# Motor Vehicle Noise Studies

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THE noise associated with motor vehicles has been receiving more and more attention in recent years. This is due partly to the general public concern about increases in all kinds of noise in every day life, such as that from home appliances, office machines, jet planes and so on. It is also due to the tremendous increase in the volume of automobile and truck noises which is a consequence of both greater engine power and more vehicles.

As a result of these trends, the highway has become a serious source of disturbing noise. Since 1944, the number of automobiles has increased 76 percent, and trucks 109 percent. The average size of truck engines has also increased - and 600-hp diesel truck engines are being advertised. These increases have brought a corresponding increase in the number of complaints of excessive noise. More and more people are saying that "there ought to be a law against excessive highway noise".

The prospects for the future all point to an intensification of this problem. The number of automobiles and the number and size of trucks will doubtless continue to increase. It is to be expected that heavy traffic will become more and more channelized on freeways and that many of these freeways will pass through districts where there may be vigorous objections to the roar of traffic.

These matters have been the subject of continuing investigation by the Institute of Transportation and Traffic Engineering at the University of California. The present study is concerned with some of the characteristics of noise generated by traffic streams. Test sites were selected so as to be representative of various operating conditions on facilities of the expressway type.

As a subject of mutual interest to the Institute of Transportation and Traffic Engineering and the California Division of Highways, a part of this study was undertaken as a joint project, conducted under an agreement between the University and the Division. The Institute is grateful to all those who assisted in this study, and particularly to John L. Beaton, R. M. Gillis, Rudolph Hess, and F. N. Hveem, all of the Division of Highways, and to W. A. Partridge, J. A. Fogle, and C. W. LeRoy, of the Institute staff.

There are two main objectives in this study: (1) to determine the magnitudes of the noises associated with various types of vehicles and highway facilities, and (2) to attempt to evaluate the noises in terms of physical measurements that correlate with subjective appraisals.

The problems of measurement and evaluation of vehicle noises are technically complicated and they have not been completely resolved. For example, the California Vehicle Code refers to "unusual" or "excessive" noises. There is a need for a definition of "excessive noise" and a practical, convenient method of measurement that may be supported by jury appraisal. This standard should account for the annoyance of the noise as well as its loudness. Annoyance usually increases with loudness, but not always. For instance, intermittent noises are usually considered more annoying than continuous ones, and noises containing high-frequency components are more objectionable than those of the same intensity which are composed of low-frequency components. Probably some of the most bothersome noises from vehicles on the highway occur when the vehicles are operated at high engine speeds during acceleration and just prior to shifting gears. This condition gives rise to a combination of high-frequency components and an intermittent noise pattern, as well as high intensity.

The time-pattern factor for intermittent noises has at least two components. The first involves the length of time the noise remains at an annoying level;

most people feel that a noise is less annoying if its duration is short. In the case of highway noise, this is determined mainly by the time the vehicle remains within a certain distance of the person or persons who hear it. The second component involves the length of time between passing vehicles which are responsible for the noise; noises that occur periodically are generally considered less annoying than those which occur at irregular intervals.

Annoyance is a subjective quality, so a precise, quantitative expression of it probably cannot be found. Also loudness, by physical definition, is subjective. The techniques of measurement that have been used in this study permit comparisons to be made on either an annoyance, loudness, or intensity basis if the correlations that are shown between the meter readings and the subjective quantities are considered adequate.

### Scope

The material presented in this paper is in two parts corresponding to the objectives already mentioned. Part I covers the data obtained on noise levels adjacent to expressway-type highways under conditions that are typical of many such areas in the United States. Part II covers the project of analyzing the noise spectrum from various types of vehicles as observed on the road and as measured on a test dynamometer. Jury appraisals of the latter noise spectra were also obtained and correlations determined between jury ratings and measurements.

## *Part 1*

## *Noise Measurements on Expressway-Type Facilities*

● The objective of the investigation was to obtain data on noise levels adjacent to freeways under conditions that are typical of many areas in the United States. Data were collected at 15 test locations in California, scattered from Vallejo in the central part of the State, to Los Angeles in the south. The locations were of five types, as follows:

1. Inclined. A rural freeway with a long steep grade. The extended incline created a condition where maximum noise could be determined for representative traffic under full-load, steady-state operation.
2. Intersection. An intersection on a freeway in an area having high traffic volumes. This permitted noise measurements both for continuous traffic movement and for vehicles accelerating from a stop.
3. Level. A level, high-traffic-volume freeway. Here traffic could be observed when operating near maximum permitted speeds.
4. Elevated. An elevated section of freeway. This served to indicate the effect of having the noise source above the surrounding terrain.
5. Cut. A freeway section in a cut. Here the effect of absorbing or reflecting surfaces could be evaluated.

### TEST LOCATIONS

The following descriptions of each type of test location indicate the characteristics of the actual freeway sections investigated.

### 1. Inclined Type

American Canyon Highway, US 40, north of Vallejo, Calif. (Figure 1). A 4-lane divided highway with a positive grade for northbound traffic and a negative grade for southbound traffic. Division of northbound and southbound traffic by means of a raised island approximately 6 ft. wide and bounded by an 8-in. curb on each side. The pavement surface is asphalt. Surround: to the west, a steep negative slope; to the east, fairly level for 22 ft., then low rolling hills; no obstructions or reflecting surfaces of

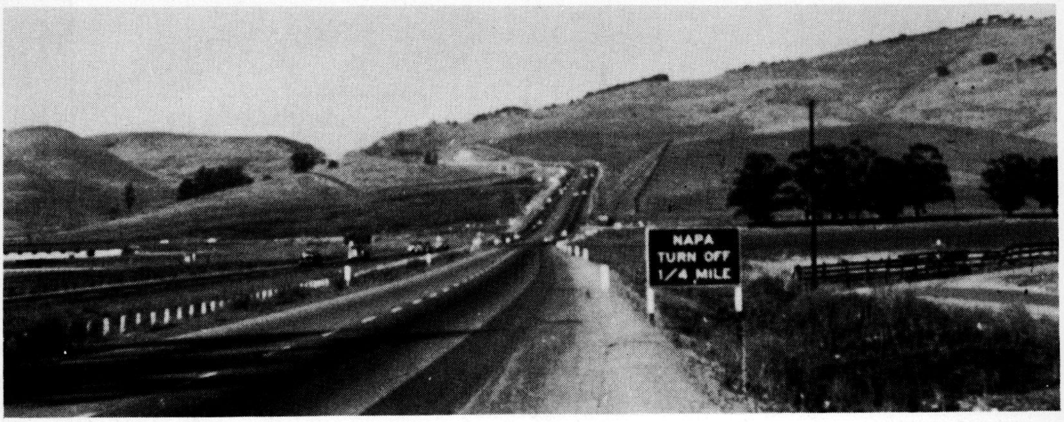

Figure 1.

any significance within 100 ft. of any test site. Test sites were located on the east side of the highway.

### 2. Intersection Type

Washington Blvd. and Telegraph Rd., Los Angeles, Calif. (Figure 2). An intersection of two 4-lane highways. An elevated section of freeway, approximately 300 ft. away, created a high noise level background. The east side of the intersection was bounded by open flat land. On the west side of the intersection was a 10- to 15-ft. fill, which has a section of the Santa Ana Freeway. Eastbound traffic on Washington Blvd. approaches the intersection as it ascends from an underpass beneath the freeway. Reflections of sound from large buildings or the fill on the west side of the highway were probably negligible, owing to their distance from the test sites and the high background noise level due to direct transmission.

Road surfaces were asphalt. With the exception of the eastbound traffic lanes, all approaches were level.

Traffic was controlled by a simple two-phase controller in conjunction with three-color traffic signals. Traffic was handled in two movements, left turns being made simultaneously with the movement of through traffic.

The test sites for this location were at the usual distances of 50, 150, and 300 ft., but were measured along a line approximately bisecting the angle of the corner.

Meter readings and tape recordings were made only of traffic moving on Washington Blvd.

### 3. Level Type

East Shore Freeway near Oakland Airport, San Leandro, Calif. A 4-lane divided highway section. The pavement was concrete or concrete with an asphalt surface. The

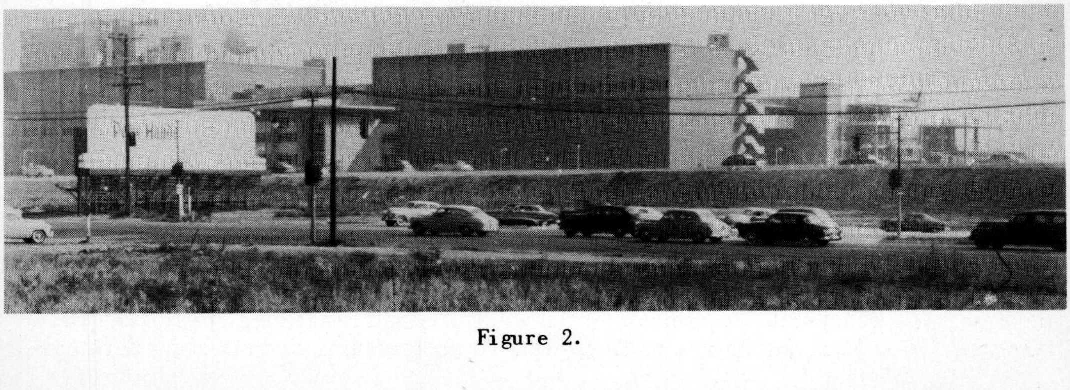

Figure 2.

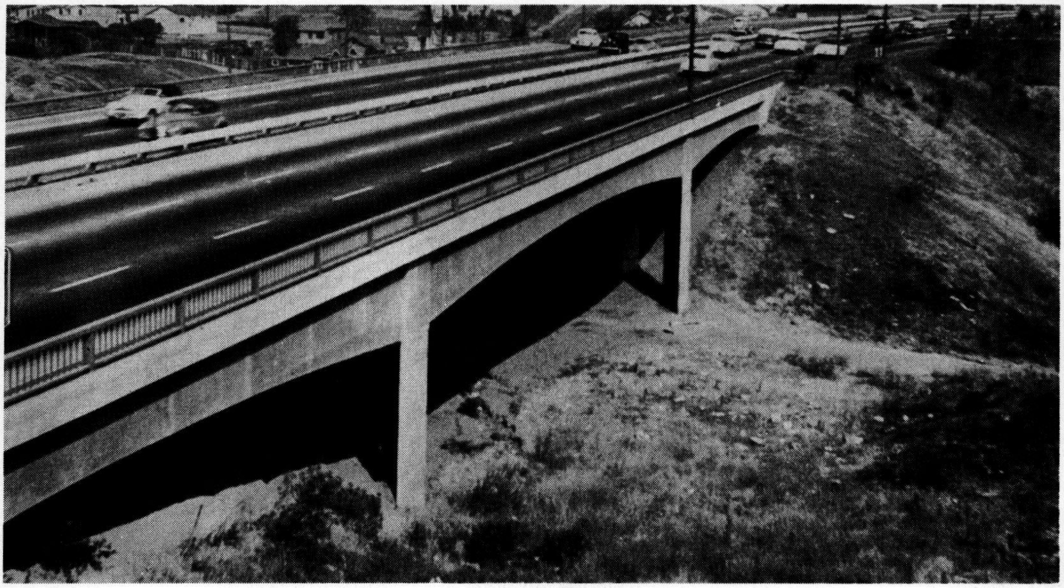

Figure 3.

surrounding terrain was level land with no obstructions or reflecting surfaces. Opposing traffic flows were separated by a concrete island which extended down the center of the roadway. Highway was straight and level.

## 4. Elevated Type

Santa Ana Freeway at Soto St., Los Angeles, (Figure 3). A 6-lane divided highway. The freeway section was on a bridge which was buttressed at each extremity by a fill. Opposing traffic lanes were divided by a concrete island down the centerline upon which was a steel railing. The bridge structure was concrete. The test sites ranged from 30 to 50 ft. below the level of the roadbed.

## 5. Cut Type

Hollywood Freeway: Cahuenga Pass near Barham Blvd., Los Angeles (Figure 4). Six main center lanes, two secondary lanes on either side of the 6 center lanes, and two turn lanes on the outside on each side making a total of 14 lanes. The six center lanes pass through an underpass. All lanes have a slight grade, as can be seen in the photograph. Pavement was concrete. The cut depth was 7 to 8 ft., and the center 10 lanes were bounded by concrete walls. Opposing traffic lanes were divided by ten feet

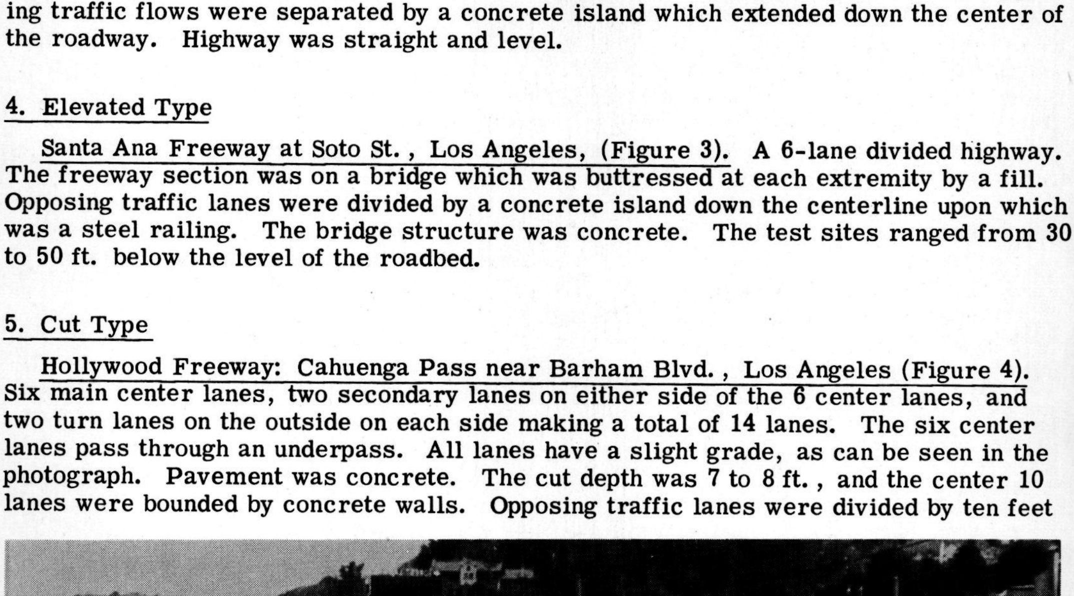

Figure 4.

of land. The overpass was approximately 75 feet northwest of the test location. Hills extended along the boundary of the freeway, parallel to its path.

## TEST PROCEDURE

At each location instruments were set up to measure the vehicle noises from 50, 150, and 300 ft. away from the centerline of the nearest traffic lane (except that no 300-ft. readings were obtained at the one inclined-type location).

The sound level instruments were standard ASA type equipment and are described in detail in Reference 1. Adequate calibration and checking procedures were used to insure accurate readings.

The sampling of vehicles was random, but each situation was recorded both on magnetic tape and on data sheets so that the type of vehicle could be identified. The coding system used for vehicle identification and a complete description of the test set-up is given in Reference 2. An attempt was made to obtain at least 10 readings on a given class and type of vehicle so that the measurements would have reasonable significance. This was not possible at all locations because of the predominance of one or more types of vehicles. The data are given on the summary data sheets in Reference 2.

Three meter readings were taken on each test vehicle, one meter being set on each of the three (A, B, and C) meter scales, and three test distances from the highway were utilized. Therefore, each tabulation of the results for a particular type of freeway section has nine independent parts: one result for each of the three scale readings at each of the three test distances. For this reason, it is impractical to attempt to present all the results in the form of independent statements. Some of the more outstanding results will be presented here, but it is suggested that reference be made to the tabular summaries which may be found in Reference 2 for detail studies.

Several problems arose during the course of the work that could not be predicted in advance. Lack of a stable portable power supply was one of the primary obstacles. Since the tape recorder employed synchronous motors to drive the tape, a frequency-stable power supply was essential. Several different portable generators were used as a power supply but none was completely satisfactory in this respect. Owing to this difficulty, some of the magnetic tape was not acceptable for frequency analysis.

Increasing winds at the test locations presented additional problems, some of which went unsolved. Screening the microphones with silk cloth reduced the erratic meter indications due to wind by a significant amount, but the effect of the wind upon the indicated sound level was sometimes indeterminate. The change in the effective distance through which the sound had to travel due to the wind was calculable, provided the wind was constant, but gustiness created effects which could only be estimated. It was not feasible to estimate these effects or to calculate correction factors for every reading taken. Thus the wind, when present, presented an uncontrollable source of error that our technique could not accommodate.

The ASA type sound level meter has several advantages over other possible types of equipment, some of which are: (1) high degree of portability, (2) rugged construction, (3) rapid and continuous indication, (4) immediate availability of results, and (5) absolute numerical evaluation, as opposed to arbitrary evaluation required by some methods.

## TEST RESULTS AND DISCUSSION

Any large group of data such as collected in this study affords the possibility of a great number of analyses. The analyses submitted herewith were limited to those considered to be most significant to the freeway problem. The complete data are tabulated in Reference 2 for any additional studies that may be desired.

The measured levels of the noises of vehicles passing the test location depend to some degree upon the background level, therefore, the background levels existing at the time of the tests are considered first (see Table 1). By way of explanation, the background level is that noise measured by the meters which exists because of the nature of the surrounding area and the activity taking place therein. This includes traffic noise which is not due to the vehicle or vehicles specifically under test. If the background level is sufficiently high, the noise of a passing vehicle may not increase the meter reading by a measurable amount.

The background level also plays a large part in the relative annoyance of vehicles. For example, if the background level is relatively low, traffic noise may seem louder to the ear than it would seem if masked by a relatively high background level. The background noises of Table 1 are normal values for daytime conditions and are higher than would be measured in the very early morning hours (3 A. M. ).

TABLE 1
AVERAGE BACKGROUND NOISE LEVELS

| Type of Location | Test Distance feet | Decibels A Scale | Decibels B Scale | Decibels C Scale |
|---|---|---|---|---|
| 1. Inclined | 50 | 50 | 59 | 69 |
| | 150 | 48 | 58 | 62 |
| 2 Intersection | 50 | 57 | 67 | 76 |
| | 150 | 52 | 64 | 73 |
| | 300 | 52 | 63 | 69 |
| 3 Level | 50 | 48 | 56 | 65 |
| | 150 | 46 | 56 | 72 |
| | 300 | 43 | 55 | 66 |
| 4. Elevated | 50 | 59 | 65 | 72 |
| | 150 | 53 | 56 | 63 |
| | 300 | 50 | 55 | 64 |
| 5 Cut | 50 | 59 | 65 | 72 |
| | 150 | 52 | 60 | 68 |
| | 300 | 46 | 58 | 64 |
| Averages for all locations | 50 | 52 | 60 | 69 |
| | 150 | 50 | 58 | 68 |
| | 300 | 48 | 58 | 66 |

## Automobile Noise

Automobile traffic (exclusive of trucks and commercial vehicles) is the most common source of noise on the highways, although it is not the loudest. The following outlines some important results of the study concerning automobile traffic alone.

The average noise level due to autos was computed separately for each test site at each location. At every location and at all three distances from the highway, the average noise generated by autos was generally loudest during acceleration from a stop (intersection). The loudest average auto noise, as recorded on the C scale was 84 db at the 50-ft. test destance. At 300 ft. , the highest average was 73 db. It must be kept in mind that the loudest average noise does not mean the loudest single reading obtained, but rather, the loudest group of readings obtained at various test sites at the same distance from the highway and same type of freeway section (i. e. , cut, fill, intersection, etc. ). The loudest single reading would be considerably greater than the average.

For all types of freeway sections, the average auto noise ranged from 75 db at 50 ft. to 69 db at 300 ft. , as measured on the C scale. B and A scale readings were on the average, 9 and 15 db lower than the C scale readings, respectively. In the over-all average for all distances at all locations, auto traffic noise was louder than the background level by 7 db on the A scale, and 5 db on the B and C scales.

At locations where the background level was high, many cases arose in which the noise generated by light auto traffic was not discernable from the background level, except at the 50 ft. distance (see Table 2). One incident arose in which the meter readings on auto traffic were lower than the average background level. This was due to the fact that background level measurements were taken at times when there was no traffic in the immediate vicinity of the test location, but with the possibility of heavy traffic at a distance. This condition occasionally caused higher meter readings than that due to a few slow moving autos in the test area. Such a condition may exist at an intersection when traffic is traveling in platoons between signals. Heavy traffic may be approaching the intersection from some distance away, or may be stopped at the intersection and there is traffic at a distance.

TABLE 2
DIFFERENCE BETWEEN AUTO NOISE AND BACKGROUND LEVEL

| Test Distance feet | Type of Location | Average Decibels A Scale | Average Decibels B Scale | Average Decibels C Scale |
|---|---|---|---|---|
| 50 | 1 Inclined | 11 | 8 | 9 |
| | 2 Intersection | 5 | 8 | 6 |
| | 3 Level (high speed) | 11 | 10 | 7 |
| | 4 Elevated | 8 | 6 | 5 |
| | 5 Cut | 6 | 4 | 3 |
| 150 | 1. Inclined | 10 | 4 | 9 |
| | 2. Intersection | 7 | 7 | 3 |
| | 3. Level (high speed) | 8 | 6 | 2 |
| | 4. Elevated | 4 | 4 | 5 |
| | 5. Cut | 5 | 6 | 7 |
| 300 | 1 Inclined | - | - | - |
| | 2. Intersection | 3 | 2 | 0 |
| | 3. Level (high speed) | 6 | 2 | 7 |
| | 4. Elevated | 4 | 3 | 2 |
| | 5 Cut | 9 | 1 | 5 |

The tests showed that the difference between auto noise and background levels decreased with distance from the highway (see Table 2). This pattern appeared on all meter scales. The differences at any one type of freeway section were largest on the A scale, less on the B scale, and least on the C scale. This is to be expected because of the weighting networks

TABLE 3

NOISE LEVELS OF TRUCKS, AUTOS, AND BACKGROUND

Averages are given for each test distance and type of freeway section.

| Section and Vehicle | Distance feet | Average Decibels |  |  |
|---|---|---|---|---|
|  |  | A Scale | B Scale | C Scale |
| 1. Inclined |  |  |  |  |
| Trucks | 50 | 73 | 79 | 86 |
| Autos | 50 | 61 | 67 | 78 |
| Background | 50 | 50 | 59 | 69 |
| Trucks | 150 | 66 | 76 | 80 |
| Autos | 150 | 54 | 61 | 67 |
| Background | 150 | 48 | 58 | 62 |
| 2. Intersection |  |  |  |  |
| Trucks | 50 | 77 | 84 | 91 |
| Autos | 50 | 64 | 75 | 84 |
| Background | 50 | 57 | 67 | 76 |
| Trucks | 150 | 66 | 77 | 84 |
| Autos | 150 | 58 | 71 | 79 |
| Background | 150 | 52 | 64 | 73 |
| Trucks | 300 | 62 | 70 | 78 |
| Autos | 300 | 57 | 67 | 73 |
| Background | 300 | 52 | 63 | 69 |
| 3. Level |  |  |  |  |
| Trucks | 50 | 69 | 79 | 83 |
| Autos | 50 | 59 | 66 | 72 |
| Background | 50 | 48 | 56 | 65 |
| Trucks | 150 | 65 | 72 | 77 |
| Autos | 150 | 54 | 62 | 73 |
| Background | 150 | 46 | 56 | 72 |
| Trucks | 300 | 53 | 60 | 71 |
| Autos | 300 | 47 | 53 | 69 |
| Background | 300 | 43 | 55 | 66 |
| 4. Elevated |  |  |  |  |
| Trucks | 50 | 60 | 70 | 80 |
| Autos | 50 | 55 | 59 | 66 |
| Background | 50 | 48 | 55 | 62 |
| Trucks | 150 | 58 | 66 | 72 |
| Autos | 150 | 54 | 58 | 67 |
| Background | 150 | 53 | 53 | 63 |
| Trucks | 300 | 55 | 60 | 70 |
| Autos | 300 | 54 | 58 | 66 |
| Background | 300 | 50 | 55 | 64 |
| 5. Cut |  |  |  |  |
| Trucks | 50 | 69 | 72 | 77 |
| Autos | 50 | 65 | 69 | 75 |
| Background | 50 | 59 | 65 | 72 |
| Trucks | 150 | 58 | 65 | 74 |
| Autos | 150 | 55 | 61 | 70 |
| Background | 150 | 52 | 60 | 68 |

TABLE 3 (Cont'd)

| Section and Vehicle | Distance | Average Decibels | | |
|---|---|---|---|---|
| | | A Scale | B Scale | C Scale |
| 5. Cut (cont'd) | | | | |
| Trucks | 300 | 56 | 65 | 72 |
| Autos | 300 | 51 | 59 | 69 |
| Background | 300 | 46 | 58 | 64 |
| Highest Average Truck Noise | 50 | 77<br>(intersection) | 84<br>(intersection) | 91<br>(intersection) |
| | 150 | 66<br>(intersection) | 77<br>(intersection) | 84<br>(intersection) |
| | 300 | 62<br>(intersection) | 70<br>(intersection) | 78<br>(intersection) |
| Loudest Single Truck Noise | 50 | 90<br>(intersection) | 97<br>(intersection) | 102<br>(intersection) |
| | 150 | 81<br>(inclined) | 88<br>(inclined and intersection) | 93<br>(inclined intersection and level) |
| | 300 | 77<br>(Elevated) | 84<br>(Elevated) | 87<br>(Elevated) |
| Over-all Average Truck Noise | 50 | 70 | 77 | 83 |
| | 150 | 63 | 71 | 77 |
| | 300 | 57 | 64 | 73 |
| Over-all Average Auto Noise | 50 | 61 | 67 | 75 |
| | 150 | 55 | 63 | 71 |
| | 300 | 52 | 59 | 69 |

used in the instruments and is further substantiation of the known fact that the high frequencies are more rapidly attenuated than the lower frequencies. The largest differences occurred under conditions of (1) maximum power on an inclined freeway section, (2) acceleration from a stop at an intersection, and (3) high speed on a level freeway section.

## Truck Noise

As was expected, trucks were found to be a more intense source of highway noise than autos (see Tables 3, 4, and 5). On an over-all average, the truck noise level was 6 db above that for autos. This figure is small and is due to the grouping of all trucks together, there being many more light trucks than heavy ones. The number of readings on the various types of vehicles comprising the test samples were reasonably proportional to the frequency with which each type of vehicle passed the test location. Since there were greater numbers of two-axle trucks than other types, more meter readings were taken on this type of truck. Due to the fact that the noise generated by these light trucks is, on the average, not much greater than that of an auto, the average of all trucks combined was reduced.

Average readings on each type of truck at various test distances and on various types of freeway sections may be found in Table 4. Average truck noise was found to exceed that of autos in all locations and at all distances (see Table 5). The difference between truck and auto noise at a single distance and location ranged from 1 to 13 db on the A scale, 1 to 14 db on the B scale, and 1 to 11 db on the C scale. The greatest difference occurred under the condition of maximum power on an inclined freeway section, where the average truck noise exceeded that of autos by 11 db on the A scale, 14 db on the B scale, and 10 db on the C scale. The least difference was noted on elevated freeway sections.

## TABLE 4
## NOISE LEVELS FOR VARIOUS TYPES OF TRUCKS

Averages for each distance and type of freeway section.

| Type of Location | Test Distance feet | C Scale - Decibels (average) Light Gasoline-Powered Trucks | Heavy Gasoline-Powered Trucks | Diesel Trucks |
|---|---|---|---|---|
| 1. Inclined | 50 | 82 | 85 | 89 |
| | 150 | 73 | 79 | 82 |
| 2. Intersection | 50 | 91 | 92 | 91 |
| | 150 | 82 | 82 | 86 |
| | 300 | 76 | 79 | 81 |
| 3. Level | 50 | 78 | 85 | 89 |
| | 150 | 71 | 83 | 84 |
| | 300 | 73 | 74 | 76 |
| 4. Elevated | 50 | 71 | 82 | 83 |
| | 150 | 70 | 76 | 79 |
| | 300 | 69 | 74 | 76 |
| 5. Cut | 50 | 79 | 81 | 81 |
| | 150 | 72 | 71 | 74 |
| | 300 | 71 | 71 | 73 |

The loudest single truck noise was noted during acceleration from a stop at an intersection. The maximum noise registered on each of the three scales was as follows: C scale, 102 db; B scale, 97 db; A scale, 90 db. These readings were taken at a distance of 50 ft.

The average truck noise was computed for all trucks at each individual test site (see Table 3). The highest average was found to occur at an intersection under the condition of acceleration. The averages for the other conditions may be found in Tables 3, 4, and 5.

## TABLE 5
## AMOUNT BY WHICH AVERAGE TRUCK NOISE EXCEEDED AVERAGE AUTO NOISE

Difference between the averages of truck noise and auto noise for each distance and type of freeway section.

| Type of Location | Test Distance feet | A Scale | Decibels B Scale | C Scale |
|---|---|---|---|---|
| 1. Inclined | 50 | 13 | 12 | 8 |
| | 150 | 11 | 14 | 10 |
| 2. Intersection | 50 | 13 | 9 | 11 |
| | 150 | 7 | 6 | 4 |
| | 300 | 4 | 3 | 6 |
| 3. Level | 50 | 9 | 7 | 10 |
| | 150 | 12 | 6 | 4 |
| | 300 | 5 | 4 | 1 |
| 4. Elevated | 50 | 2 | 4 | 3 |
| | 150 | 2 | 4 | 3 |
| | 300 | 1 | 1 | 3 |
| 5. Cut | 50 | 4 | 5 | 3 |
| | 150 | 3 | 4 | 4 |
| | 300 | 7 | 5 | 4 |

An analysis was made to determine the difference in decibel readings between the averages of light gasoline-powered two and three axle trucks, heavy gasoline-powered trucks, and diesel-powered trucks, at each distance and each location (see Table 5). Only the C scale readings were used. In general, the results show that heavy gasoline-powered trucks were noisier than light trucks. In some cases the heavy trucks were several times as noisy. The difference between heavy gasoline-powered trucks and diesel-powered trucks averaged about 2 db for all sites.

## *Part 2*

## *Appraisal of Motor Vehicle Noise*

Reference has been made in the introduction to the difficulties of measuring and evaluating motor vehicle noise due to the subjective nature of the phenomena. There have been repeated attempts to define loudness, annoyance, speech interference, and damage to hearing due to noise intensity. All of the definitions and degrees of objectionableness are of necessity subject to a range of values because of the vagaries of human judgement. It is possible, however, to made measurements of a physical quantity and corresponding judgements by observers which can then be compared by statistical methods to obtain a measure of the correlation between the quantities. Such a precedure has been used on a portion of the data collected in Part I and on subsequent data taken on vehicles operated on a chassis dynamometer. Before attempting to review the test procedure and results it is advisable to consider briefly the quantities used to measure sound.

### The Decibel - What Is It?

There have been several references in the preceding material to the decibel, also called by its abbreviation, "db". Most people think that the decibel is uniquely associated with noise measurements, but actually it is a term borrowed from electrical engineering and represents a ratio of two quantities.

Since air-borne sound is a variation in atmospheric pressure, the pressure variations are used as the measure of the noise. The reference pressure is usually taken as the threshold of hearing for young ears and has been set at 0.0002 microbar. This is "0" decibels on the noise level scale.

Because of the great range of sound pressure and power, it is convenient in measurements and calculations (either electrical or accoustical) to express the ratio between any two amounts of power or pressure in units on a logarithmic scale. The decibel (1/10 of a bel) on the base-10 scale, is in almost universal use for this purpose. The number of decibels, $N_{db}$, corresponding to the ratio between two amounts of power, $P_1$ and $P_2$ is

$$N_{db} = 10 \log_{10} \frac{P_1}{P_2}$$

When the sound-pressure is known instead of the sound power, the equation for decibels becomes

$$N_{db} = 20 \log_{10} \frac{\text{Sound Pressure (in microbars)}}{0.0002}$$

The equation using sound-pressure has the same form as the power equation, but the multiplier changes from 10 to 20 because the power is proportional to the square of the pressure.

Because of the logarithmic definition of the decibel it is not possible to add db's directly.

In order to combine two sounds it is necessary to know either the accoustic power or the sound pressure with respect to a common reference. These quantities can then be added and the resulting number of decibels computed. For example, if one sound has twice the power of another, then

$$N_{db} = 10 \log_{10} \frac{2}{1} = 10 \times 0.301 = 3.0 \text{ db}$$

So if two sounds are equal when measured in terms of accoustic power (or db), their sum will be 3.0 db higher than either one. For example: Two trucks each produce 90 db at a particular point. The two trucks together will develop 93 db.

Check: For each truck $90 = 10 \log \frac{P_1}{P_{ref}}$:

so $\frac{P_1}{P_{ref}} = \text{anti log} \frac{90}{10} = 10^9$

Adding the two power ratios gives

Truck No. 1 + Truck No. 2 =

Power ratio of $10^9 + 10^9$

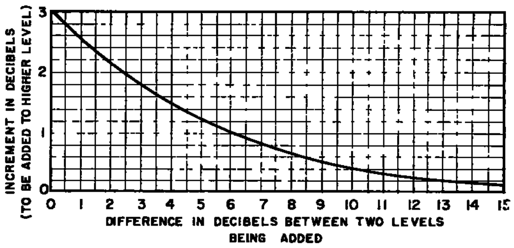

Figure 5. Chart for combining noise levels.

$$
\begin{aligned}
\text{Total db} = 10 \log_{10} 2 \times 10^9 &= 90 + 10 \log 2.0 \\
&= 90 + 3.0 \\
&= 93 \text{ db}
\end{aligned}
$$

Instead of going through the calculations as indicated it is simpler to use a chart giving the number of db to be added to the most intense sound when several sounds are combined. The curve of Figure 5 gives the data for combining noise levels.

## Loudness - Phons

The loudness of a sound or noise is a subjective quantity and relates to the individual's appraisal of the sound power. One generally accepted definition of a physical method of specifying loudness is as follows: The loudness level of any pure tone is given by the intensity level of a 1000-cycle-per-second tone which sounds equally loud

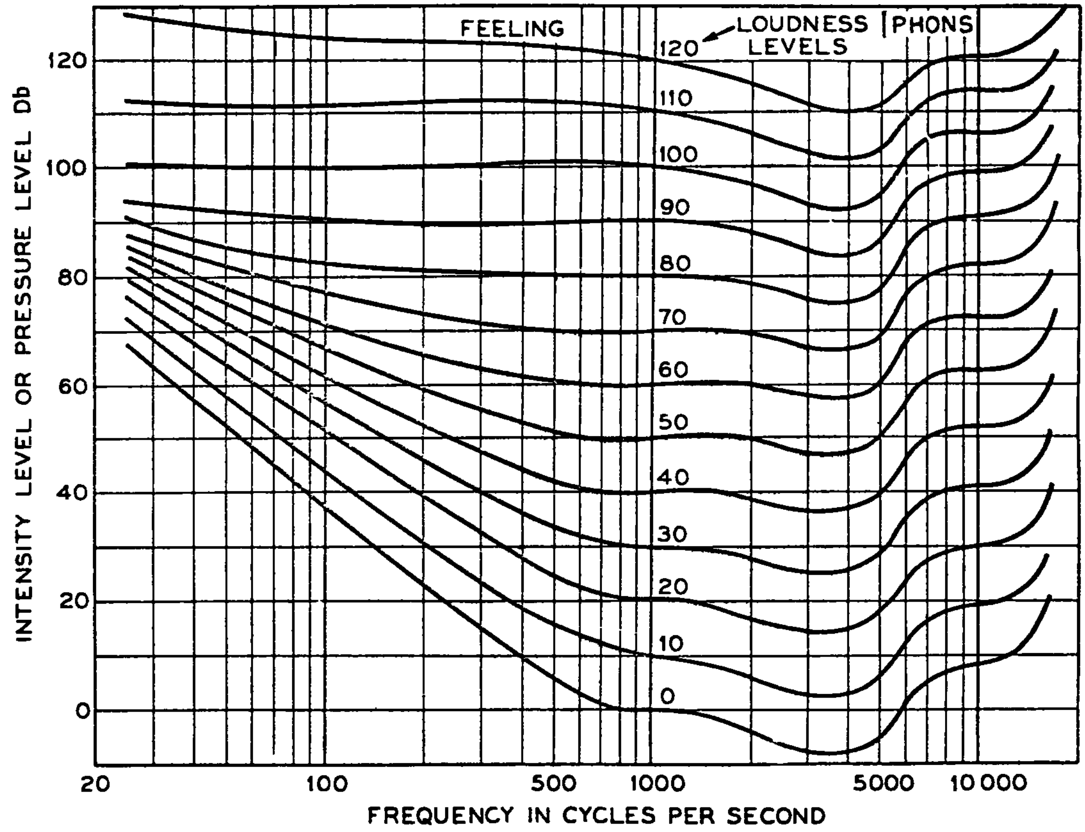

Figure 6. Equal loudness contours of pure tones (Fletcher-Munson curves).

when compared by an average human ear. For complex tones the loudness level is equal to the sum of the intensity levels of the 1000-cycle equivalents of all the components. The addition is not the arithmetic sum but is obtained by combining the accoustic power due to each component and evaluating the total power in decibels as explained in the foregoing section. The intensity level of the reference tone is reported in phons. Figure 6 gives the data relating loudness level in phons to intensity level in decibels.

The subjective loudness, or the degree to which a complex sound affects a person, is not the same as the loudness level defined above because the human ear adds the components in a different manner. To obtain the subjective loudness, in phons, of a complex sound it is necessary to compare it directly with a 1000-cycle tone. The comparison must be made many times by each of several observers and the results averaged. This is evidently not a suitable method for measuring the noise of a passing truck.

## Loudness - Sones

We do know and we frequently remark that some sounds are louder than others. How much louder? Well perhaps twice as loud or three times as loud, we may estimate. This type of appraisal is entirely subjective. This is the field of the psychologist. Such judgment or sensation evaluations defy measurement directly, but the psychologists have found that when people are asked to make judgments of the loudness of noise (complex sounds) they are quite consistent in stating when one noise is twice, three times, or one-half as loud as another. Thus a scale of loudness which rank-orders sounds from "soft" to "loud" has been devised. The units of this scale are sones.

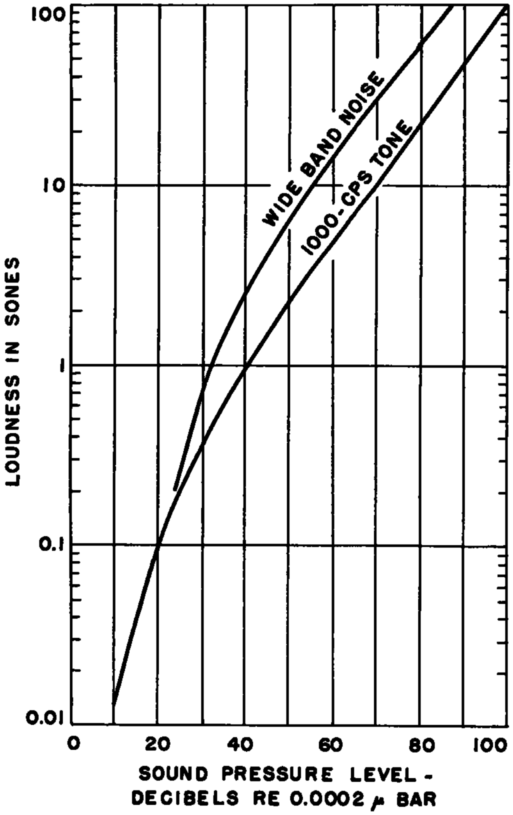

Figure 7. Loudness versus sound-pressure level for wide-band random noise and a pure tone.

The physical quantity that has been measured simultaneously is the sound-pressure level in decibels. As a reference, a sound-pressure level of 40 db (40 phons) relative to 0. 0002 microbar for a 1000-cycle tone is taken as 1 sone. A tone that sounds twice as loud is 2 sones. A chart relating the sound-pressure level of a 1000-cycle tone and the corresponding number of sones is given in Figure 7. Also shown is the relation for a particular wide-band noise (sort of a hishing sound). To get the combined loudness of two or more noises in sones, one can add directly the value of sones for each noise. Thus, the total loudness of three noises of 15, 18, and 30 sones is 63 sones.

## Sound Level Meters and the Human Ear

The sound level meter approved by the American Standards Association (ASA) for measuring noise level does as good a job in measuring loudness as does any single commercial instrument on the market, but it is not entirely adequate in itself. It contains electrical networks which make its sensitivity for a pure tone of each frequency quite similar to that of the average human ear at a given adaptation level. The theory of this sound level meter as a means of measuring loudness is based on two assumptions: (1) The loudness of a pure tone is not affected by the presence of other tones, and (2) Tones of different frequency add in the same way as do tones of the same frequency.

The functioning of the human ear makes these assumptions invalid for certain types of sound. The ear drum reacts to sound pressure in much the same way that a microphone diaphragm does. A linkage of small bones conducts the motion to an inner diaphragm to which is attached the basilar membrane. This membrane runs down the center of a tapered duct which is coiled like a snail. The endings of the auditory nerves are distributed along the basilar membrane. The nerves at any particular position are used to hear sounds of a particular frequency, but their frequency response is rather broad. Each nerve ending therefore can detect sounds in a considerable range.of frequencies. The electrical potentials produced by the nerves when the ear is stimulated are proportional to the sound pressure up to a certain degree and thereafter show distortion of increasing degree. In addition to exciting some particular nerves more strongly, a loud tone will excite the nerves in a longer section of the basilar membrane. If one tone partly saturates the nerve response in a section of the basilar membrane the ear will be less sensitive to other sounds which excite some of the nerves in this section. The result is that two simultaneous tones loud enough to cause some saturation will not be as loud if they are of almost the same frequency as they will be if they are far apart on the frequency scale. This phenomenon is called masking, and it is something which the ASA sound level meter does not take into account.

The fact that the ear distorts the sound before it reaches the auditory nerves also has a considerable effect on our hearing of some kinds of sounds, for it results in the introduction of subjective harmonics. If the external sound also contains harmonics these may interfere either constructively or destructively with the subjective harmonics. This again is something which a sound level meter cannot readily evaluate, especially since very little is known about this effect.

It seems then that the loudness of a tone is affected by the presence of other tones, that tones of different frequency do not add in the same way as do tones of the same frequency, and that in fact we do not know just how the components of a complex sound are added in the human ear.

Yet it is known that for many kinds of sound, whether simple or complex, the ASA sound level meter readings can be converted to loudness values with a fair degree of accuracy. The important question to consider here is whether or not this is true for truck noises. The largest discrepancies between subjective loudness and meter readings have been found in cases where there were important sound components below 300 cps and where the sounds were predominantly of a harmonic nature. Unfortunately, truck sounds, as shown by our analyses, are largely harmonic and do have important components below 300 cps.

A recent study of the truck noise problem has been made by the Armour Institute in Chicago (21) in which a technique of analysis using octave bands of frequencies has been used. With this technique the total noise is first recorded on a magnetic tape. The tape is then evaluated in terms of the sound-pressure level in each of eight bands. These components are then converted into sones using the curves of Figure 8 and the total loudness in sones is determined by adding the individual values for each band. It is claimed that the results of this technique correlate well with jury ratings of the noises.

Even after we have measured loudness we are faced with another problem: What is the relationship between loudness and objectionableness or degree of annoyance? These are highly subjective quantities which are difficult, if not impossible, to evaluate. The important thing to know now is whether or not the correlation is close enough so that we can be satisfied that a loudness reduction will bring the desired improvement in human living conditions. We need to learn just what factors other than loudness contribute to annoyance caused by noise.

It has been found that high frequencies are intrinsically more annoying than low and that the least objectionable tones lie between 256 and 1040 cps. For high intensities the change in annoyance with frequency is more pronounced than for low intensities.

Because of differences in design, there are large differences in the frequency components present in the noises from different trucks. Since it takes a shorter chamber to muffle a high frequency than it does a low one, it is possible for a conventional muf-

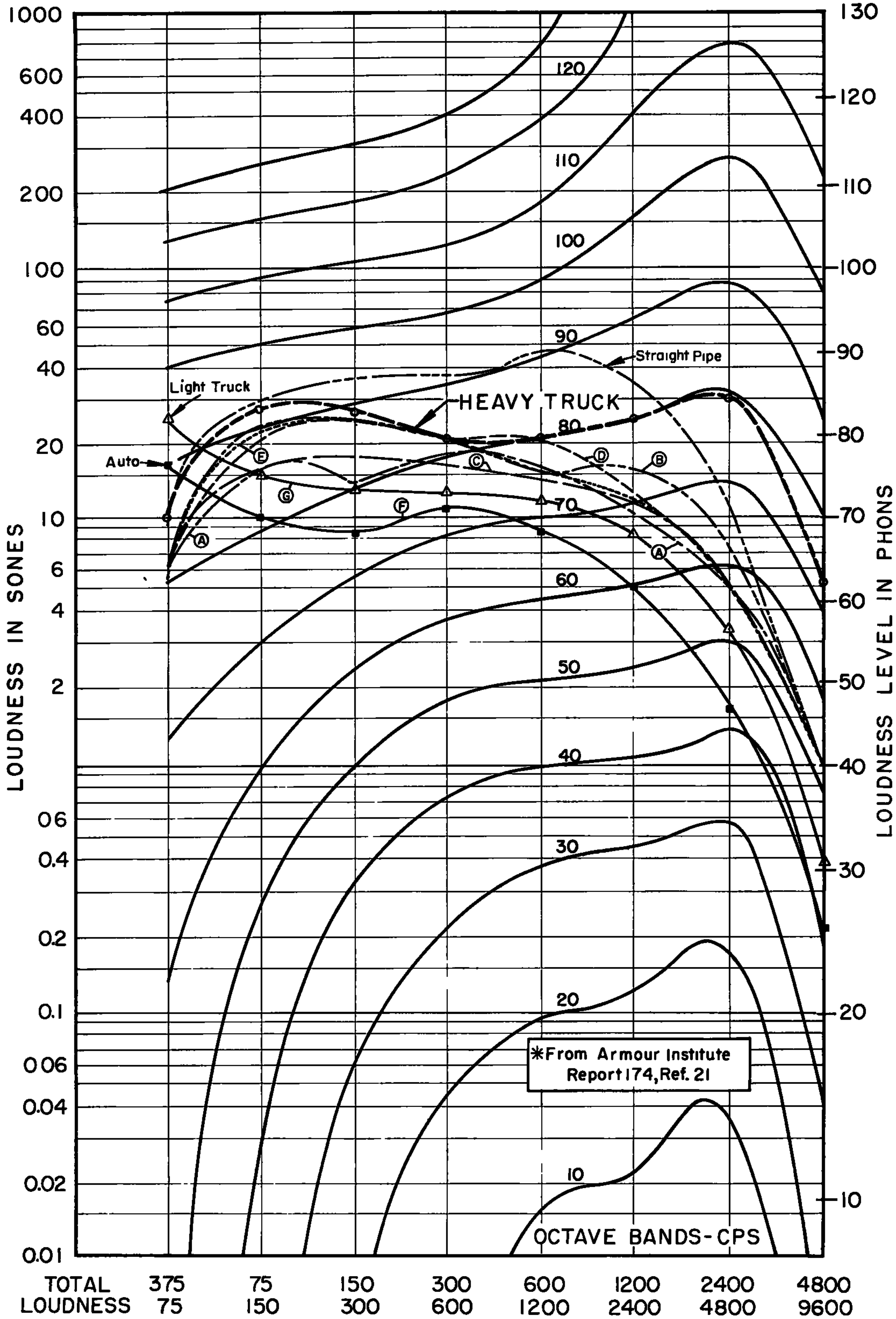

Figure 8. Conversion chart - Db to sones.

fler to do a satisfactory job at frequencies above 300 cps but the same muffler may be quite unsatisfactory for the lower frequencies. At the latest testing sessions of the California Motor Transport Associations, Inc. (6) most of the mufflers tested were very effective at frequencies over 300 cps, though several were quite unsatisfactory.

Large variations of frequency also arise from the operation of the truck at various speeds and with various gear ratios. Probably the most bothersome noises come from trucks when the high engine speeds reached just before shifting create a noise of particularly high intensity and high frequency.

When a truck is accelerating and changing gears there are three factors greatly affecting the annoyance: (1) greater sound intensities are generally reached under these conditions than under other modes of operation, (2) the sounds are of higher frequency than normal, and (3) there is great variation in the loudness level. This variation in the loudness level may account for a considerable part of the annoyance value, for it is known that intermittent sounds are more annoying than steady sounds of the same intensity.

Since our basic aim is to reduce the annoyance caused by highway traffic the factors which materially affect the amount of annoyance certainly need to be considered in any broad view of the problem. But, except for loudness, these factors are all so variable with persons and circumstances that it is difficult to see how they could have any place in legal definitions or law enforcement practices. While one person may prefer high-pitched noise and another one low, and one person may prefer a steady noise and another a varying noise, it is safe to assume that, for highway noise at least, the annoyance increases with loudness, both in its effect on each person and in the number of persons affected. If we assume a uniform distribution of population adjacent to a highway, noise twice as loud will be heard by four times as many people.

## EVALUATION PROCEDURE

The tape recordings made during the field tests of Part I were reviewed. As noted previously, there were quite a number of runs in which either the calibration voltage or frequency was not stable; therefore these were not used. Out of several hundred tapes, a group of 23 were selected covering the complete range of automotive noises including a quiet automobile, a very noisy truck, a truck with a straight pipe exhaust

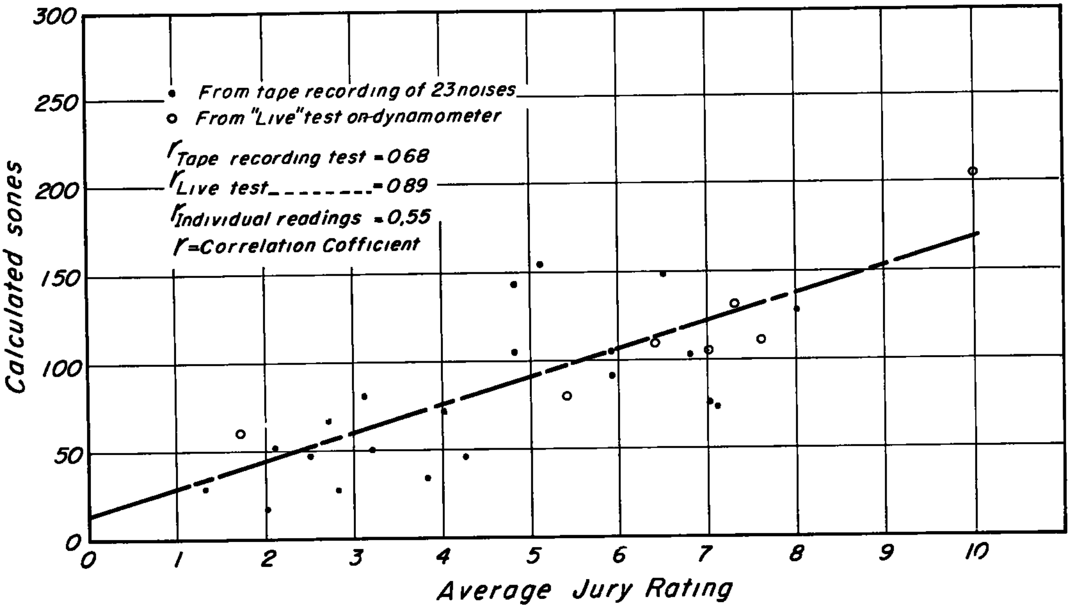

Figure 9. Calculated sone values versus average jury ratings.

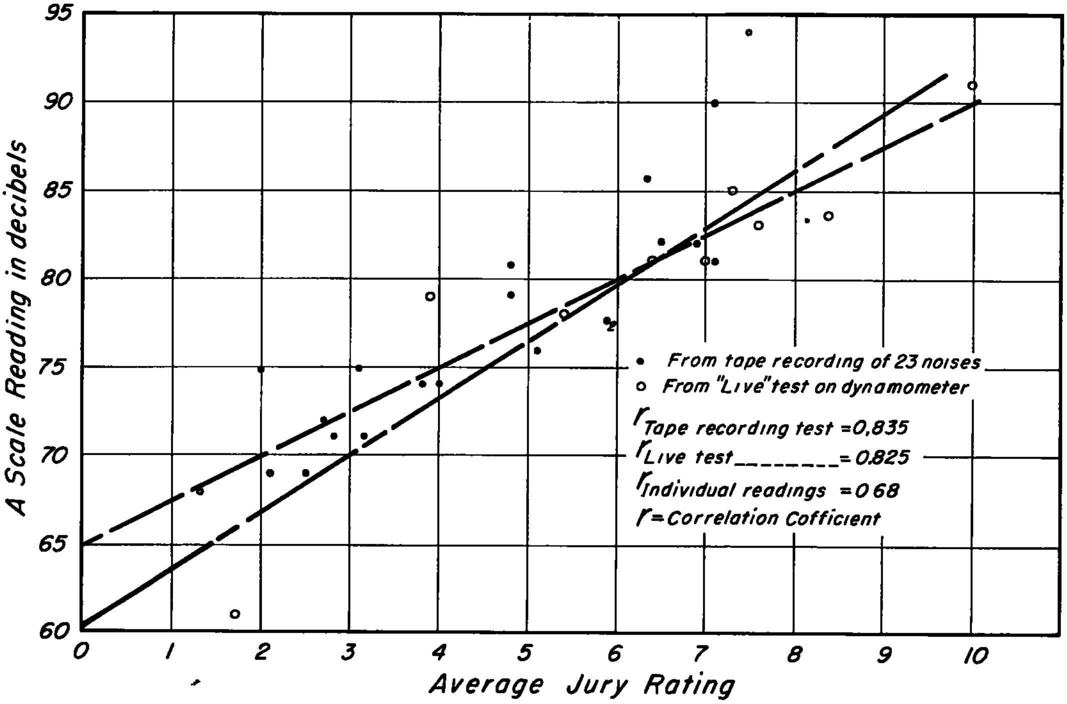

Figure 10. A-scale readings versus average jury ratings.

and a jet airplane.

Each tape was carefully analysed using the sone (octave band) analysis method, and with the A and C scales of the ASA meter.

The individual tapes were assembled into a reel with an introductory statement and an explanation of the appraisal system. The instructions given were as follows: "You are asked to listen to the noise produced by trucks and passenger vehicles of various kinds and operated with different engines, mufflers, speeds and loads and to evaluate their noise on a relative scale. The scale runs from 1 to 10, where 1 is to be considered very inoffensive and 10 is to be considered very annoying to the extent of being irritating or painful. A midscale value of 6 will be considered as the borderline between acceptable and unacceptable.

"The basis of rating is to objectionableness, rather than loudness. We are particularly interested in the annoyance aspect. You may find that some noises are more annoying even though they are no louder than others.

"The rating is to be made from a point approximately 50 feet from the edge of the roadway in the general area of the microphones."

The reel of automotive noises has been run for a number of observers, including a group of approximately 65 people participating in a public hearing of the motor vehicle noise problem on November 10, 1954, at the Institute of Transportation and Traffic Engineering, University of California, Berkeley, California. Each observer was requested to rate the noises in accordance with the above instructions.

In addition to the reel of automotive noises recorded on the magnetic tape a series of "live" tests were conducted during the November 10 public hearing. The noise tests were conducted on the chassis dynamometer at the Engineering Field Station of the University of California at Richmond, California. Five types of vehicles were used, including a passenger car, a pick-up truck, a gasoline powered city delivery truck, a gasoline powered city bus and a diesel powered 200 hp heavy duty truck tractor. All were operated at maximum power output at a road speed of 40-45 mph on the dynamometer.

The truck tractor was operated with five different commercial mufflers and a straight pipe.

The jury was assembled approximately 50 feet away from the vehicle on the dynamometer. Except for a few muffler manufacturers in the jury, the people were not aware of the details of the exhaust systems and were as unbiased and heterogeneous as could be obtained in a group of 65 individuals.

## APPRAISAL RESULTS

The results of the appraisals of the magnetic tape recordings and the live tests have been analyzed statistically to determine the relationships, if any, between the jury ratings and the meter readings. In order to compare several methods of measuring the noise of motor vehicles, three sets of data are presented: (1) A plot of the average jury ratings vs. the "sone rating" for both the tape recordings and the "live" tests; (2) the jury ratings vs. the "A-scale ratings" for the same conditions; and (3) the jury ratings vs. the "C-scale ratings" for the same conditions.

The average jury rating for each test condition is shown plotted on the scatter diagrams of Figures 9, 10, and 11. The regression line and the correlation coefficient for each set of conditions are shown. In addition the correlation coefficient for the individual jury appraisals has also been computed and is shown on the corresponding figure.

A correlation coefficient of 1.0 would indicate complete and exact correspondence between jury rating and meter rating. Similarly a coefficient of 0.0 would indicate no relationship. A value greater than 0.5 indicates better than a chance relationship and begins to have significance. Since it is not possible ever to obtain a coefficient of 1.0 it will be necessary to select a value that will be reasonably acceptable. It would seem that a correlation coefficient of 0.80 would be satisfactory for establishing the relationship between jury appraisals and motor vehicle noises.

The data on Figure 9 for the "sone-rating method" show that the same regression line fits both the data for the magnetic tape and the "live" tests. The correlation coefficient for the average jury appraisal vs. the "sone-rating" is 0.89 for the "live" tests and 0.68 for the magnetic tape data. If each individual rating is used instead of

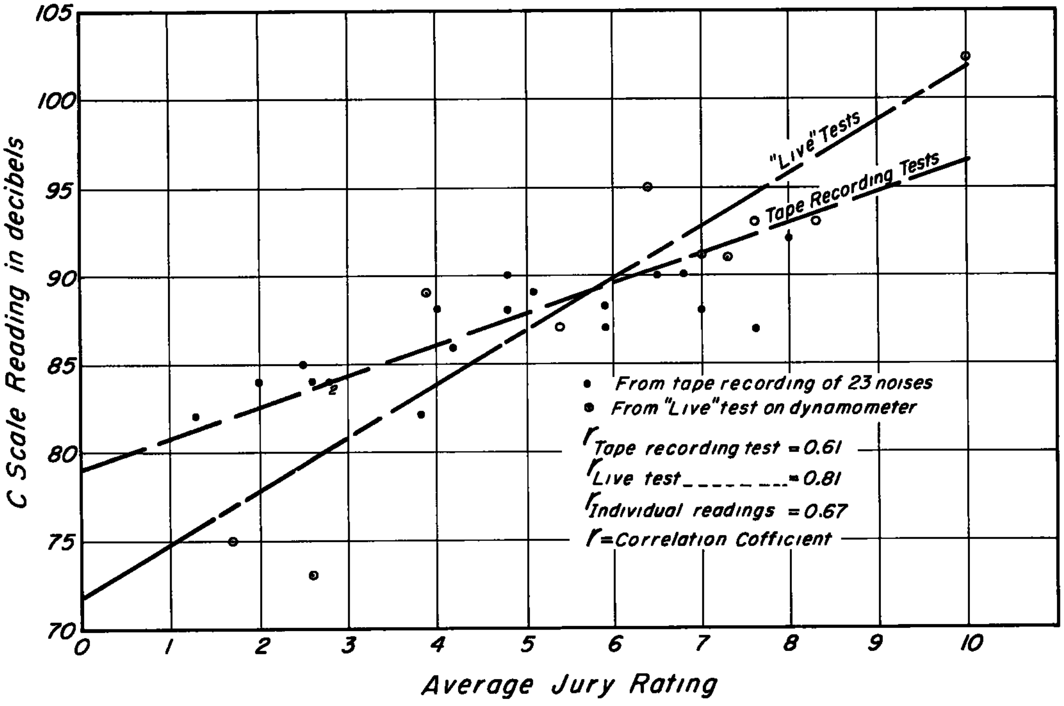

Figure 11. C-scale readings versus average jury ratings.

the average for the jury the correlation coefficient for the magnetic tape data drops to 0. 55.

The "A-scale rating method" data are shown in Figure 10. The regression lines for the magnetic tape and "live" tests are not exactly the same, but have approximately the same slope. The correlation coefficients are shown to be 0. 835 and 0. 825 for the magnetic tape and "live" data respectively for the average jury ratings. The correlation coefficient for the individual jury ratings is 0. 68.

The "C-scale rating method" data are given in Figure 11. These data show substantially different regression lines and correlation coefficients for the average jury ratings. The values are 0. 61 for the magnetic tape data and 0. 81 for the "live" data. For the individual jury appraisals the correlation coefficient is 0. 67.

## DISCUSSION OF JURY APPRAISALS

The above data show that both the "sone-rating method" and the "A-scale rating method" give correlation coefficients above 0. 80 for the average jury ratings. The values are sufficiently high to be useful in measuring motor vehicle noises. The "C-scale" correlation is not high enough to be useful in evaluation techniques. This conclusion is substantiated by other references given in the bibliography.

The correlations based upon the individual jury appraisals are lower in all cases than when the average jury ratings are used. This is to be expected because of the wide range of subjective interpretations given to each noise by the various individuals. Taken as a group of individuals the correlation has to consider a much broader range of values to include each and every appraisal than when the weighted average of the group is used for each noise condition. Even if the individual readings are considered the correlation has statistical significance but not as much as when the average jury rating is used.

For purposes of analysis the sone-rating method yields more information than the A-scale method because of the 8-band spectral breakdown. It is possible with the sone method to determine in a broad sense the frequency distribution of the noise source. On the other hand, the sone method is not readily portable and cannot be used for field work except by making a tape recording and subsequently performing a laboratory analysis.

The A-scale method has distinct advantages as a field enforcement instrument and the equipment is readily portable. It has been shown that it yields correlation coefficients comparable to the sone method and should therefore be equally acceptable as an over-all single reading instrument to use as a means for determining compliance with an acceptance specification.

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