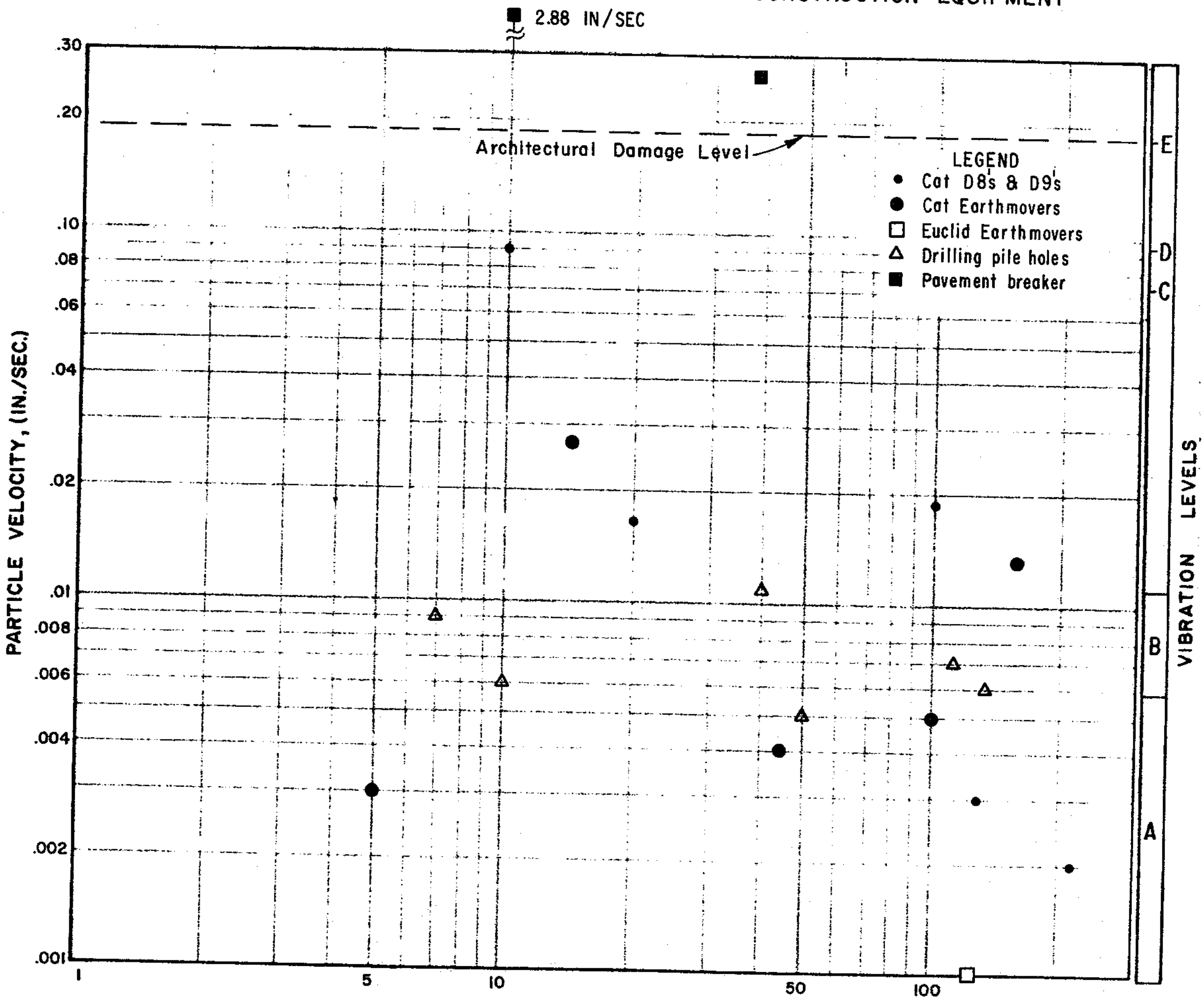


Figure 9

Figure 10

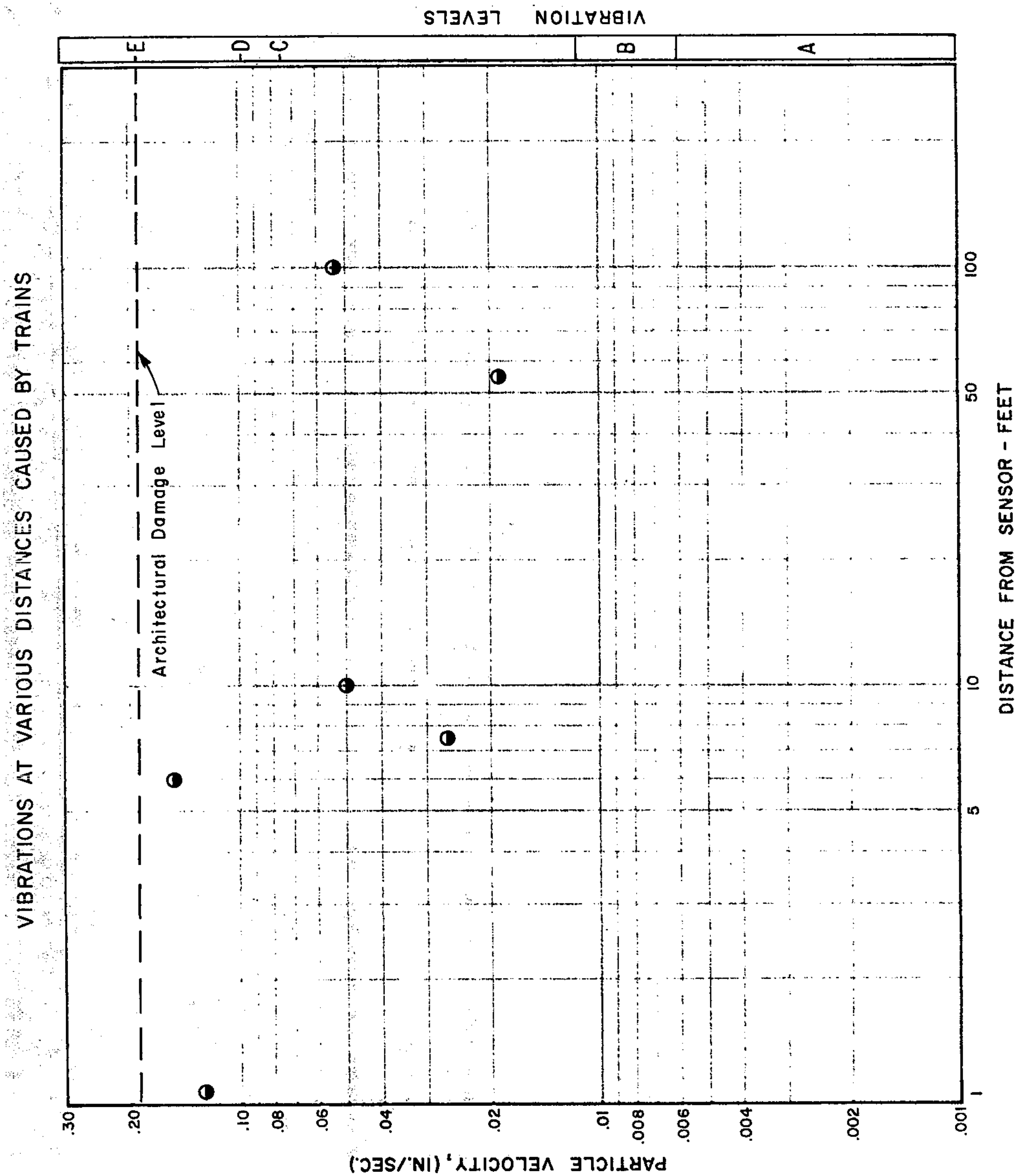

VIBRATIONS AT VARIOUS DISTANCES CAUSED BY TRAINS
VIBRATION LEVELS
E
D
C
B
A
Architectural Damage Level
DISTANCE FROM SENSOR - FEET
1
5
10
50
100
PARTICLE VELOCITY, (IN./SEC.)
.30
.20
.10
.08
.06
.04
.02
.01
.008
.006
.004
.002
.001

Figure 11

BUILDING VIBRATIONS CAUSED BY IN-BUILDING ACTIVITIES

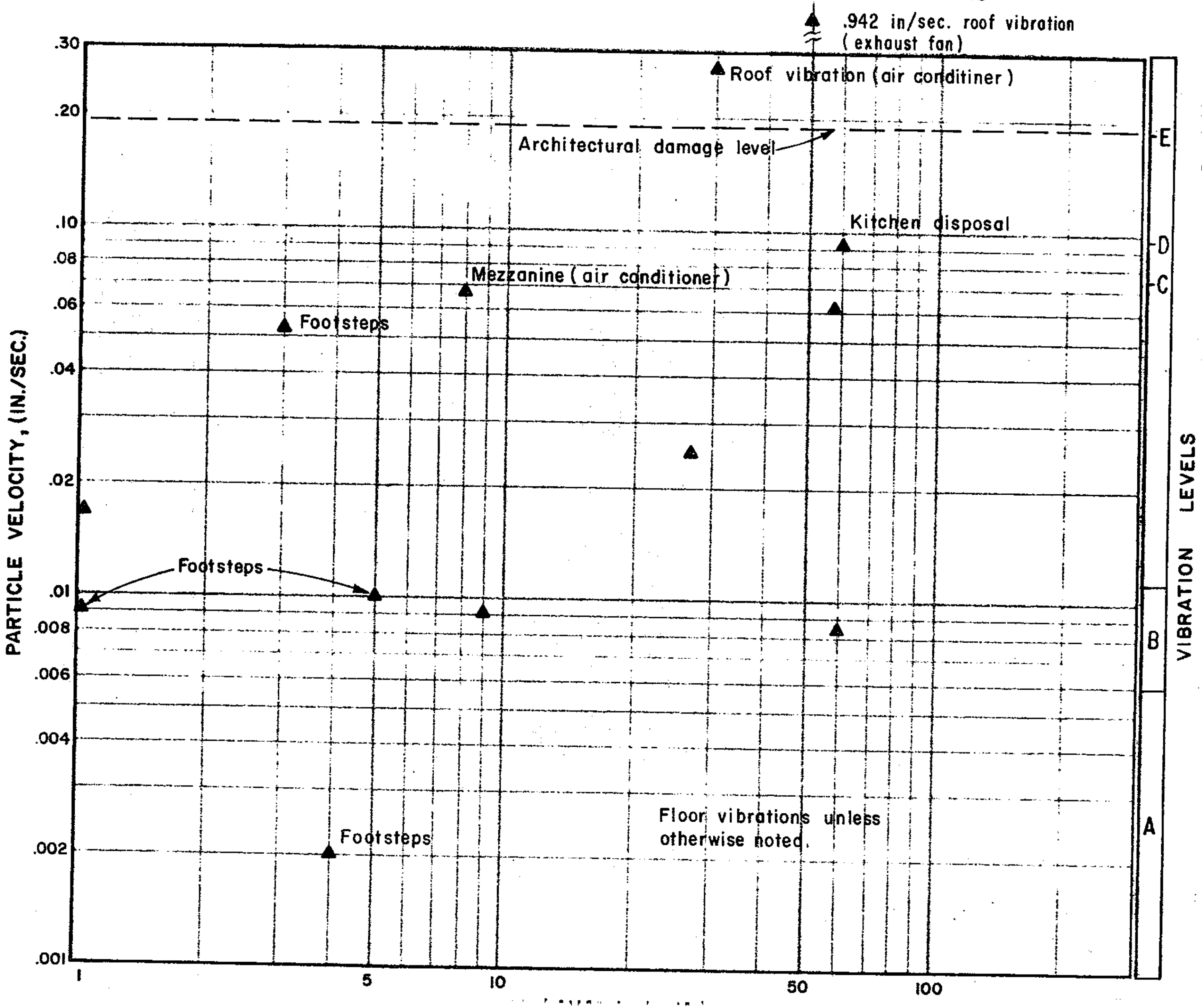
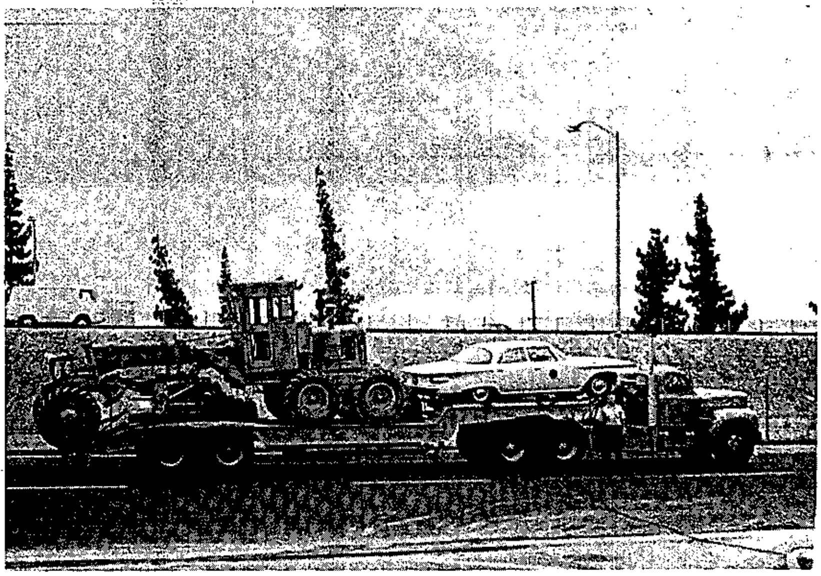


Figure 12



Caltrans Lowboy Tractor and Trailer Rig

Control Test Truck

California Division of Highways Lowboy

Front Axle 1	9,560 pounds
Tractor Axle 2 and 3	24,380 pounds
Trailer Axle 4 and 5	35,160 pounds
Total Weight	69,100 pounds