ing the mixing cell on the highway side under the conditions of low wind speed and high atmospheric stability. Conversely, as the atmospheric stability is decreased or the crosswind speed is increased beyond a certain level for west winds and equivalent emissions, or both, the carbon monoxide levels are higher when the noise wall is in place. This suggests that a higher-than-expected concentration of carbon monoxide is occurring near the wall because of aerodynamic entrapment.

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Caltrans Experiences with Earthborne Vibration

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ABSTRACT

An overview of vibration investigations performed by the California Department of Transportation since 1958 is presented. These investigations involved measurement of earthborne vibrations induced by highway vehicles, construction equipment, and train passbys. All of the investigations indicated vibration levels below the criterion established for architectural damage (plaster cracking). However, pile driving and pavement breaking were potential problems and monitoring was suggested for these situations. Two case studies are also presented, one on a train passing near a machine shop and a second on a new freeway alignment near a manufacturing plant.

Since 1958, the California Department of Transportation (Caltrans) has conducted more than 40 investigations of earthborne vibrations induced by construction equipment, highway vehicles, and train passbys. All of these investigations were performed because of complaints or concerns about adverse impacts on activities inside buildings or damage to buildings. Earthborne vibrations are caused by construction activities from pile driving, pavement breaking, and moving construction equipment. Vibrations generated by highway truck traffic become a problem when the pavement is rough (potholes) or because of stepped joints. Train passbys also create earthborne vibrations.

Presented in this paper are some of the fundamentals of earthborne vibrations, guidelines for assessing their impact, Caltrans experiences over 26 years, and some case histories.

FUNDAMENTALS OF EARTHBORNE VIBRATIONS

Earthborne vibrations are mainly from P-waves (compression), S-waves (shear), and Raleigh waves (surface). The Raleigh waves are generally the problem and are used by Caltrans in its studies.

Peak particle velocity within the range of normal earthborne vibrations correlates best with architectural damage and intrusion, whereas acceleration and displacement do not. Therefore, the peak particle velocity (in in./sec) is used as the descriptor for Caltrans studies. Particle velocity is further defined to mean the vertical velocity at which the soil particles or other materials vibrate locally as opposed to the propagation velocity of vibrations. The latter is the speed at which vibrations travel through the ground away from the source.

GUIDELINES FOR ASSESSING IMPACT OF EARTHBORNE VIBRATIONS

No single standard exists for assessing the level at which earthborne vibrations will cause annoyance to people, cause architectural damage (plaster cracking), or be disruptive to precision operations. However, Table 1 shows guideline velocities (in in./sec) from various sources. Caltrans uses the guidelines established by Whiffin and Leonard of the Road Research Laboratory in England (1).

Instrumentation

The following instruments were used to collect vibration data:

4 seismometers (Kinemetrics Ranger SS-1)
1 signal conditioner (Kinemetrics SC-1)
1 graphic level recorder (Clevite Brush 16-2300-00), oscillograph

TABLE 1 Selected Vibration Criteria

Reference or Authority	Threshold of Perception	Annoyance	Architectural Damage Risk Level	Minor Architectural Damage Likely, Structural Damage Risk Level	Remarks
Whiffen and Leonard *(1)* (used by Caltrans)	.0059-.0188 (peak)	.0984 (peak)	.1968 (peak)	.3937-.5905 (peak)	For continuous vibrations
FHWA-RD-78-166 *(2)*	.0054 (RMS) (.0077 peak)	.0306 (RMS) (.0433 peak)		.0967 (RMS) (.1368 peak)	8 to 80 Hz for continuous vibrations
Committee on Hearing, Bioacoustics, and Biomechanics Assembly for Behavioral and Social Sciences *(3)*	.0040-.0051 (RMS) (.0057-.0721 peak)	.0056-.0110 (RMS) (.0079-.0156 peak) Depending on time of day			8 to 80 Hz for continuous vibrations
Bureau of Mines *(4)*			2.0 (peak) Single blast	5.4 (peak) Single blast	Single events
ANSI S 3.29 (1983) S 3.18 (1979)	.0039 RMS (.0055 peak) For sensitive persons .0078 RMS (.0110 peak) For average persons	.0039-.0156 (RMS) (.0055-.0221 peak)			8 to 80 Hz for continuous vibrations

Note: Velocities given in parentheses were converted from other descriptors.

The equipment is calibrated using a shake table as shown in the schematic in Figure 1.

CALTRANS EXPERIENCES

The Caltrans Transportation Laboratory (TransLab) has performed investigations throughout California involving the following situations:

- Private residences
- Manufacturing plants
- Aerospace companies
- Machine shops
- Art gallery
- Movie studio
- Computer company
- Historic site
- Pile driving
- Pavement breaking

Of the more than 40 investigations, all have been resolved. Two cases went to trial with no monetary award in one case and a $25,000 judgment against Caltrans in the second. The second involved highway vibrations that affected a machine shop.

Measurements of Vibrations Induced by Highway Vehicles

Highway vehicles that induced earthborne vibrations were trucks, buses, and a Caltrans lowboy. The weight of the lowboy was 9,560 lb (front axle 1), 24,380 lb (tractor axle 2 and 3), and 35,160 lb (trailer axle 4 and 5); the total weight was 69,100 lb. On occasion, a loaded dump truck (50,000 lb) was run over 2 x 6-in. boards placed on the pavement and spaced at 25-ft intervals to simulate a worst-case situation. Measurements were taken over a broad spectrum of highway structures, cuts, fills, and level sections of highway. The soil type covered a wide range of geologic formations.

Figure 2 shows the data from the measurements, all of which were all below the architectural damage level of .1968 in./sec.

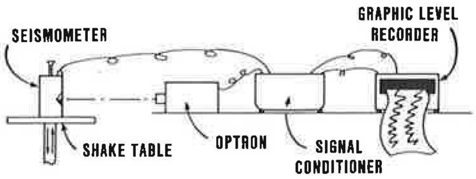

FIGURE 1 Schematic of calibration setup.

Measurements of Vibration Induced by Construction Equipment

Figure 3 shows a plot of earthborne vibrations induced by highway construction equipment versus various distances from that equipment. The largest vibrations were caused by an EMSCO pavement-breaking machine. Velocities of 2.88 and .275 in./sec were recorded at distances of 10 and 38 ft; these were the highest velocities measured in the more than 40 studies to date. Vibrations from a Caterpillar D8 and D9, Caterpillar earthmover, Euclid earthmover, and drilling piles were all below the architectural damage level of .1968 in./sec. In general, it appears that the earthborne vibrations from construction equipment were not high enough to cause architectural

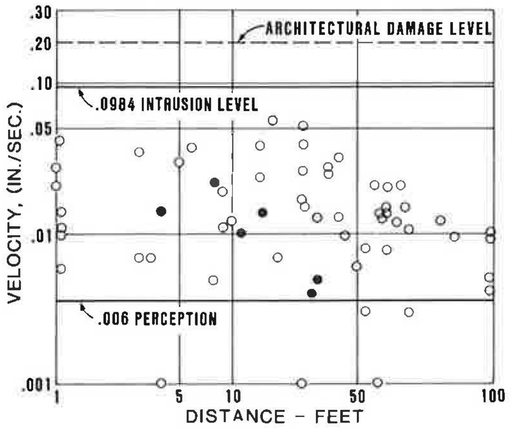

FIGURE 2 Measurements of vibrations induced by highway traffic.

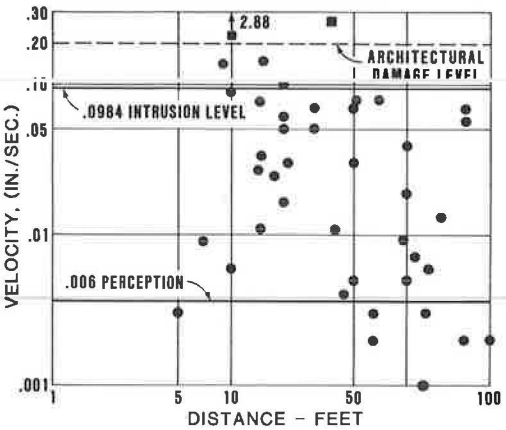

FIGURE 3 Measurements of vibrations induced by construction equipment.

damage. However, vibrations from pavement-breaking and pile-driving machines are potentially damaging and should be carefully monitored when working close to sensitive receptors.

Measurements of Vibrations Induced by Trains

Figure 4 shows a plot of earthborne vibrations induced by train passbys versus various distances from those passbys. All of the vibration levels were below the architectural damage level of .1968 in./sec.

In-House Vibrations

Normal activities associated with living in and maintaining a home give rise to vibrations that are, in some instances, capable of causing minor damage to plaster walls and ceilings in localized sections of the building. Vibration levels of various activities measured in residences are shown in the following table.

Activity	Velocity (in./sec)
Washer and dryer	.004 to .005
Walking	.008 to .187
Door closing	.010 to .056
Jumping	.219 to 5.000

All of the vibration levels except jumping are within the range of measurements of earthborne vibrations induced by transportation vehicles. Jumping in a room generates vibrations that are potentially damaging; however, the large amplitude vibrations resulting from jumping are localized and generally do not affect the entire building as earthborne vibrations do. Thus, although the potential for causing vibrations is present, it is confined to a small specific area and the probability of damage is therefore reduced.

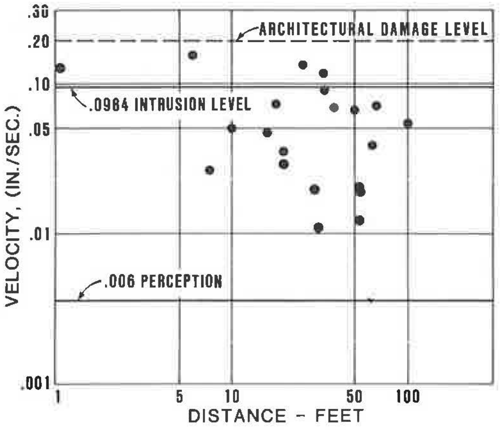

FIGURE 4 Measurements of vibrations induced by trains.

Earthborne vibrations appear to be an improbable cause of architectural damage. For residential construction, the cracking of plaster walls, ceilings, and exterior stucco is generally caused by foundation settlement, alternate shrinking, expansion due to moisture and temperature, and earthquakes.

CASE STUDY 1: VIBRATION STUDY AT KAISER

On December 23, 1980, vibration measurements were made at the Kaiser Aerospace and Electronics Company, located in San Leandro, California (Figure 5). A railroad drill track was to be relocated close to the Kaiser Aerospace Building. The initial study in 1978 indicated that earthborne vibrations from trains running on the proposed railroad track would be insufficient to adversely affect Kaiser's precision machining operations for the aerospace industry. The railroad track was constructed late in 1980.

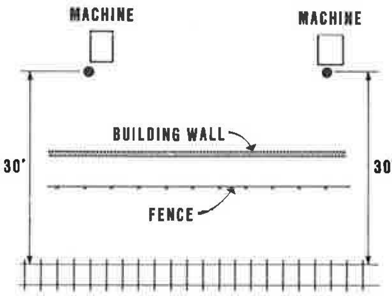

FIGURE 5 Plan of Kaiser plant.

On November 14, 1980, Kaiser Aerospace approved the Specifications for Machine Vibration Study, an in-house plan for evaluating effects of trains operating on the adjacent railroad tracks. This plan included things such as instrumentation, machining specifications, and actual cuts on materials while the train was operating on the tracks. Follow-up measurements of vibrations were made on December 23, 1980, to evaluate whether Kaiser's concern about earthborne vibrations induced by trains running on this track was valid.

Caltrans personnel observed Kaiser's operations but could not detect any adverse effects from train operation. Figure 1 shows the distances and locations of the TransLab seismometers that were used to measure earthborne vibrations from the train to Machine 386 and Machine 553. Measurements were made while the machines were making cuts without the trains, with the trains running 5 to 10 mph, and during a coupling operation (Table 2). The train consisted of one locomotive and five fully loaded cars.

Analysis of the data indicated that earthborne vibrations from the train to Machine 386 and Machine 553 were slightly lower than reported during the first study. The conclusions during the first and current study indicate that earthborne vibrations

TABLE 2 Kaiser Aerotech Summary of Vibrations

	Peak Vertical Velocity (in./sec)			
	Machine 553		Machine 386	
	Inside	Outside	Inside	Outside
Machine cut only	.0028	.0026	.0054	.0045
Train and machine cut, steady speed	.0106	.0455	.0195	.0717
Train and machine cut, coupling	.0138	.0569	.0170	.0372
Ambient, no train machine idling, no cut	.0011	.0015	.0011	.0012

Note: Measurements were made on December 23, 1980.

from the train are insufficient to adversely affect Kaiser's machining operation.

CASE STUDY 2: VIBRATION STUDY AT WESTERN GEAR CORPORATION

Case Study 2 was performed in response to concerns expressed by officials at Western Gear Corporation, Lynwood, Calfiornia, that vibrations originating from equipment and traffic during and after construction of Route 105 might disrupt the plant's precision machining operations (Figure 6).

On March 28, 1984, vibration measurements were taken inside the operations building of Western Gear Corporation and at an outside test area approximately 0.4 mile south of Imperial Highway along Alameda Street. At the outside test site, vibrations were generated by a fully loaded water truck (approximately 25 ton gross vehicle weight) driving at 35 mph across five wooden 2 x 4-in. boards spaced 25 ft apart to simulate construction activity. During the runs, vibrations were measured at seven locations to a distance of 300 ft from the test truck. Figure 7 shows a plan of the measurement site and Figure 8 gives the vibration field test data. Attenuation ratios were calculated from the measurements and combined with freeway and construction data measured in previous Caltrans studies (Figure 9). This information was used to estimate maximum expected vibrations at Western Gear Corporation during and after construction of Route 105. These vibrations were compared with measured existing vibrations made on the Western Gear Premises (Figure 10).

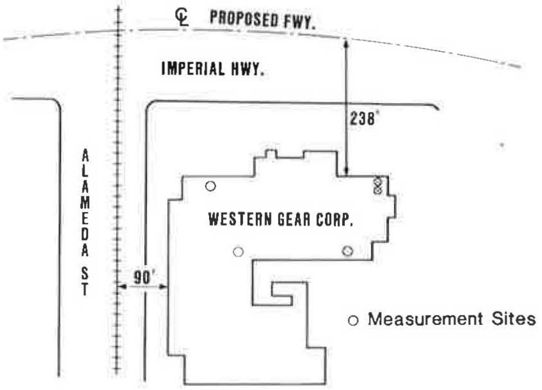

FIGURE 6 Plan of Western Gear Corporation.

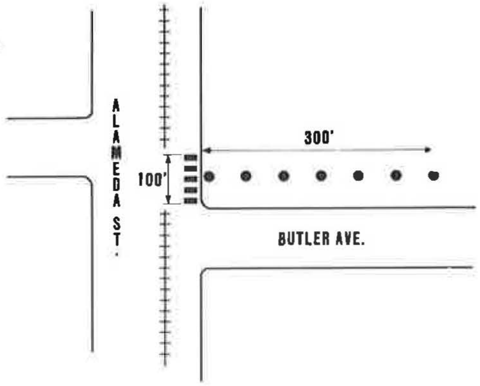

FIGURE 7 Plan of measurement site.

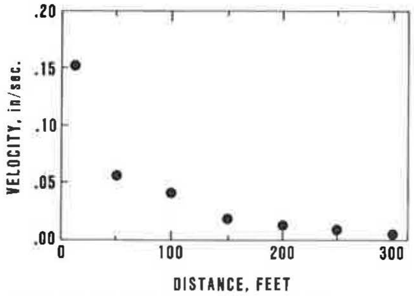

FIGURE 8 Vibration field test data.

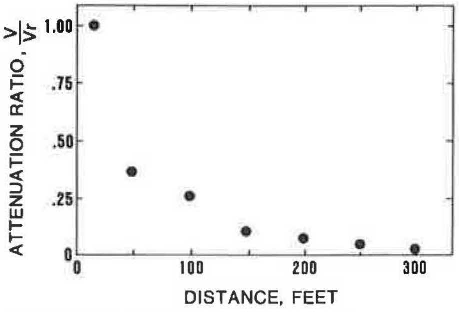

FIGURE 9 Vibration test data ratios.

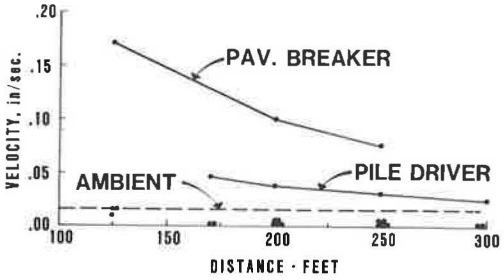

FIGURE 10 Estimated vibration levels.

From the measurements, it can be concluded:

- Vibrations induced by traffic on Route 105 will be far below vibrations currently experienced inside the machine operations building.
- Vibrations induced by construction equipment also will generally be lower than the existing vibrations inside the building. However, if pile drivers or pavement breakers are going to be used near Western Gear Corporation, vibration monitoring at less sensitive locations first is recommended for determining if the vibration levels will be acceptable for Western Gear operations.

CONCLUSIONS

1. Earthborne vibrations induced by highway traffic, construction equipment, and train passbys are below the architectural damage level of .1968 in./sec.
2. Earthborne vibrations cause annoyance to occupants of residences. This generally occurs when occupants are sleeping or engaged in a quiet activity such as reading with nothing else going on (washer, dryer, etc.)
3. Pavement-breaking machines produce vibrations exceeding the architectural damage level of .1968 in./sec. Discretion needs to be applied when used close to sensitive receptors. Although data on pile driving were not collected in sufficient numbers, it is believed that this can also be a problem.
4. In-house activities often create larger building vibrations than those caused by earthborne vibrations.

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