A HIGHWAY DESIGN ENGINEERS CONSIDERATIONS OF HIGHWAY NOISE

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ABSTRACT

A HIGHWAY DESIGN ENGINEERS CONSIDERATIONS
OF HIGHWAY NOISE

by

Art Jones

Traffic noise is becoming an increasingly important consideration in the urban environment. Currently, traffic noise is the predominant and most widespread source of urban noise, and it is clear that in future urban planning the design and routing of new highways should include traffic noise as one of the major parameters.

Questions related to highway noise levels and their impact on sensitivities and activities of adjacent environment should be a major concern in the planning and design of a highway facility. Therefore it is important to have means of evaluating probable noise levels adjacent to a highway so that noise levels can be considered in the planning and design of the highway and be reduced by noise control measures and/or by enforcement of on-the-spot vehicle regulations.

Art Jones

This project will take a look at design of highway features and their capacity for generating noise. It will also look at techniques for evaluating noise which a highway designer can use to predict noise levels (Chapter VII).

A lengthy treatise on the subject has not been attempted; rather the aim has been to provide a guide to modern developments in the field of traffic noise impact for today's highway designer.

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by

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I appreciate the Michigan Department of State Highways allowing me to attend a seven and one-half hour seminar on traffic noise conducted by M.D.S.H. Research Department. Techniques to predict a generated traffic noise level was presented at the seminar and are taken from section three--The Methodology of Traffic Noise Prediction (13).

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CHAPTER I

INTRODUCTION

Traffic noise is becoming an increasingly important consideration in the urban environment. Currently, traffic noise is the predominant and most widespread source of urban noise. It is clear that in future urban planning the design and routing of new highways should include traffic noise as one of the major parameters. Questions related to highway noise levels and their effects on sensitivities and activities of the adjacent environment should be a major concern in the planning and design of a highway facility, particularly in an urban area. It is, therefore, important to have means of evaluating probable noise levels adjacent to a highway so that noise levels can be considered in planning and design of a highway and can be reduced by control measures or by enforcement of on-the-spot vehicle regulations.

Variables of the General Traffic Noise Situation

Sources:		Are Influenced by:		Situation Generated:
Passenger cars		Weather conditions		
Diesel trucks		Time of day		A
Motor buses	PLUS	Road surface	EQUALS	traffic
Sports cars		Surrounding structures		
Motorcycles		Speed, type of flow		noise
		Traffic density		
		Type of vehicle mix*		increase

The primary generators of traffic noise are automobiles and diesel trucks. The noise generated by an individual automobile is somewhat uniform, relatively quiet and does not vary much from vehicle to vehicle. Individual automobiles traveling in large volume at fast speeds can generate a combined noise level which may create disturbances. Noise from individual heavy trucks and buses is not as uniform and is much louder than that from automobiles; for example, a volume of 4480 automobiles per hour traveling at 50 mph on a four-lane freeway generate noise levels which would be generated by a volume of only 80 trucks per hour (13).

It is only recently that unwanted sound has become a real problem. Transistorized electronic measuring instruments have subsequently been developed which allow

*Number of automobiles and trucks.

possible remedy for intrusive highway noise. Noise prediction methods have been developed with variables dependent upon traffic characteristics (speed, traffic density, vehicle mix, etc.), acoustical attenuation (shields, distances from source, vegetation, etc.), roadway characteristics (configuration, pavement type, type of facility), and noise sources (ambient noise, induced traffic noise).

Scope

This project considers the design of highway features and their capacity for generating noise. It will also look at techniques for evaluating noise which a highway designer can use to predict noise levels, beginning with the formulation of facts which are pertinent to highway designers.

Today's sophisticated mathematical approach is shallow on definition and usable statement for designers to describe sound. It is important that we are talking about the same qualification and quantification of a sound characteristic. This paper will first identify sound.

The ensuing discussion takes up investigation of highway features and their capacity to generate or reduce traffic noise, (2) development of a highway sound system, (3) techniques for evaluating and predicting traffic noise level, and (4) guidelines for development of noise criteria for highways which assure that the human environment is carefully considered. Lastly, a design guide for highway designers is presented which will aid in answering the following questions:

1. How will the introduction of a new highway influence the noise environment?

2. How acceptable will this new environment be to noise-sensitive land use and activities in the vicinity of the highway?

3. What methods might be pursued to remove or reduce any adverse impact caused by the highway noise? (13).

The purpose of this design guide is to provide the highway designer with a tool necessary to answer these questions. The design guide developed identifies variables necessary for traffic noise prediction in terms of roadway parameters familiar to highway designers, the intention being to provide a "cookbook approach." These parameters are then identified for a particular traffic situation and, through a simple procedure, transformed into noise level estimates through the use of design aids.

Evaluation of the particular traffic situation is achieved by comparing the estimated traffic noise against those of a design criteria. The design criteria provide maximum levels for a variety of situations and for both inside and outside use (13).

A lengthy treatise on the subject has not been attempted. Rather the aim has been to provide a guide to modern developments in the field of traffic noise impact for today's highway designer.

The ray of light to understanding sound mechanics was the writer's development of a concept and appreciation of the sensation of sound's logarithmic nature of magnification, as it affects our auditory discrimination.

$$S = k \log R$$

in which: "S" is sensation (what we hear)

"R" is stimulus (sound's energy)

This logarithmic nature of sound's magnification is an application of the Weber - Fechner law in psychology (7).

Summary

The province of noise and the physics of sound and its acoustics have been somewhat outside the range of the highway designer's normal training and experience. However, the activity of sound and the science of the production, transmission, reception, and effects and control of unwanted, harmful sounds are becoming more a part of the considerations designers are responsible for. Because of the training, experience and practical approach which designers use to answer a need, the writer has undertaken the subject of traffic noise for a thesis. Presented are facts found useful in bridging the gap between the practical and the theoretical approaches.

A noise problem solution should begin by describing the characteristics and ascertaining the cause of the noise. A physical description of noise includes a sound pressure level (SPL) measurement relative to the average energy contained in the noise for a range of audible frequencies, say, 20 to 20,000 cycles per second (cps), and a spectrum showing how the energy is distributed through the frequency range. Usual sound measurements are expressed in decibels (db) in accordance with the formula:

$$db = 20 \log_{10} \frac{P}{P_{ref.}}$$

"P" is the root-mean-square average of the sound pressure fluctuations being measured and $P_{ref.}$ is the reference root-mean-square sound pressure fluctuations, usually 0.0002 microbar, considered the weakest audible sound pressure.

A-weighted noise level measurements are used to gauge the annoyance value of traffic noise. The A-weighting selectively discriminates against low frequency and, to a lesser extent, high frequency sound in a manner which conforms to human response to loudness sensation produced by different frequency sounds. A-weighted values also have a relativeness to the receivers' objectionability ratings of highway traffic noises, because of inability of humans to communicate.

A-Scale values are not as useful as a banded spectrum in traffic noise evaluation. For effective solutions, depend on locating the specific frequencies contributing the most energy to the noise. The spectrum is also used to compute a perceived noise level. The perceived noise level is a subjective measure for the different frequency of sounds set at various intensities and other considerations.

Factors that influence a community's reaction to traffic noise are psycho-social in nature. The number of annoyance complaints vary with the previous environmental characteristics of the impacted area and with the inhabitants' conditioning to traffic noise. Time of day is a significant factor. People are not as tolerant of disturbances in the evening as they are in the daytime.

Solutions described in this thesis reflect three basic approaches to the traffic noise problem--aspects of site selection, attenuations along its path and reduction through the design of roadway.

CHAPTER II

IDENTIFICATION OF SOUND

The province and the physics of sound lie somewhat outside the range of the highway designer's normal training and experience. For this reason, rather than provide a list of references--which might confuse rather than help the designer, the intention is to provide the highway designer with a working knowledge of sound.

Qualifying Statement

What is sound? The physicist may answer "physical energy;" the psychologist most likely would say "sensation." Physicists will view sound as an auditory stimulation caused by molecules in motion. The physicist is interested in the source. (Figure 1 shows liberated sound energy in characteristic pattern). A psychologist is looking for the sensations evoked and the individual's subjective response to sound, and will identify factors which determine one's acceptance or rejection of a sound sensation.

A subjective response is the individual's own judgment of an impression or impressions arising from a sense organ--in this case the sense of hearing. Discordant sound, sound without value or unwanted sound (noise) entails both the objective evaluation of physical sound and the subjective impression in the listener's mind (23).

Since the term "sound" has been used for both the physical energy and the sensation the physical energy causes, it is important to remember that a change in sound sensation is not directly related to a change in the physical sound.

For the purpose of this thesis, sound shall be considered a by-product of matter in motion. This vibratory motion propagates longitudinal waves through states of matter to a point of dissipation. The term "waves" is applied to the disturbances propagated through the air or other medium between the sound source and the ear. The sound waves that reach our ears ordinarily come through the atmosphere which has no free surface, over a distance to where a receiver reacts to its audibleness. Propagation is the spreading of something into new regions.

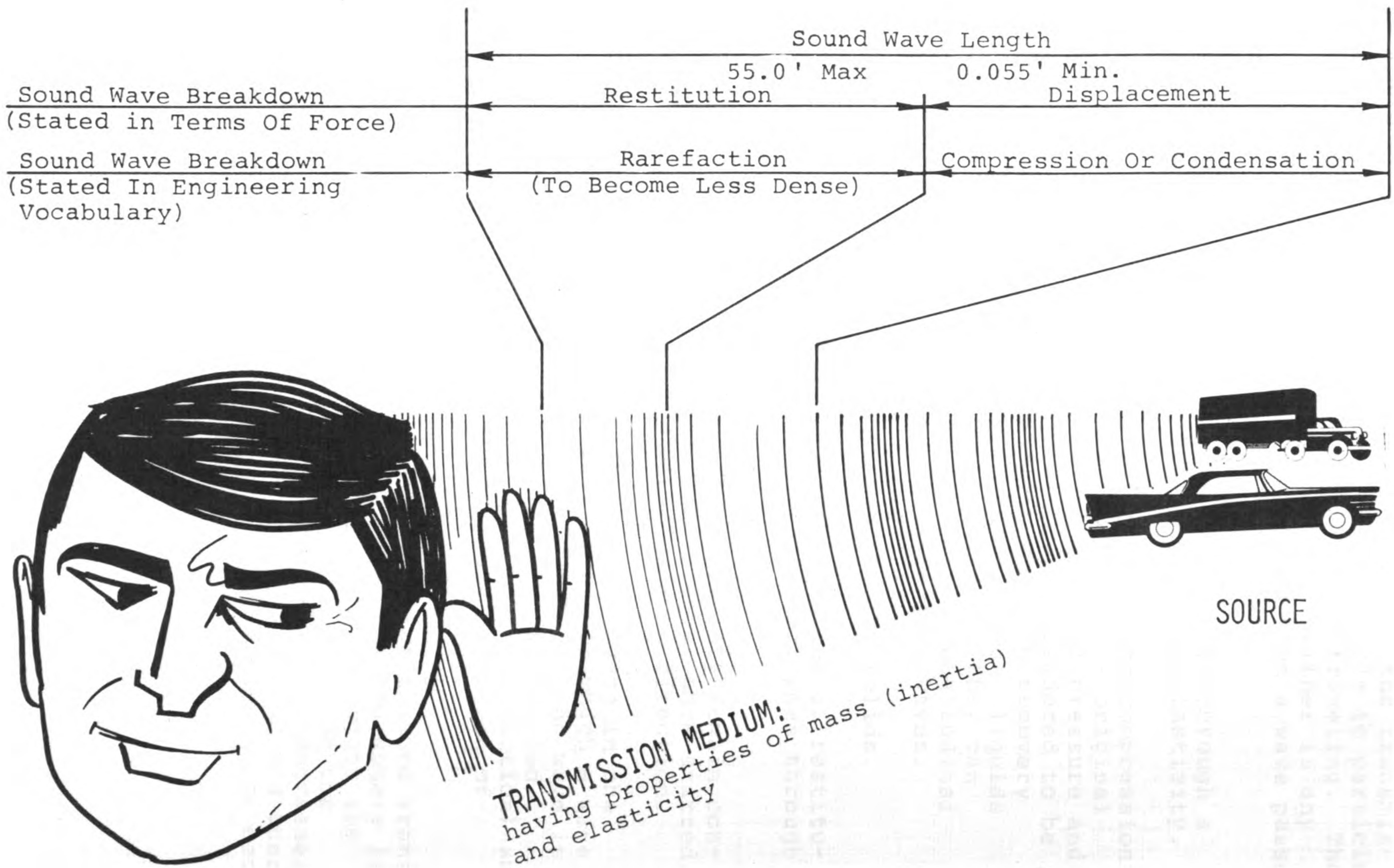

Figure 1.--Highway Sound System.

Sound Propagation

a. Wave propagation is accomplished by the transmission of vibratory motion from particle to particle of the medium in which the wave is traveling. The medium as a whole does not move, neither is any part of it permanently displaced when a wave passes through it (10).

b. In order for a wave to be transmitted through a medium the medium must have mass and elasticity.

c. If a volume of air is compressed (and compression released), the air will return to its original volume when restored to the original pressure and temperature. (Therefore air is considered to be perfectly elastic, making a complete recovery after distortion) (11). Since fluids (liquids gases) have only volume elasticity, they can transmit only compressional, i.e. longitudinal waves. Sound waves are longitudinal waves.

d. Sound waves are also transmitted by solids.

e. Inelastic mediums do not have a force of restitution, therefore, a sound wave cannot pass through them.

f. As long as the density and elasticity remain constant throughout the medium, a wave, once started, continues to move without change of direction.

g. Whenever and wherever there is a change in the elasticity or density of a medium in which a wave is traveling, a part of the energy of the wave is turned (reflected) and a part is transmitted, usually with a change in direction (refraction) and frequently with absorption and dissipation of energy (10).

h. There is a strong relationship between sound transmission and weather conditions. The atmosphere is in constant motion and change and the longer the transmission path, the more attenuation on the received sound pressure. Sound pressure decreases inversely with the square of the distance and there is about a 6-db decrease in sound pressure for each doubling of the distance (11).

Quantitative Statement

The physical measurements of sound involve the following of sound's characteristics: intensity, frequency and duration. Intensity is determined by measuring the sound's pressure relative to a reference sound pressure. This measured pressure directly indicates the intensity of sound involved and the Bel, a dimensionless unit, is used to describe this sound intensity.

A simple sound source radiates energy in the form of elastic waves uniformly in all directions. Designate this total sound energy "E" and assume that there are no losses in the air surrounding the sound source. Therefore, all of the sound energy radiated must pass through any surface that completely encloses it. As the sound moves from its source, the sound energy per unit area (intensity) passing a position decreases because the total sound energy diverges with distance.

Envision a spherical surface ("S" = square units) surrounding our simple sound source with the intensity of sound energy the same at every point on the surface. The total sound energy ("E") is equal to the intensity of sound energy ("e") per square unit, multiplied by the total area of the surface "S". The result is the amount of sound energy passing through a unit area which is the intensity of the sound.

$$E = eS$$

or

$$e = \frac{E}{S}$$

It is difficult to measure the intensity of sound directly because there are no practical sound instruments for this purpose. But our sound instruments are capable of measuring the sound pressure, which is related directly to the sound's intensity of energy involved.

The ear is capable of receiving a wide range of sound intensities. The important fact about these intensities or pressures involved is that each audible change is a definite level of sound. Also, the degree of perception of this change has been found to be logarithmic in nature. This means that each change in sound level represents a large change in sound pressure. For these reasons a system is needed to cope with this wide range of audible sound and its degree of change. Therefore, the wide range of sound pressure measurements has been compressed into a more workable range of zero to 14 Bel units, or 140 decibels.

The Bel scale is a logarithmic relationship whose base is 0 Bel; zero is not silence or the absence of sound, however. Zero Bel represents the threshold of hearing for healthy young ears. One Bel has been divided into 10 levels and one-tenth of a Bel is called a decibel (db). For most practical purposes the decibel represents the smallest level change in sound pressure which can be detected by the human ear. This Bel scale represents measured sound pressure which can be twice, ten or a million times or more greater than a reference pressure. The relation of these pressures to 0-Bel is expressed as logarithms, to the base 10. Thus, if the measured pressure is 10 levels greater than the reference pressure, the logarithm would be 1, the sound level relationship being designated 1 Bel. A relationship of 100 levels would be 2 Bels; 1,000 levels, 3 Bels.

There is one unfortunate complication of the Bel scale. Bel (a logarithmic measurement) really defines intensity of sound (a linear measurement), whereas the sound level meter reads absolute sound pressure (a second degree measurement). No serious problem exists, however, because intensity of sound and sound pressure are directly related. Energy, therefore, increases as the square of the pressure.

When converting a pressure measurement into an energy measurement to give a decibel measurement, the conversions are: squaring of logarithm which means multiplying by 2; converting from Bels to decibels, which means multiplying by 10. For example:

$$\text{Sound Pressure Level (SPL)} = \text{Log}_{10} \frac{P^2}{P^2_{ref.}}$$

$$\text{SPL (db)} = 2 \times 10 \ \text{Log}_{10} \frac{P}{P_{ref.}} \qquad \text{eq. 1}$$

$P_{ref.}$: Reference sound pressure level equals .0002 microbar which is most commonly used for atmospheric pressures. (One Microbar, μ bar, equals approximately 1×10^{-6} atmospheres). Using .0002 μ bars for $P_{ref.}$ and rearranging equation 1,

$$\text{SPL (db)} = 20 \log_{10} \frac{P}{P_{ref.}}$$

$$\text{SPL (db)} = 20 \log_{10} P + 20 \log_{10} \frac{1}{P_{ref.}}$$

$$\text{SPL (db)} = 20 \log_{10} P + 20 \log_{10} \frac{1}{.0002}$$

$$\text{SPL (db)} = 20 \log_{10} P + 20 \log_{10} (5000)$$

$$\text{SPL (db)} = 20 \log_{10} P + 20 \ (3.69897)$$

$$SPL\ (db) = 20 \log_{10} P + 74$$

where "P" is the absolute sound pressure in dynes/square centimeter.

Most sound measurements are made in terms of absolute sound pressure--atmospheric pressure deducted--and referenced to the threshold of hearing. An absolute sound pressure is obtained by having a hole in the microphone's diaphragm which allows equalization of the atmosphere's pressure. The absolute sound pressures that are of usual concern to individuals range from .0002 μ bar at the threshold of hearing to 100,000 μ bars which is common for a blast phenomenon.

The common sound level meter measures the sound pressure level in db with respect to the reference pressure of 2×10^{-4} μ bar by converting the sound pressure into a voltage, via a microphone, and weighting network.

When applied to traffic sounds, the A-weighting correlates as well with human judgments of the acceptability of environmental sounds as do the more elaborate methods. Another advantage of the A-scale sound level is ready availability of good instrumentation for field measurement. The traffic sounds we measure are rarely pure tones. They are usually a jumble of sounds that may range from a low-frequency roar to a high-frequency squeal that is to the human ear almost always dissonant.

The layman is impressed by the technology for analyzing sound, but he is more concerned that this technology be directed to suppressing those sounds coming from roadways, railroad tracks, automobiles, airplanes and machinery of all kinds. A consideration more important than evaluating sound by a sound meter's response is measuring for a high correlation between human judgment of acceptability of the sounds and the values assigned to each. Individuals respond to these sounds in different ways that depend not only on the overall sound levels, but also on the composition of the sound as a function of frequency and duration, which are not discussed in this thesis.

CHAPTER III

OVERVIEW OF HIGHWAY DESIGN COMPONENTS

There are several possibilities available to the highway designer for controling traffic noise and its impact during the study and preliminary design stage of a highway project. Motor vehicle noise causes certain public reactions when the exterior noise becomes severe enough to interfere with interior conversation, sleep, telephone usage or the enjoyment of musical and TV programs, also when exterior noise levels prevent the intended enjoyment of outside recreation. It is apparent from cases studied that the complaints become stronger as the noise level rises. There is, however, considerable variation in individual reaction to traffic noise; for example, only a few complaints are received from commercial or industrial areas (9, 14).

Highway Traffic Noise Generation

Roadway Surface and Tire Interaction

At high speeds, the tire noise of large trucks becomes the dominant generator of traffic noise. The data researched indicated that several parameters contribute to tire noise levels. The most influential are tread design, degree of tire wear, type of pavement surface, vehicle speed, loading and tire location on truck. Secondary parameters are carcass design, rubber composition, inflation pressure and other design features (16, 21).

Tread design is a primary producer of tire noise and contributes to the frequency of the noise emitted from tires. Cross-bar tires and certain retreads are noisier than rib type tires.

Tire wear causes increased traffic noise. The curvature across the width of the tire is significant where wear is concerned. Curvature is also important. It determines how much load is carried on the outer edges of the tread where major discontinuities exist.

The road surface causes variations of sound level. It is found that roughest paved road surfaces produce the higher sound levels, while aggregate road surfaces produce the lower sound levels.

Speed affects the level of tire noise. There is a direct correlation between vehicle speed and noise emanating from tires with considerable level differences for particular tread designs.

Noise level increase from truck tires is associated with increased loading. The data shows a 15 dbA difference in the noise produced by a pocket retread between the no-load and fully loaded condition. Load compresses the tire for a more perfect seal of air in the pockets. Load acts similarly to wear; i.e., increased load flattens the tire and places more load on the outer edges of the tread.

These five parameters--tread design, tire wear, road surface, speed and loading--affect the overall noise level. Secondary parameters with influence include carcass design and wet surface. Composition of the tires has some bearing on the noise level produced.

Nylon is noisier than rayon and the damping characteristic of the cord appears to have effect on noise and vibration output of the tire. Further, as the number of plys in the tire increase, there is a decrease in noise; e.g., a six-ply tire will produce more noise than an eight-ply tire.

The data show the effect of wet surface on tire noise is a considerable increase for frequencies above 1,000 cps. The sound pressure levels at lower frequencies were similar for wet and dry surfaces.

Tire noise is caused by the tire tread coming in contact with the road surface, interacting with it. Tire treads cause energy to be dissipated as noise. As a tire moves, regularity in tread pattern causes discrete tonal noise caused by compression and the release of air trapped in grooves as the tread makes and breaks contact with the surface. Therefore, the sealing-unsealing process generates traffic noise which is dependent on the specific tread design and tire wear condition (21).

Design Components Which Reduce Traffic Noise

During location studies, the impact of potential traffic noise of each alternate alignment should be determined. With all other factors equal, the alignment having the least noise impact and the most benefits should be selected. These two factors are seldom equal, which makes a final decision difficult to render. Here the highway designer must check to see if the greatest possible array of social, economic and environmental effects are being considered in his final decision.

The effective methods of controlling vehicular traffic noise are quieten the source (design-muffle-shield), interrupt the path (by placing a dense, impervious shield), protect the receiver (enclose, absorb). The highway designer has a range of control over these effective methods because each highway design presents its own peculiar noise radiation characteristics. Differences between various designs can affect the induced noise to a slight (2 dbA), significant (5 dbA) or dramatic (12 dbA) degree; or a particular design modification may further reduce the noise level. The degree of the noise reduction that modifications can achieve depends upon how well the modifications are fashioned to the total engineering package.

When a shield (barrier) is used between the source and receiver, the amount of sound reaching the receiver is further reduced (attenuated). "The attenuation for all frequencies increases with increasing barrier height, with the higher frequencies showing more reduction than the low frequencies. This greater attenuation of high frequency sound is significant for control of community noise problems" (8), because the high frequency sounds are judged more annoying than some low frequency sounds.

Near the highway, the noise level is usually 83 dbA and if there is no form of shielding, it drops off to about 68 dbA at 200 feet. A 12-foot shield could reduce the noise level by 15 dbA near the 200-foot mark.

A highway designer's real contribution to resolving the highway noise problem can be by modifying his basic design, i.e., locating the roadway to minimize noise impact.

CHAPTER IV

DEVELOPMENT OF A HIGHWAY NOISE CONTROL SYSTEM

The writer views a sound system as consisting of a source, a transmission medium and a receiver (Figure 1). Traffic noise reduction (attenuation) involves modifications of one or more of these elements. These modifications can be physical modifications of the source, vehicular operations modification, transmission medium modification and/or architectural modification.

Physical Modification of the Source

Source modification is the most effective because it benefits all receivers. Noise reduction at the source includes modification of the engine--air intake, exhaust system and enclosure, brakes, transmission and other moving parts; changes in tire tread design and road surface texture to tone down the noise from tire roadway interaction. The highway agencies have limited control in this regard, therefore, highway designers will have to deal with the given sources.

Vehicular Operations Modification

Rerouting

Through-traffic could be rerouted before it enters the urban area. This action would alleviate discomfort and annoyance to a large number of people in a short period of time. One should remember that a bypass may be the longest route, but it should be the quickest way to get to the other side of the urban area.

Night Traffic

A vigorous campaign for driver courtesy can increase an awareness which can bring about a quieter urban night to counteract shorter and shorter lulls in traffic noise levels at night. A very practical approach to this problem can be implemented by stricter enforcement of existing noise codes.

Traffic Flow

Stop-and-go traffic noise of deceleration, braking and acceleration (at intersections) is the significant element in urban traffic noise. Reduction of stop-go traffic is possible by use of synchronized traffic signals and one-way streets. On the other hand, one-way streets may lessen congestion in one area at the expense of increasing traffic noise level where streets were relatively quiet.

Other vehicular operations modification may be accomplished by enforcement of existing public nuisance ordinances against reckless vehicle operations and nuisance use of horns, bells, sirens, etc.

Type of Source

Traffic noise generally decreases with increasing distance, but the amount of the decrease depends on the nature of the source. One noise source is produced from a composite of free flowing vehicles which act as a line source, with the source and receiver at the same level, with no shielding structures and with average atmospheric reductions included. The noise caused by a point source decreases more rapidly with distance than noise caused by a line source.

Transmission Medium Modifications

When a new arterial highway is needed within an urban area, it is important to establish during initial planning what effect various road designs will have on the induced noise levels. After methods of attenuation have been explored, and it is impossible to meet acceptable levels, then consideration should be given to land uses and activities which are more compatible with the noise levels generated.

Street Width

The width between building fronts can create a noise problem by increasing amplification and reverberation: for a 40' width, a sound level of 95 db is increased to 100 db; 20' width, 95 db is increased to 105 db; when the width exceeds 80', appreciable increases are not noticed (22).

Buildings as Noise Shields

Buildings cause a noise level attenuation of about 5 to 10 decibels which is primarily independent of the number of intervening structures. Very few buildings are designed as noise shields; therefore, most buildings reflect sound waves.

Road Design

Expressways in urban areas may call for the use of noise shields or unusual road design features to permit construction on land which would not allow its existence if environmental acceptance levels are to be observed.

Tunnels are effective in removing the noise source from the receiver and in maintaining existing traffic routes. But there are problems with tunnels such as channeled noise and exhaust fumes to the above environment, intra-tunnel noises beyond reasonable limits for comfort of the vehicle occupants, overhead buildings, etc.

Zoning

One governmental approach to noise control would be to establish zones with allowable noise levels. A governing body would define the noise levels acceptable in each zone and allow individuals to choose the zone that best suits their sensitivities and activities.

Architectural Modifications

If vehicular noise and their noisy operations or the modification of the transmission path is impossible, the remaining control is through architectural modifications.

Windows

Windows are the weakest link in insulating occupants from outside noise. Noise level difference between the outdoors and indoors, with windows open, average about 14 db; with windows closed, about 24 db; double window panes, about 45 db. The noise attenuation is governed by the amount of leaks around the glass panels (22).

Interior Building Layout

The effect of noise can be reduced by locating vulnerable parts of a building as far as possible from the source. When planning, the areas which are sensitive to noise should be shielded by less sensitive areas. Offices, bedrooms, studies, etc., should be located as far as possible from the exterior walls next to the street traffic.

The increase of traffic noise is not just an isolated disturbance or annoyance. "The perceived loudness of traffic noise in some cities has more than doubled in the past two decades. Some impacted communities already have noise levels that are comparable to those found in industry" (23). Recent studies have shown that by 2000 A.D., all persons in such impacted communities will be stone deaf if the present increase of traffic noise is maintained.

Noise Effects on Receivers

Noise as a pollutant has only recently attracted attention, therefore we will first attempt to define noise. Noise is discordant sound, unwanted, unpleasant and intolerable; as a pollutant is an untrammeled din of voices and movement; hubbub. Its disgusting quality and quantity affect large numbers of people both physically and psychologically, depending upon how the individual is affected by the sound pressure.

Even ordinary sound may at times be unpleasant; for example, hearing a polka at 7:00 in the morning would tend to be irritating simply because one is not conditioned to it. Whereas, at 9:00 in the evening we appreciate it much more for the music it is meant to be.

Physiological Effects of Noise

At the ear, noise may produce significant reactions if long continued and intense. Long continued, loud noise may actually result in partial loss of hearing; it, at the least, interferes with understanding between communicants. Most of the research which has been conducted on the physiological effects of noise during the past few decades has been concerned with its effects upon hearing. Hearing impairment is only one of many adverse effects of noise.

Loud noise causes a number of reactions in the human body which the recipient cannot control, in addition to psychic shock. The blood vessels constrict, the skin pales, the pupils dilate, the eyes close; one winces, holds the breath, and the voluntary and involuntary muscles tense. Gastric secretion diminishes and the diastolic pressure increases. Adrenalin is suddenly injected into the blood stream, which increases neuromuscular tension, nervousness, irritability and anxiety. These are some of the ill effects of noise described by Samuel Rosen in "Noise, Hearing and Cardiovascular Function" (23).

Psychological Effects of Noise

Mental and emotional damage is hard to measure, but it is apparent that certain noise levels impair our peace of mind. Individuals exposed to prolonged impairing noise levels are more inclined to argue, fight or perform irrational behavior. Noise has been held responsible for fatigue, social conflict, the high divorce rate and loss of sexual desire. Just as many people are allergic to pollen, others are particularly sensitive to certain noises, and it does not matter whether one is conscious of the unpleasant sound.

Sound impulses travel by the nerves to the human brain. The sensory impulses pass first through the midbrain, when only a part of them are transmitted to the cortex (the gray substance which forms the outer surface of the cerebellum) (20). Emotional disturbance is produced here that can lead to loss of attention, quarrelsomeness, insomnia and the like.

Noise can be defined in physio- and psycho-engineering terms as a disturbance in our integrated equilibrium. Humans exist in a limited and delicate integrated equilibrium which can be disturbed in many ways, creating a stress on the body. There <u>is</u> more to sound than meets the ear (5).

CHAPTER V

EVALUATION AND PREDICTION OF TRAFFIC NOISE

Evaluation of Traffic Noise

The primary generators of traffic noise are the large trucks and passenger cars, trucks being the noisiest component, even though muffling and operation characteristics are generally good. Cars represent the largest component of the highway traffic volume. Individual passenger car emitted noise varies only slightly because of similarities in the different manufacturers' products.

Trucks are dissimilar noise generators because of great diversity in sizes, engine designs, auxiliary equipment, etc. Motorcycles, whose muffling characteristics could be improved, are also a large generator of traffic noise. The noise coming from different models of motorcycles has hardly any relationship to the power and/or size of its engine, but rather to different individual preference to muffling the exhaust noise.

Passenger Cars

A general characteristic noise spectrum of frequency distribution has been developed which gives a good approximation of passenger car noise of different manufacturers, models, age, speed and roughness of the road. This generalized spectrum gives a visual account of traffic noise and its direct relationship between its intensity and frequency. The spectrum is relatively flat across frequencies of 32 to 2,000 cps and at 2,000 cps and higher the frequency drops sharply (14).

With the previous factors in mind and under usual operating conditions, the spectrum is a compound of engine, exhaust and roadway surface and tire interaction. Noise levels generated by passenger cars can be generally described by empirically derived Equation 2, which includes parameters for surface, distance and speed. Equation 2 states: (14)

$$L_{auto} = 16 - 10 \log_{10} \left[\frac{d}{50}\right]^2 + 30 \log_{10} v$$

L_{auto} = approximate generated noise level — dbA

16 = average surface roughness — constant

d = distance; auto to receiver — in feet

v = average auto speed — miles per hour

Road Surface.--Since the spectrums differ slightly for various types of road surfaces, these variations will be considered for the constant term "16" in Equation 2, which is the average of 11 for very smooth and 21 for very rough surfaces.

Distance.--The user of Equation 2 is cautioned that it does not apply for distances under 25 feet and, because of atmospheric attenuation, distances greater than several hundred feet.

Speed.--This term is indicative of existing traffic conditions. Its variable is derived by considering traffic flow conditions at the time period being studied.

L_{auto}.--The equation also accounts for sound's logarithmic nature of magnification. "At 50 mph this equation gives a noise level of 67 dbA at 50-foot distance. Maximum acceleration conditions for automobiles produce noise levels of the order of 6 dbA above those for cruise conditions" (14).

Trucks

The truck component is heterogeneous in nature, therefore, noise levels at a given distance from roadway will vary considerably from truck to truck. The diesel truck's primary noise generator is the engine and exhaust system. A diesel truck noise spectrum showed an A-scale noise level of 82 dbA at 50 feet with truck at cruise speed. A general comparison of truck noise to passenger car noise requires 30 cars producing noise levels of 67 dbA each to equal the 82 dbA noise level of one truck.

The effect of grade on trucks is about 2 dbA on 3 to 4 percent upgrades. Acceleration on zero grade produces about 5 dbA higher noise level. The effect of speed on noise emitted from a diesel truck is not clearly understood. "Since trucks tend to operate at nominally constant rpm, engine and exhaust noise does not vary appreciably with vehicle speed under level roadway cruise conditions" (14).

There are appreciable relationships between road surfaces and truck noise. Comments appear in Chapter III, "Roadway Surface and Tire Interaction."

Other Vehicles

Motorcycles and sports cars are noisier than passenger cars, in a few situations noisier than trucks. There is no apparent relation between the noise emitted and the power or size of the vehicle. The noise level differences are coming from muffling practices. For these vehicles, tire-roadway interaction noise is comparable to that made by passenger cars.

Additional Considerations

Diesel engine noise is a real offender of the thoroughfares. The diesel engine truck has become prime-mover on our highways. One reason for this being it consumes about half the fuel as does the gasoline engine. Its popularity has caused its manufacturers to yield to the buyer demand of increased power output and reduced engine weight. The results are increased vibrational and exhaust noises, which compounds a noise from a higher compression ratio.

Observation of measurements taken along freeways revealed level grade produced the higher sound levels; on grades, where traffic slows slightly, the result was lower sound levels; and lower sound levels were reported for on-ramp acceleration. The control of low frequency exhaust noise is a must, because lower frequencies tend to travel farther than higher frequencies. Designers should keep in mind that the usual diesel exhaust outlet is 12 to 15 feet above the surface.

It is hard to believe, but it appears that more people are worried by highway traffic noise than any other form of noise. In just 12 years (1960-72), the sound levels have increased by about 12 dbA (22).

Prediction of Traffic Noise

Designers of proposed urban highways must be able to predict the induced noise impact on adjacent environments. Prediction of noise levels, their fluctuation and impact are paramount considerations during the planning stage of any highway.

Techniques for Predicting Traffic Noise

Before and after comparison.--A useful technique is an analysis of probable change, using present traffic noise levels from the existing traffic situation (local streets, etc.) and comparing predicted noise levels for the proposed highway. Clues about neighborhood and/or individual responses to the existing situation can be useful when evaluating induced impact on environment (12).

Simulation method.--The prediction of noise level by simulation is the forecasting of highway noise from information on traffic characteristics. This method relies on a similar situation instead of empirical prediction based on field data. Simulation allows analysis of situations which cannot be stated by formula simplification. Such a formula cannot relate traffic parameters exactly to traffic noise produced, although the contribution of an individual noise source can be computed by formulas and a summation performed for a set of sources (14).

Traffic noise from individual vehicles can be represented accurately in terms of a measurable physical value noise level in dbA. Mixed flow traffic noise can be represented accurately by simulation.

Attitude sampling.--Prediction of people's subjective reactions to traffic noise is not as straightforward as prediction of the noise levels because there is no satisfactory objective measure of the subjective effects of noise. Humans can judge relative strength of noise accurately when the noises are presented in controlled conditions, but their expressed annoyance with traffic noise in their natural environment varies. This results from the wide variation in individual differences in thresholds of annoyance which is tempered by habituation to noise, experiences with noise, content conveyed by specific sounds, the meaning of the source of noise itself, etc. The urban highways appear to be so pervasive a part of the neighborhood environment that people do not consider its noise completely apart from other aspects of the environment.

Further, because the urban highway is so important in people's lives, judgments of annoyance with traffic noise are often mixed with attitudes towards highways in general, and especially toward any highway that is part of the immediate neighborhood. Spontaneously voiced objections, however, may be a relatively unbiased indicator of annoyance since they may quite probably indicate the salience of the respondents' feelings before their attention is focused on supposed noise problems (14).

People's expressed annoyance with highways is found to be strongly affected by their frames of reference to them in general, each individual having different factors of judgment relating to convenience, intrusiveness, attractiveness, necessity for the freeway, etc. Other physical characteristics of the environment which are related to the highway are shown to be important variables influencing people's judgments toward the highway. The adjustment for the subjective meaning of "intruding highway noise" is difficult to estimate and is beyond the scope of desired generality. Evidence of the large variation in acceptable noise levels resulting from individual subjective evaluations of highways suggests that it is meaningless to design for other than the average response with some margin of safety.

CHAPTER VI

GUIDE FOR FORMULATING ACCEPTABLE HIGHWAY TRAFFIC NOISE LEVELS

General Considerations

The United States has over 113 million separate identifiable highway transportation vehicles. Each of these is a transportation noise source which penetrates communities, interrupting privacy. Urban traffic noise--the noise emanating from the more than 90 million automobiles, 20 million trucks, 2.6 million motorcycles and 400,000 buses that use our nation's streets and highways--above tolerable levels is the most objectionable to people who live nearby.

Purpose for Guidelines

To provide noise guidelines for highway agencies and others which will assure that the human environment is carefully considered in the development of highway improvements and that adequate measures are taken to meet the acceptable noise levels for different land uses. Page 59 shows the level of probable protest to be expected from any noise source (2).

Authority Vested in Legislative Bodies

General legislation states that guidelines will be promulgated (made known by open declaration) which assure that possible adverse economic, social and environmental effects relating to any proposed project under its jurisdiction shall have been fully considered in developing the project; that the final decisions on the project are made in the best overall public interest, taking into consideration the need for fast, safe and efficient transportation, public services, and the costs of eliminating, or minimizing, adverse effects of traffic noise.

Legislators, after consultation with appropriate and interested persons or authorities, should develop and promulgate guidelines for highway noise levels compatible with different land use. The guidelines should consider the desirability of incorporating noise control measures into the original design and construction where there is sufficient justification to reduce traffic noise. The initial decision to reduce traffic noise should be based on a consideration of need, long term benefits, and the difficulty of later incorporating noise control into developed land.

Considerations for Studies

Analysis of traffic noise and assessment of its effects should be made and considered during the location and design studies. The following guide is given for making these studies:

a. Identify all existing noise and its effect on developed land uses or activities.

b. Identify proposed traffic noise and its effects on existing and proposed land uses or activities.

c. Compute (for the land use or activity identified) the noise levels generated by the traffic expected to use the improved facility, keeping in mind the most important traffic noise parameters are motor vehicle speed and traffic volume.

d. Compare the predicted noise levels with the accepted noise level and determine its impact upon the noise sensitive land uses or activities previously identified.

e. Identify and analyze possible means for reduction or control of noise impact.

f. For each alternate route, the location phase should include a study of noise impact on sensitive land uses and activities and the feasibility of introducing noise reduction measures.

g. The design should incorporate reduction measures necessary to meet the desired noise levels.

h. Balance the costs and effects of desired noise reduction against the benefits which can be achieved, as against other conflicting values such as economic reasonableness, esthetic impact, air quality, highway safety, or other similar values.

    1. Consider reduction measures that could result in a significant lowering of noise levels, though perhaps not to the desired levels, and state to what extent they meet economic reasonableness, practicability, impact and other values outlined in "h."

Criteria

In the development of highway noise criteria, the principal consideration is that in such criteria are some measure of human objective and subjective responses to noise. These responses are reflected in one or more of the following considerations:

a. The relation of induced highway noise to the ambient--

    1. Task interference as associated with speech, sleep, learning and other on-going activities;

b. The relation of induced highway noise to the receiver--

    1. Physiological, as associated with cause of personal injury and/or insurance of human survival;

    2. Psychological, as associated with maintenance of efficient performance and preservation of comfort and enjoyment.

Ambient

Added highway traffic noise is an intrusion on existing ambient noise levels and this increase in noise level is a must consideration at the planning stage. "It has often been common practice to require that any new noise intruding on an environment be controlled only to an extent compatible with the existing ambient" (13).

The consequence of this philosophy is actually an upward movement of the environmental noise impact of about 3 dbA. Although such a level change is not desirable, the intrusive noise may not cause too much response from the impacted communities, that is until the environment becomes unacceptable for task performance or general annoyance conditions exist.

The Receiver

Traffic noise has become a definite part of our environment. To control its impact on our everyday existence, a criteria has to be related to our well-being in a noise impregnated environment. The state of an individual's health appears to be the more logical indicator and is a quantitative measure of our physical and/or emotional condition; for example, the presence or absence of deafness or schizophrenia, as described below.

Physical malady - principally an organic disability affecting the normal sensations of sound received at the cortex through the auditory mechanism (external ear canal, middle and inner ear) - noise induced hearing loss.

Emotional malady - principally a feeling of resentment noise evokes when it invades individual privacy of thought - disturbing, annoying, causing schizophrenic tendencies.

Of these quantitative measurers, noise hazard ranges from nuisances to challenges of survival. Annoyance denotes a feeling of concern or anxiety which is usually educed by a provocation, such as prolonged blowing of an automobile horn. The usual effect of an annoyance type disturbance is reduced performance (5).

Reduced Individual Performance Caused by Interference

When considering interference, we are interested in the ways that noise prohibits or inhibits the performance of various functions. Such activities are speech communication, sleep, TV and radio use, etc. Speech communication appears to be a valid topic to show how interference reduces our effectiveness. The net result of many speech communication investigations over the past years is that people tend to rate their surroundings on the ability to converse in either face-to-face communication or by telephone.

Speech communication as a basis for establishing maximum allowable noise levels for highway traffic.--The real problem is the detection of speech signal above the traffic noise background. We must decide the minimum speech intelligibility (the effect of noise on communication) by a psychological procedure of testing for percent of spoken words heard correctly in a noise condition.

The articulation index is a short cut method which uses a physical engineering measurement for arriving at an estimated intelligibility rating. For example:

> When the articulation index is approximately 0.40, communication is effectively stopped without a change in voice level or a change of separation distance. An articulation index of 0.60 is associated with approximately 83% of the spoken words heard correctly.

Then, establish the fraction of the time for which it is tolerable for speech communication in a talker-listener situation to deteriorate beyond a fixed limit of speech intelligibility (3, 18).

As a rule initial hearing losses occur in frequencies above 4,000 cps and it is essential for clearly understanding speech that these sound levels not be missed, because good speech communication is essential for an individual to operate efficiently in today's environment.

A communicable conversation requires 88% of all words to be distinctively heard. Also, most speech sounds we use are below 4,000 cps, therefore interferences in those frequencies must be avoided. Conversational speech sounds are between 100 and 6,000 cps. We find the vowels in our speech under 2,000 cps and consonants above this frequency. Consonants determine the quality of speech intelligibility, and are often unheard because they are the weaker part of our speech (5).

Background noise level is vital to speech distinctiveness, for at 76 dbA hearing accuracy declines rapidly. Allowable upper levels of background noise are called speech interference levels (SIL). This index, when used with traffic noise, is based upon the overall A-weighted network. SIL readings of 73 decibels indicate prohibitive telephone conversation; at 55-60 decibels, telephone conversations are communicable, and 53 decibels is desirable for office operation.

Response

It has been found that large variations in acceptable noise levels result when studying individuals' subjective evaluation of a highway noise. This suggests that it is useless to design for more than the average response with a margin for comfort.

Persons of high socio-economic status express high sensitivity to highway noise, while other property owners show concern about its effect on property values. Adjustments for the subjective impact of highway noise are difficult to estimate because they are complex.

Another response to be considered is the amount of noise inside residences and occupied buildings. The consideration for the indoor levels may be accomplished by a correction for properties of typical building constructions.

CHAPTER VII

A DESIGN GUIDE FOR HIGHWAY DESIGNERS

The problem: A highway is proposed to be located along a definite route. Considerations to be analyzed during the planning and study stage are: how acceptable the new noise environment will be to the inhabitants who live or have activities in it; what can be done to remove or reduce any of the adverse influences caused by the induced highway noise; how the introduction of the proposed highway will influence the noise environment.

Since a working knowledge of noise and physics of sound are not within the highway designers normal training and experience, Chapters II, III, IV and V have been presented to give a brief overview and to stimulate thinking in the area of noise generated by a proposed highway.

Terms Associated with Analysis

Prediction of highway traffic noise levels in areas adjacent to a highway is dependent upon a number of dimensional and traffic parameters. These parameters are identified and briefly discussed below.

Roadway Elements

An element is a section of roadway with constant geometric and traffic characteristics. For any selected receiver point, the number of elements present must be determined and the noise radiating from each element calculated separately. These results are then db summed to predict the level of noise at the receiver.

Lane Groups

A lane group is by definition one or more contiguous traffic lanes (each lane assumed to be 12' wide). A roadway "element" may contain one or more lane groups. For example, an element taken across a four-lane, divided expressway would contain two lane groups, each containing two lanes; but an element across a four-lane, non-divided highway would include only one lane group.

Traffic Volume

The average daily traffic (ADT) in each separate lane group.

Percent ADT

$$\text{Percent ADT} = \frac{\text{DHV}}{\text{ADT}} \times 100$$

Percent Truck Mix

This term refers to the percentage of trucks (% commercial) in traffic stream.

Vehicle Speed

Since the noise produced by vehicles is a function of speed, the average speed of each of the two vehicle types (autos and trucks) must be specified.

Receiver Distance

The perpendicular distance (D_N) between the center of the near lane for each roadway element and the receiver point (measured at the receiver elevation).

Roadway Element Type

This element type is based on multiples of the receiver distance, D_N.

I. Infinite roadway element is one which extends a minimum of $4D_N$ on either side of the perpendicular intersect point.

II. Semi-infinite roadway element is one which extends across the $4D_N$ limit in one direction but terminates within the $4D_N$ limit in the other direction.

III. Finite roadway element is one which starts and finishes within the $4D_N$ limit on each side.

Traffic Flow

It is known that interrupted traffic flows produce 2 to 4 dbA higher sound pressure levels than free flow conditions (13).

Roadway Surface

Depending upon the pavement surface type--asphalt, smooth concrete or rough concrete, the noise level for each is modified by -5, 0, +5 dbA, respectively (13).

Grade Correction

Grade changes of 2% or more cause vehicles to radiate more noise. The following level corrections (plus or minus grades) are used to account for this effect:

% Grade	dbA Level Increase	
2	0	
3-4	2	
5-6	3	
7	5	(13)

Shielding

In those instances where the pavement is depressed, elevated or a wall of sufficient mass is placed between the highway and the receiver, the following additional parameters need to be considered.

a. Relative pavement - receiver elevation--The vertical distance between the pavement surface and receiver height.

b. Wall height and type--the height of a wall (if present) and its type (infinite, semi-infinite, finite).

c. Shield position--The location of the shield relative to the receiver plus the subtended angle if the shield is not infinite in length (equal to or greater than 8 times the perpendicular distance between receiver and shield).

In the case of a depressed highway, the distance from the cut to the receiver is used.

Environmental Noise Parameters

Subjective (consciously perceived) effects. Irritation and annoyance by traffic noise to the receiver are caused by:

a. The intensity or sound pressure level;
b. The frequency spectrum of sound;
c. The time - variance character of sound

Traffic noise parameters a and b are adequately handled by measuring and/or calculating the sound in terms of the A-weighted sound pressure level. Parameter c relates to the fact that highway noise is seldom constant; it is different for different periods and intervals of time.

Traffic Noise Parameters

The major source of highway noise is emitted from two types of highway vehicles (13, 14):

a. Automobiles' noise emissions increase relative to the third power of their road speed;

b. Diesel trucks are noisier than automobiles by the nature of their present design, but their emitted noise is not related to road speed because of maintenance of constant engine rpm provided by the use of reduction gears at different road speeds.

Traffic parameters which affect our prediction are:

Vehicle volume - total number of vehicles passing a definite point;

Vehicle mix - proportion of trucks in the traffic population;

Average speed of vehicles.

Roadway characteristics

Generally five parameters define the geometry of roadway elements being analyzed:

a. Pavement width (number of main traffic lanes),

b. Vertical alignment (elevated or depressed, with respect to the surrounding terrain),

c. Traffic flow (steady or stop-and-go, which calls for changing vehicle speed--breaking and acceleration),

d. Percent of gradient, and

e. Pavement surface, which describes its roughness.

Receiver characteristics. Receiver's physical location relative to the roadway element--perpendicular distance to the element, ear height above or below the surface of element, angle subtended from receiver to ends of element; shielding between receiver and the element.

Procedure for Solution to Problem

Attack on a noise problem is to work from a reference noise condition, which is adjusted by parameters that affect the noise environment. From a practical consideration of the reference noise level (worst case), the receiver is placed 100 feet from the road at grade and with no shielding present. This reference noise level is measured as a median level called L_{50}. (The 50% level is that level which is exceeded 50% of the time).

A manual method is presented that will enable a highway designer to evaluate traffic noise in an area adjacent to a highway (13).

The solution, for an illustrated example, is shown in figures 2, 3 and 4 of this thesis and design aids are given in "A Design Guide For Highway Engineers," appendix A, section three (13).

To evaluate computed noise levels, compare line 14 of figure 4 to the probable complaint to expect shown in figure 5.

Once the expected noise level at the receiver is known, its meaning must be evaluated in terms of a predetermined noise criteria. If the evaluation shows the proposed highway design to be undesirably noisy or to cause significant protest, the highway designer must modify his design until re-evaluations are within acceptable limits of all concerned.

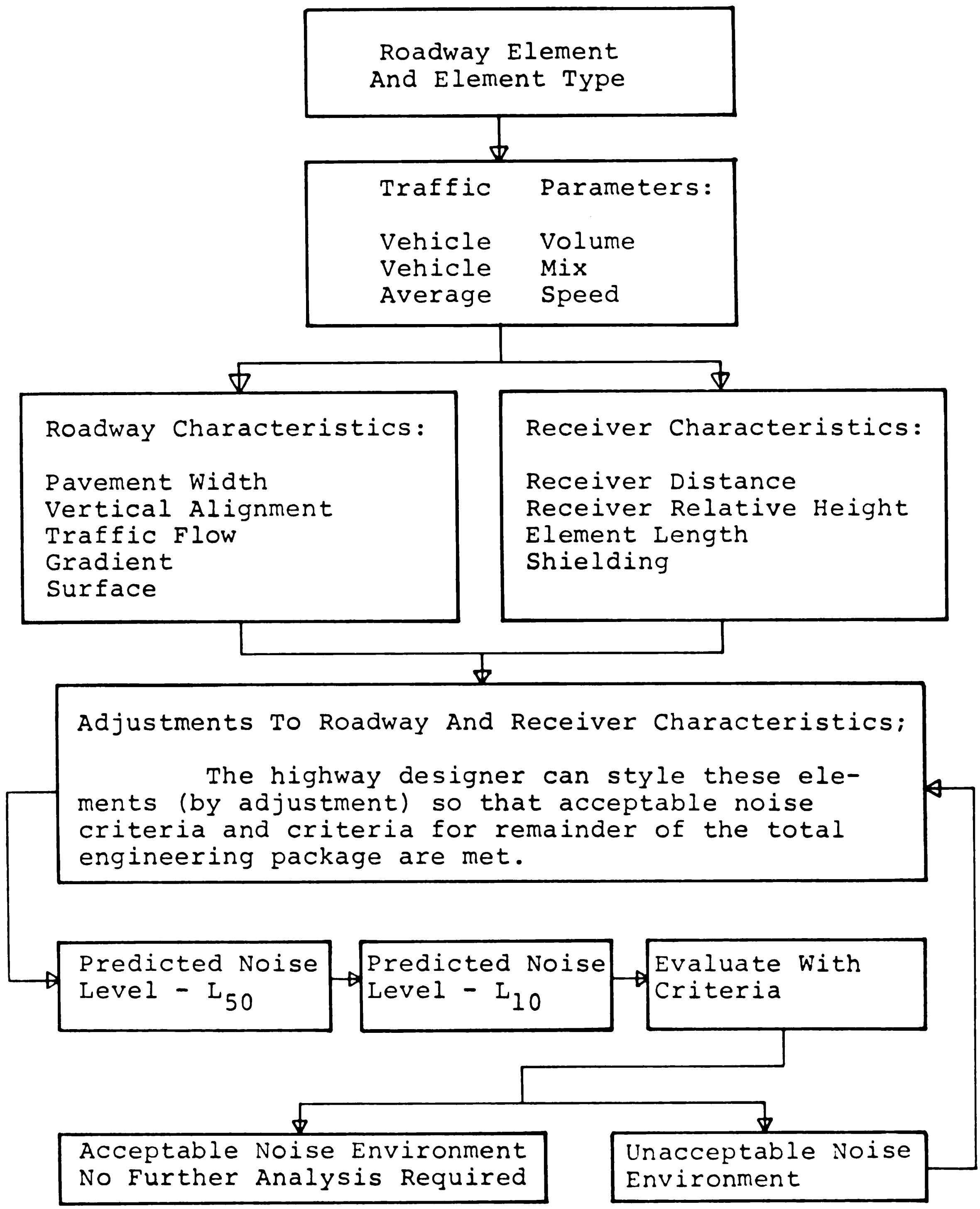

Figure 2.--Flow Diagram for Noise Level Prediction (13).

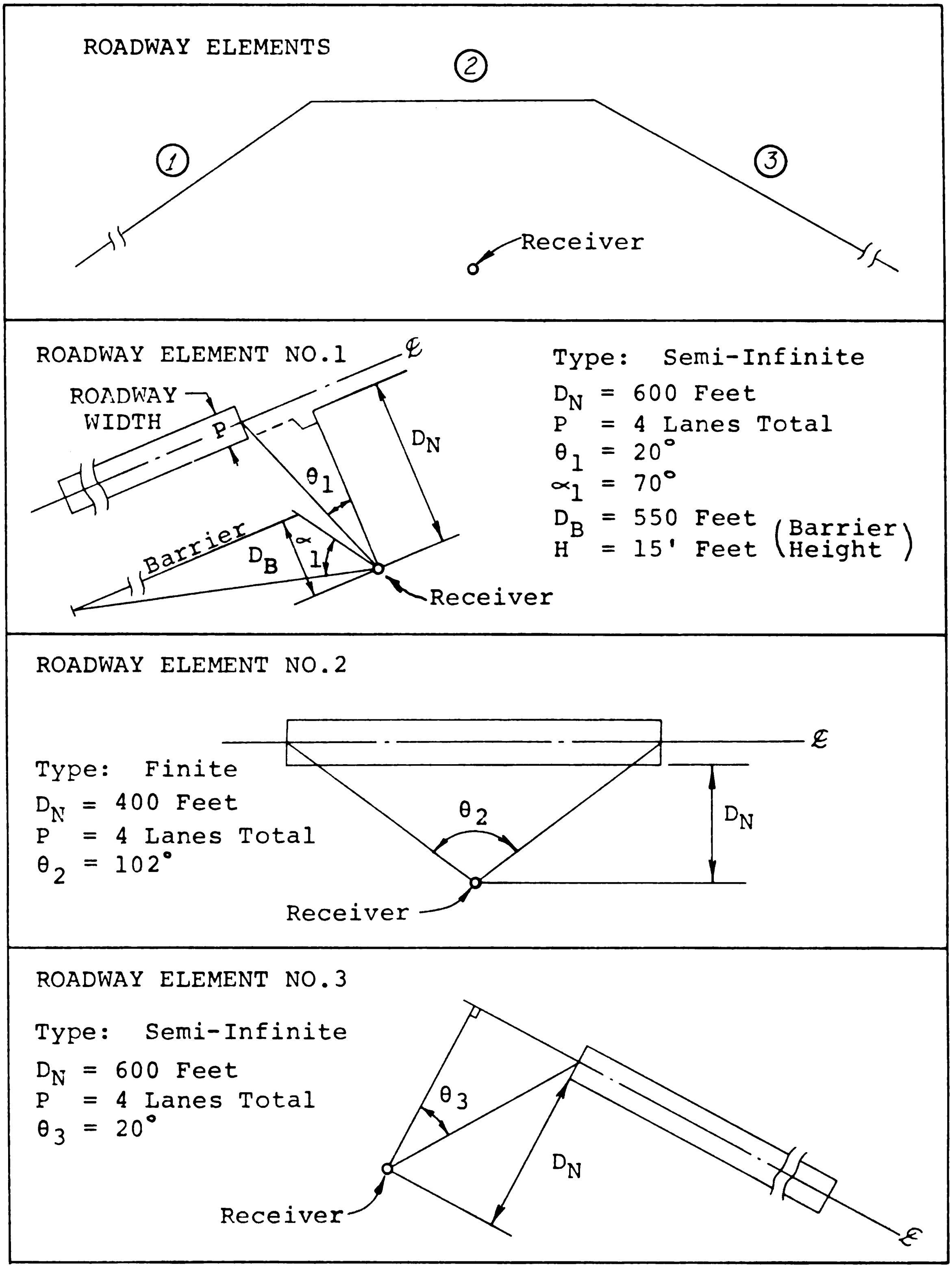

Figure 3.--Illustrated Example of Noise Level Prediction (13).

Data:

4 - Lane, normal surface, free flow traffic, 100,000 ADT, 5% truck/auto mix, speed auto 60 and truck 50 mph, vehicle volume between 8-10 a.m. 7% ADT, % grade - level and clear terrain between receiver and all elements.

ACOUSTIC CHARACTERISTICS	Line	Symbol	Ref.	ROAD ELEMENT			1		2		3	
						Number	1		2		3	
						Type	II		III		II	
				TIME INTERVAL			8-10 a.m.		8-10 a.m.		8-10 a.m.	
				VEHICLE TYPE			Auto	Truck	Auto	Truck	Auto	Truck
	1			Reference L_{50} at 100 ft			73	72	73	72	73	72
	2	Δ_1		ADJUSTMENT	Distance		-11	-11	-9	-9	-11	-11
	3	Δ_2			Element		-4	-4	-2	-2	-4	-4
	4	Δ_3			Gradient		0	0	0	0	0	0
	5	Δ_4	W.S.3		Vertical		0	0	0	0	0	0
	6	Δ_5			Surface		0	0	0	0	0	0
	7	Δ_6	W.S. 4		Shielding	(a) Barriers	-15	-15	0	0	0	0
		Δ_7				(b) Structures and Plant.	0	0	0	0	0	0
	8			TOTAL ADJUSTMENT (add rows 2 through 7)			-30	-30	-11	-11	-15	-15
	9			L_{50} AT RECEIVER (add row 1 to row 8)			43	42	62	61	58	57
	10		W.S.5	L_{10} - L_{50} ADJUSTMENT			+1	+4	+1	+4	+1	+4
	11			INTERRUPTED ADJUSTMENT			0	0	0	0	0	0
	12			L_{10} AT RECEIVER (add row 10 & 11 to row 9)			44	46	63	65	59	61
	13		W.S.6	ELEMENT TOTAL		L_{50}	46		65		59	
						L_{10}	48		67		63	
	14		W.S.6	GRAND TOTAL			L_{50} = 66 dBA			L_{10} = 69 dBA		
	15						$L_{10} - L_{50}$ = 3 dBA					

Figure 4.--Worksheet of Illustrated Example of Noise Level Prediction (13).

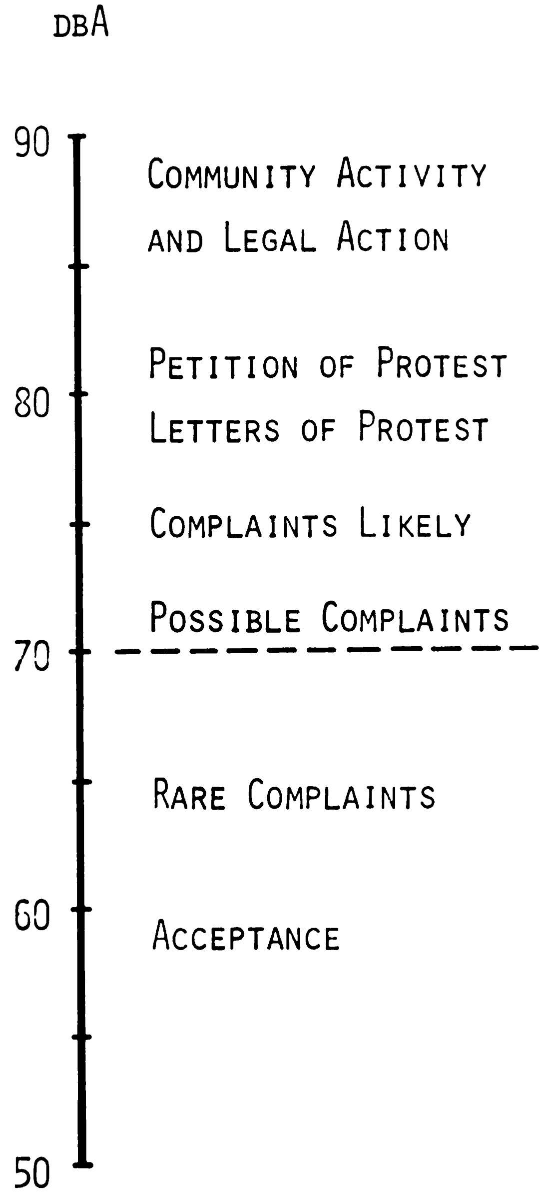

Figure 5.--Noise Levels and Probable Receiver Protests (2).

Summary

Highway noise impact prediction is now a reality. Prediction can be either for shielding an area or analyzing a problem area in detail. Prediction has also been computerized for fast and inexpensive investigations. Highway designers can now use judgment, based on quantitative analysis, for noise prediction and noise reduction techniques. What is needed now is acceptance of a design criteria and its "cookbook" application to traffic noise.

Cost of noise control can add some .4% - .6% to total project cost and this is not insignificant, but neither are the benefits.

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