NBSIR 77-1241

Seismic Detection of Motor Vehicles

James M. Kenney

Institute for Materials Research
National Bureau of Standards
Washington, D.C. 20234

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PREFACE

Highway measurements were made by permission of the Maryland State Highway Administration. The vibration sensors used were fabricated by S. Roth, P. Freeze, and S. Edelman. The work was supervised and assisted by S. Edelman.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

The use of raised reflective markers on the pavement to supplement the painted lines separating lanes on highways has proven quite effective in southern areas. In northern areas, however, their use has not been feasible due to their vulnerability to destruction by snowplows. While efforts are underway to modify the design of the markers to protect them from snowplows, the Federal Highway Administration of the Department of Transportation is also investigating the feasibility of using flush-mounted electric lights as active-source substitutes for the (passive) reflectors. In order to conserve power, particularly if batteries were used, it would be desirable to have these lane-marker lights lit only when vehicles were near. The National Bureau of Standards was asked to determine if it were technically feasible to trigger these lights by seismic means, i.e., by the detection of road vibration induced by an oncoming vehicle.

MEASUREMENT PROCEDURES AND RESULTS

A search of the literature revealed no previous experimental work in the detection of pavement vibration induced by motor vehicles. The preliminary phases of this study were therefore necessarily engaged in the establishment of suitable techniques for the detection and analysis of such vibration. The first objective of this effort was to determine the presence of vibration at distances suitable for the illumination of lane marker lights. The DOT-established minimum distance for this purpose is 25 metres (82 feet), with a design goal of 50 metres (164 feet), for a vehicle of 900 kilograms (2000 lbs) travelling 50 kilometres per hour (30 miles per hour).

The earliest measurements were made using battery-powered ac meters and preamplifiers. These proved of little value due to the long meter response time relative to the passby time of even a slow vehicle. Useful experience was obtained during these measurements, however, in the establishment of reliable sensor bonding techniques and in suitable sensor design. The most satisfactory type of sensor for this purpose was a ceramic (lead zirconate titanate) piezoelectric double disc, 2 1/2 cm (1 in) in diameter, 6 mm (1/4 in) thick, and with a mass of about 29 g (1 oz). A description of piezoelectric sensors is given in the Appendix. A quick-setting gypsum plaster was used to bond this ceramic disc to the road, and also to bond a metal "seismic" (reaction) mass of about the same diameter to the opposite (top) side of the disc. This mass, of about 150 g (1/3 lb) and 24 mm thick, together with the mass of the ceramic, served to convert acceleration to force. A heavy metal shield covering the sensor was also bonded to the road with plaster, to provide isolation from airborne noise and electromagnetic pickup (ignition noise, CB transmission, etc.), reduce wind noise, and protect against precipitation. Wind noise, in particular, was found to produce large spurious signals from any type of unshielded sensor, and appeared to be the limiting factor in amplifying signals from even a well-shielded one.

A battery-powered oscilloscope provided the first indication that vehicles could be detected at reasonable distances, but human reaction time made distance evaluation difficult.

Acquisition of a battery-powered instrumentation recorder enabled the first reliable (and permanent) evidence of detection distance to be presented. After some experimentation, the most satisfactory time-domain data was obtained (as shown in figure 1) by use of a 30 metre (100 foot) cable between the recorder and one preamplifier ("channel 2"); the input of the latter was connected to a piezoelectric polymer strip cemented to the pavement 30 metres "up-traffic" from the ceramic vibration sensor. This strip had an active area length of about 53 cm (21 in). A description of piezoelectric polymers is given in the Appendix. The pavement was asphaltic concrete (AC), with portland cement concrete (PCC) curbs retaining the soil of the surrounding broad lawns. (Some readers may be more familiar with the less technical terms "asphalt" or "blacktop" for this type of pavement.)

The right front and right rear wheels of a vehicle passing over the piezoelectric strip generated two very sharp pulses. (Diode limiters and cascaded attenuators were used to protect the preamplifier.) As may be seen from the lower traces in figure 2, these pulses are quite distinctive. The important thing to note in these oscillograms is that the road vibrations, shown in the top traces, exhibit an amplitude distinctly above the noise levels (approximated at the far left of the top trace) in the region where the wheel-spikes occur, thus demonstrating that the vehicle was detectable at the 30 metre distance.

From an analysis of the oscillograms of 13 single-vehicle passbys, it was estimated that in 9 of these the signal was perceptibly above the noise level just before the front wheels of the vehicle passed over the piezoelectric polymer strip. Average vehicle speeds over the 30 metre distance were estimated from the separation between the leading (front wheel) voltage spike and the apparent peak of the vibration transient envelope detected by the ceramic sensor. (A second piezoelectric polymer strip could have been used to more precisely mark the moment the vehicle passed opposite the ceramic sensor.) Average vehicle speeds ranged from an estimated 16 to 18 km/h (10 to 11 mph) (which produced a poorly defined transient envelope) to 73 km/h (45 mph) for two vehicles. Average speed for the 13 vehicles was 44 km/h (27 mph). Four vehicles had an average speed over 50 km/h (30 mph), all of which were judged easily detectable at 30 metres or more. Of the four vehicles judged not detectable (or questionable), two were the slowest. Of the seven vehicles with speeds of 33 km/h (21 mph) or over but less than 50 km/h (30 mph), five were judged detectable

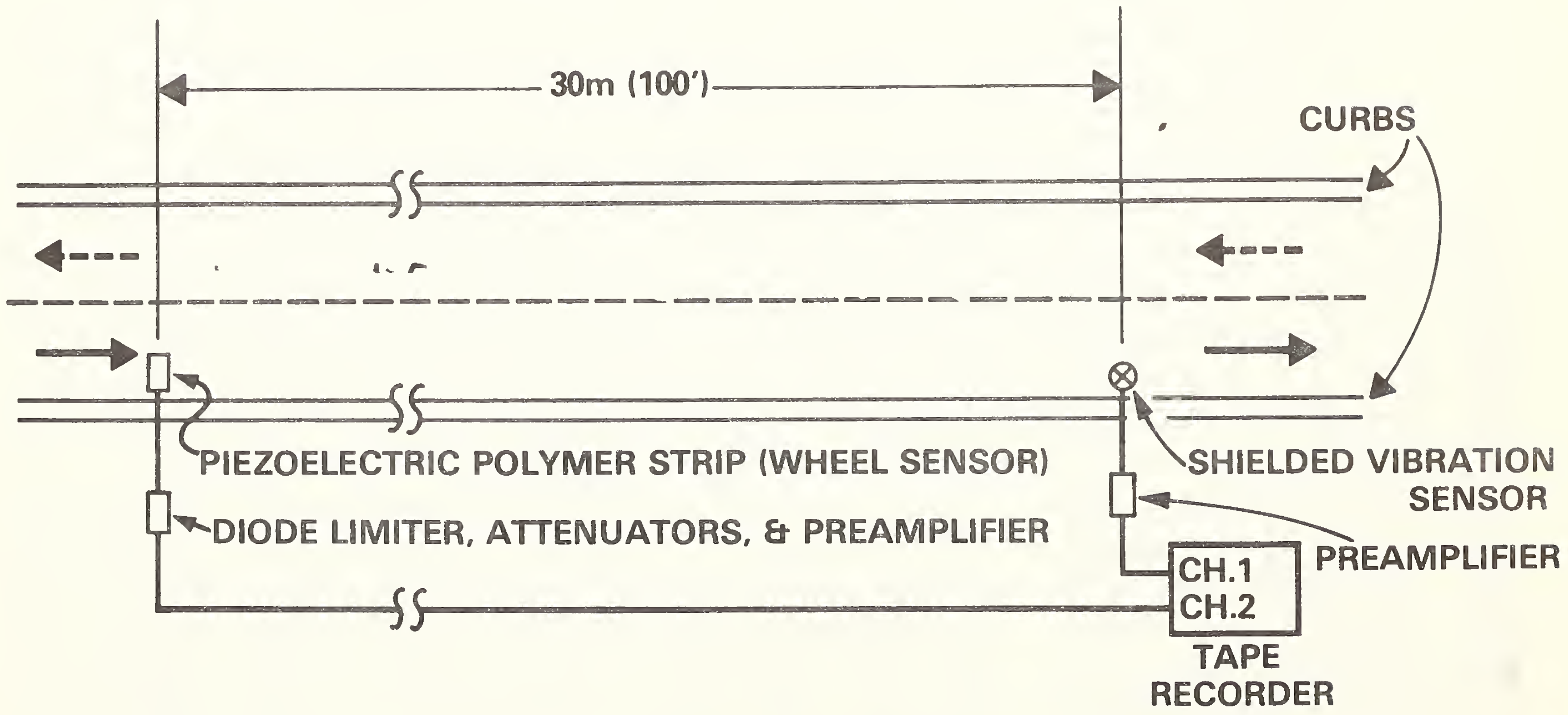
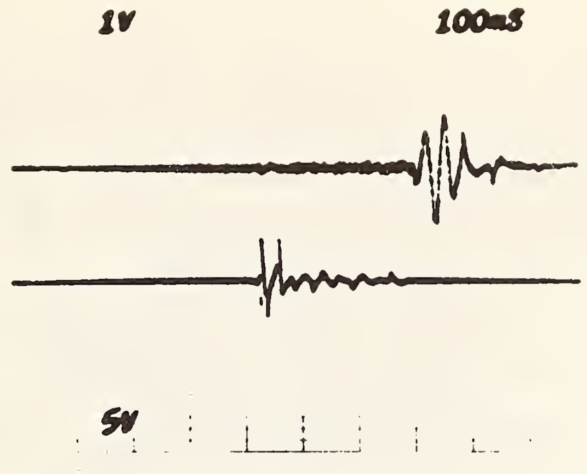
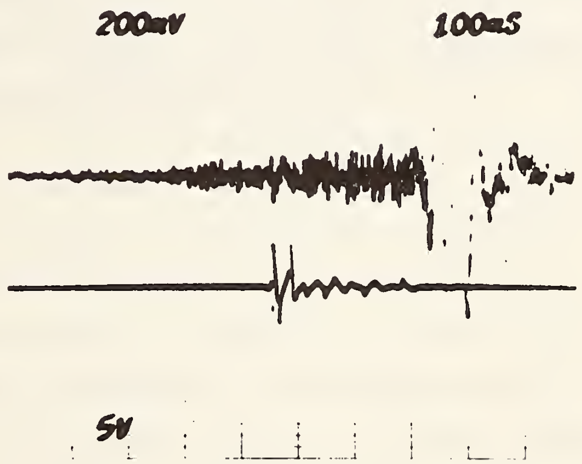


FIGURE 1. Set-up for single-vehicle (time-domain) road vibration measurements. Right wheels of vehicle (going from left to right in figure) passing over piezoelectric polymer strip generated a distinctive pair of narrow pulses, thereby recording when vehicle was 30 m (100') from sensor, and also permitting an estimation of average vehicle speed (see figure 2).



(a) Low gain for ceramic sensor output (top trace) shows passby transient at its highest amplitude.



(b) High gain for ceramic sensor output shows that transient is above noise level (leftmost part of top trace) when vehicle is more than 30 metres from ceramic sensor, indicated by pair of narrow wheel spikes in the output of the piezoelectric polymer strip at this distance (bottom trace).

FIGURE 2. Typical time domain recording of single vehicle passby on undivided AC* secondary road (on NBS grounds). Top trace in each photo is output of shielded ceramic sensor; bottom trace is output of piezoelectric polymer strip 30 metres from ceramic sensor passed over by right wheels of vehicle. Vertical scaling is arbitrary; horizontal scale is 0-10 seconds (1 second per major horizontal division) due to 10:1 increase in tape speed on playback. Estimated speed of vehicle is 33 km/h (21 mph).

* Asphaltic concrete (no portland cement concrete underlayer).

at 30 metres. The fastest in this speed range, however, was not, possibly being an unusually light vehicle. (Vehicle types were not correlated with transients: most, however, were ordinary passenger cars.) From these measurements it was concluded that the probability of detection with even a relatively unsophisticated trigger circuit would be quite high.

The next stage was to attempt a frequency analysis of the signal in order to determine the passband requirements for a seismic switch. After considerable effort had been expended in capturing passby transients in the spectrum analyzer and matching their spectra with time-domain oscillograms, it was found that the observed spectral structure was poorly defined, and was not reproducible from one passby to another. Most importantly, it was not feasible to obtain a spectrum from only that part of the transient when the vehicle was at a distance from the sensor. It was found, however, that distinctive and reproducible vehicle vibration spectra could be built up to significant amplitude by spectrum averaging -- a valuable feature of the analyzer used. To separate useful signal (sensor output) from instrumentation noise, channel 2 of the recorder was used as a noise reference, matching that of channel 1, which was used for the sensor signal, as shown in figure 3 where the small separation between traces is due to slightly greater noise from the reference channel. Of four available preamplifiers, two were chosen which by adjustment of channel gain matching pots (provided in the preamplifier-to-recorder adaptors to compensate for microphone sensitivity differences) would allow the closest match of instrument noise between channels at the record-gain setting commonly used. Spectral analysis of the channel 2 "reference noise" was made from each length of tape from which a channel 1 signal analysis had been made. A dual averager memory in the spectrum analyzer allowed both spectra to be stored. They could then be photographed together by double exposure while being alternately displayed on an oscilloscope (the preferable method) or by a single long exposure with the analyzer alternating the two spectra in rapid sequence.

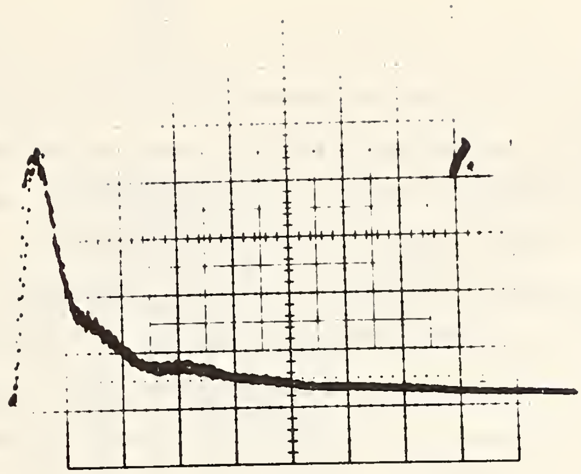


FIGURE 3. Average spectra, 0-50 Hz (5 Hz per major horizontal division). Noise match between channels. With no sensor at the input of either channel, the channel noise levels were matched to the degree shown. The sensor impedance is assumed to be sufficiently high at these frequencies as to have negligible effect. On this and all following spectrograms, the vertical deflection is linear with voltage; vertical scaling is arbitrary, but signal processing is identical for both channels. Horizontal scaling is linear with frequency. All spectra shown are average, covering very many individual spectra and many vehicle passbys.

The procedure used for most road vibration recordings was to connect the sensor and its preamplifier to the recorder with the 30 m cable previously mentioned, the sensor being down-traffic from the recorder, as shown in figure 4. The recorder was manned inside a vehicle parked just off the shoulder pavement of the road, from which position the tape could be rapidly stopped as vehicles passed opposite the car (initially) or (later) as they passed a safety cone set on the outer edge stripe of the nearest lane 50 m from the sensor. The tape was not restarted until the vehicles were at least those distances past the sensor, and with no others within ± 50 m of the sensor. Recordings were also made with the recorder in continuous operation. The sensor was bonded to the pavement directly on the outer edge stripe of the nearest lane, which is the nominal "edge" of the pavement of the road proper. (While usually paved, the shoulders of the highways used were at a somewhat lower level or were paved with somewhat different appearing material.)

To obtain an overall (record-reproduce cycle) frequency response down to about 2 1/2 Hz, most recordings were made at a tape speed of 3.8 cm/s (1.5 in/s) and reproduced at 38 cm/s (15 in/s), thus raising all frequencies by a factor of 10. The spectrum analyzer frequency ranges to be cited are one-tenth of the actual instrument range settings, thus referring to the original signal frequencies at the recorder input.

Examples of the average frequency spectra obtained from highway pavements in various locations by the above technique are shown in figures 5 through 10. It may be seen from these spectra that the signal (represented by the gap between the upper and lower traces in figures 5 through 9) peaks in the vicinity of 15 Hz (12 to 17 Hz). Although differing in fine detail, the general shapes of the spectra from pavements of different material or construction are similar.

The discrete spectral-lines in figure 9 demonstrate the possibility of false alarms due to seismic sources other than traffic or wind. Figure 10 indicates a high probability that the seismic switch would be activated by opposite-lane vehicles unless the threshold level for triggering was so high that the sensitivity to oncoming near-lane vehicles would be poor.

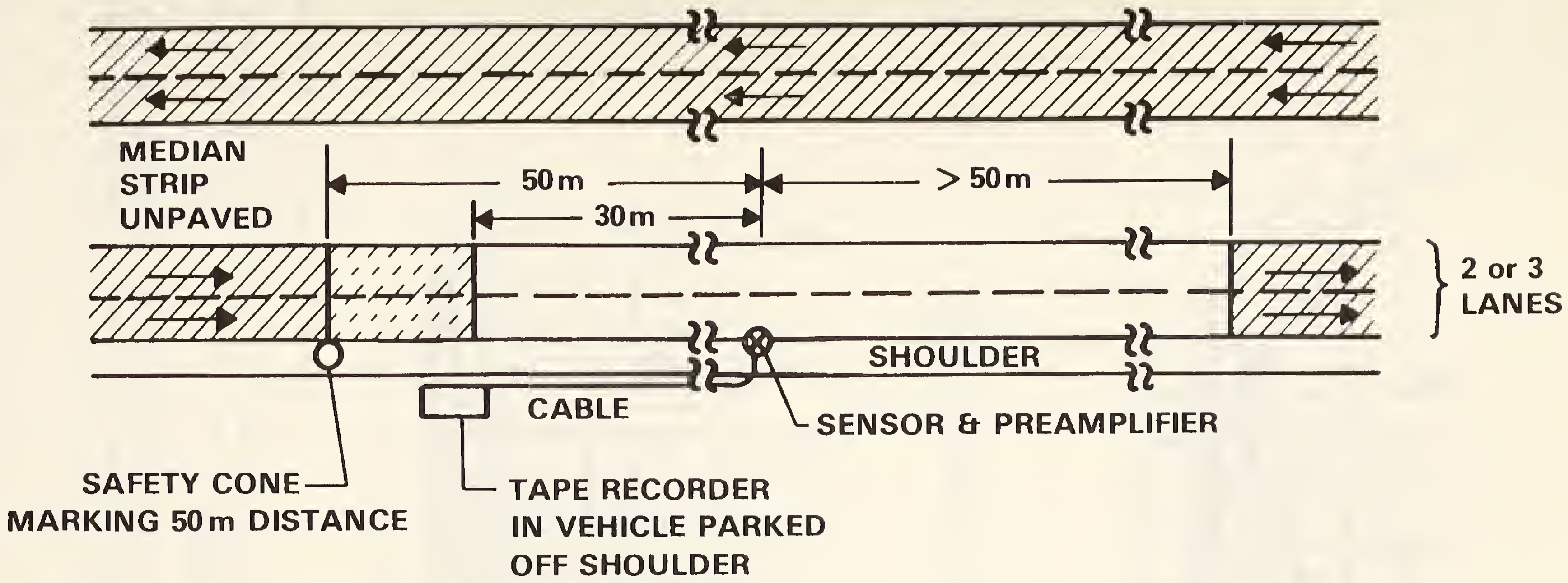
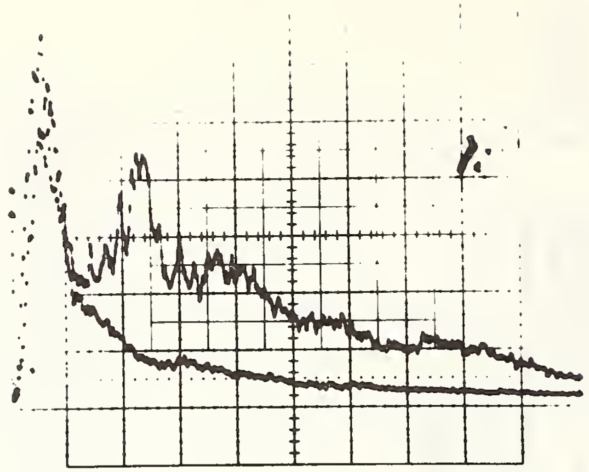
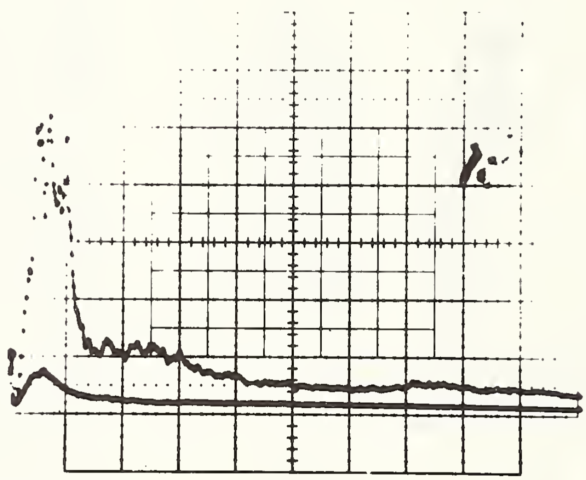


FIGURE 4. Set-up for multiple-vehicle (frequency domain) highway vibration measurements. For distant-spectra measurements (> 30 m or >50 m), tape recorder was stopped when any vehicle was within the unshaded area. Opposite lane traffic (beyond median strip) was disregarded; it was essentially continuous during all recordings, as simultaneous breaks in traffic in both directions were exceedingly rare.



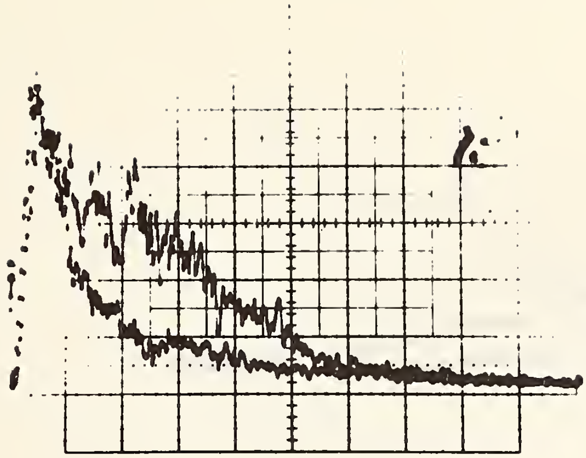
(a) Vehicles > 50 metres from sensor in either direction.



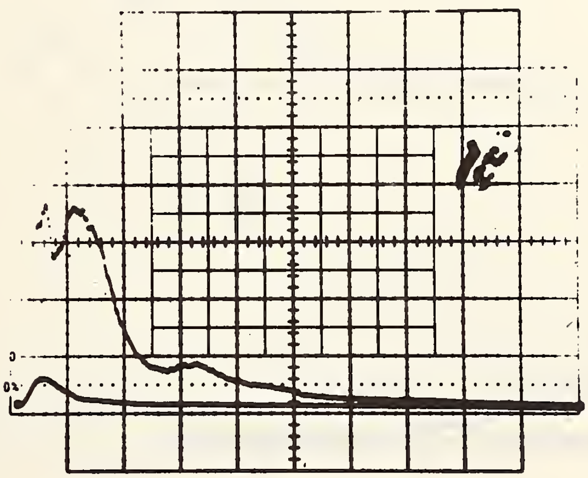
(b) Vehicles at all distances from sensor.

FIGURE 5. Average spectra, 0-50 Hz, from shielded ceramic sensor on divided segmented PCC* highway (MD-29). On these spectrograms, the bottom trace is the channel 2 reference noise.

*Portland cement concrete.



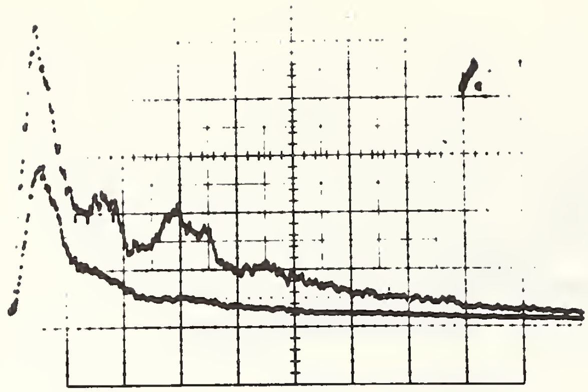
(a) Vehicles > 50 metres from sensor in either direction.



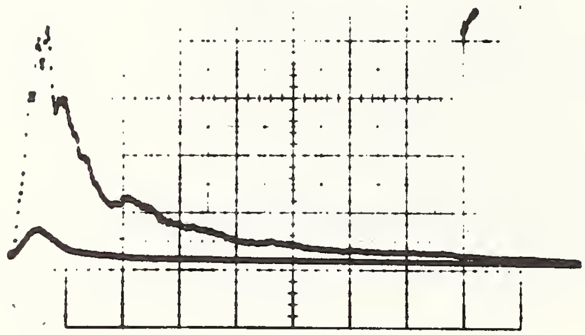
(b) Vehicles at all distances from sensor.

FIGURE 6. Average spectra, 0-50 Hz, from shielded ceramic sensor on divided unsegmented PCC* highway (I-95). On these spectrograms, the bottom trace is the channel 2 reference noise.

*Portland cement concrete.



(a) Vehicles > 30 metres from sensor in either direction.



(b) Vehicles at all distances from sensor.

FIGURE 7. Average spectra, 0-50 Hz, from shielded ceramic sensor on divided AC* highway (I-270). On these spectrograms, the bottom trace is the channel 2 reference noise.

*Asphaltic concrete (no portland cement concrete underlayer).

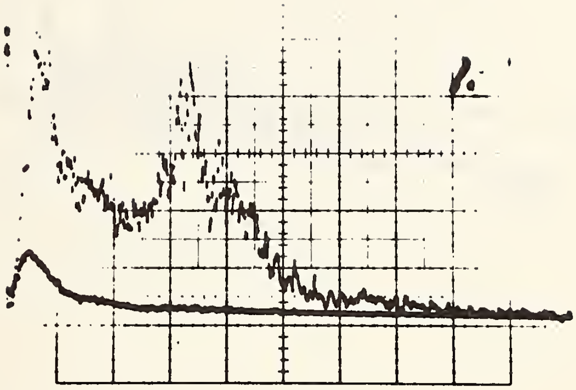
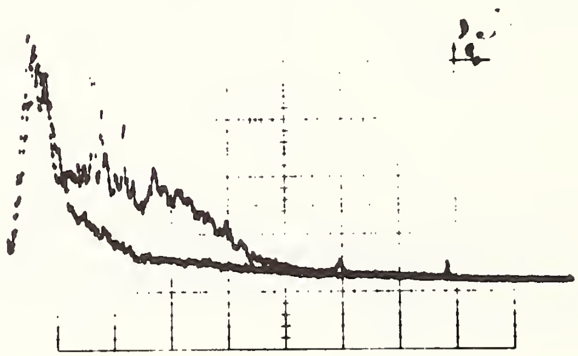


FIGURE 8. Average spectra, 0-50 Hz, from piezoelectric polymer sensor on segmented PCC* highway turnoff (unfinished extension of I-95). Vehicles > 30 metres from sensor in either direction. Rubber cement bond. On this spectrogram, the bottom trace is the channel 2 reference noise.

*Portland cement concrete.

(a) No near vehicles in either direction, including oppo~ite lane (on same pavement).



(b) Vehicles > 30 metres from sensor in either direction, including opposite lane.

FIGURE 9. Average spectra, 0-50 Hz, from shielded ceramic sensor on AC* secondary road (on NBS grounds). On these spectrograms, the bottom trace is the channel 2 reference noise.

*Asphaltic concrete (no portland cement concrete underlayer).

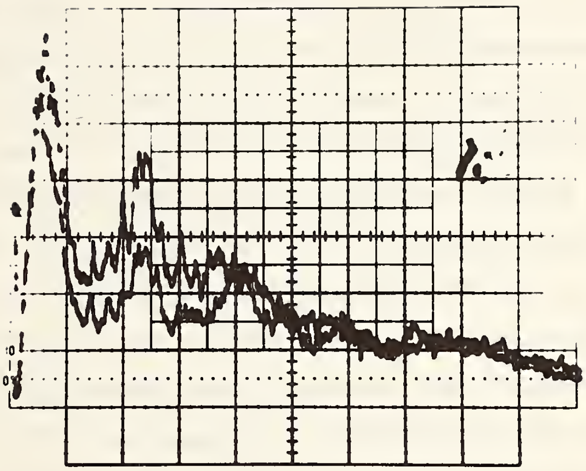


FIGURE 10. Average spectra, 0-50 Hz, from shielded ceramic sensor on divided segmented PCC* highway (MD-29). Top trace: vehicles > 50 metres from sensor in either direction; bottom trace: no close vehicles in either direction (except those in opposite lanes, in both cases, and for all other highway spectra).

*Portland cement concrete.

An effort was made to fabricate suitable piezoelectric sensors from polymer sheets (polyvinylidene fluoride). Designs included simple double-sheet sandwiches of various sizes and shapes (see Appendix) similar to the ceramic disc assembly with and without an added seismic mass, where the contacting electrodes from each sheet are connected to a cable center-conductor and are shielded by the outer electrodes which are connected to the cable ground. Also tried were multi-layer sandwiches with the layers connected electrically in series, and resonant sensors where the spring element in the mass-spring system was either an elastic foam pad or the elasticity of the piezoelectric polymer film itself. Most of these did not have a sufficiently large output relative to the amplifier or wind noise, or were found to be highly susceptible to pickup of 60 Hz power-line current and harmonics. (One exception is shown by figure 8). High resistance in the ground plane connections following repeated flexing (which cracked the conductive rubber used in the ground connection) was believed partly responsible for this pickup; poor insulation from the road surface was another factor (particularly during wet weather). The brass ground clip shown in the appendix drawing was added at a later date in response to this problem, but no measurements were made in this application using sensors having it. The wet pavement present during most of the polymer sensor measurements caused repeated bonding failures, making evaluation of these devices difficult.

These same problems also interfered with attempts to record traffic vibration in the soil alongside the road. A strong similarity was noted between the vibration spectra obtained with vehicles at 50 m and beyond, and those obtained with no near-lane traffic (i.e., those recorded with no near-lane vehicles in sight or with near-lane vehicles in sight but only at very much greater distances) as shown in figure 10. This suggested that soil transmission may be more significant than pavement transmission, since it was believed that the lower trace in figure 10 was due largely to opposite lane traffic, which was separated from the near lane traffic by a wide (unpaved) median strip. It was thought that a frequency selective soil transmission would also account for the similarity between average spectra obtained from highway pavements of greatly different construction, as shown by figures 5 through 9.

Attempts to measure soil vibration alongside a highway were made using various designs of piezoelectric polymer sensors. These were largely unsuccessful for the same reasons as noted above for pavement measurements. Even thorough wrapping with tape before burial generally failed to eliminate the strong 60 Hz pickup, and what appeared to be intermodulation products were observed about the 60 Hz spectral line in many oscillograms.

A ceramic sensor was buried alongside the road, after being wrapped in tape and plastic sheeting. To ascertain its acoustical effects, the soft insulation was cut away over the front face (opposite the reaction mass) of the ceramic disc and replaced with a rigid epoxy. This change had little effect, however. Except for amplitude differences, the corresponding spectra were essentially identical. An inexplicable shifting with time toward higher frequencies was exhibited by this sensor, following burial for three weeks. The stronger high frequencies could be due to better packing of the soil around the sensor, but this should not have reduced the low frequencies.

In all of the buried-sensor oscillograms, it was apparent that the detected spectra were quite different from those obtained from the pavement-mounted sensors, so that the shapes of the observed pavement-vibration spectra could not be attributed to the soil transmission properties. Lack of good reproducibility, however, limits the value of these observations.

Although the detection of vibration in the soil could not be accomplished with any degree of reproducibility, and though the mode of transmission of pavement vibration was not determined, there was confidence in the seismic detectability of motor vehicles based upon the time-domain oscillograms and upon the pavement vibration spectra. Accordingly, it was decided to proceed with the construction of a seismic switch to demonstrate the validity of this conclusion.

CONSTRUCTION OF A SEISMIC SWITCH (FEASIBILITY MODEL)

The sole purpose of the seismic switch (vibration-level detector) built at NBS was to prove that vehicles could be reliably detected at the established minimum or goal distances. No attempt was made to limit size, cost, or power consumption, or to make it rugged and reliable -- all factors necessary for ultimate field development. The circuit developed for this feasibility study is given in figure 11, but it cannot serve as a prototype for a production model, even for a very limited production run, since some of the components were expensive, bulky, and had a high current drain.

For successful use with the ceramic sensor used earlier for most of the vibration-spectra study, a broadly-peaked amplifier passband centered at 14 Hz, (measured, nominally 15 Hz) and down 10 dB at 5 Hz and 40 Hz (measured), with a measured center frequency gain of about 100 dB, proved satisfactory. Three op-amp stages were used: a non-inverting voltage follower followed by two ac-coupled stages of nominally 54 dB gain each. About 8 dB of overall gain at the 14 Hz center frequency was lost due to overlap of high and low frequency roll-off. The total amplifier noise was (very roughly) 60 mV at the output with the input shorted and 80 mV with the input open or, respectively, 0.6 μV and 0.8 μV referred to the input. With the ceramic sensor at the input, the best acoustic isolation of the sensor resulted in an output of about 150 mV, or 1.5 μV referred to the input. The noise was well below typical triggering levels and did not appear to be a significant factor in the detection-range vs. false-alarm-rate trade-off using this type of sensor.

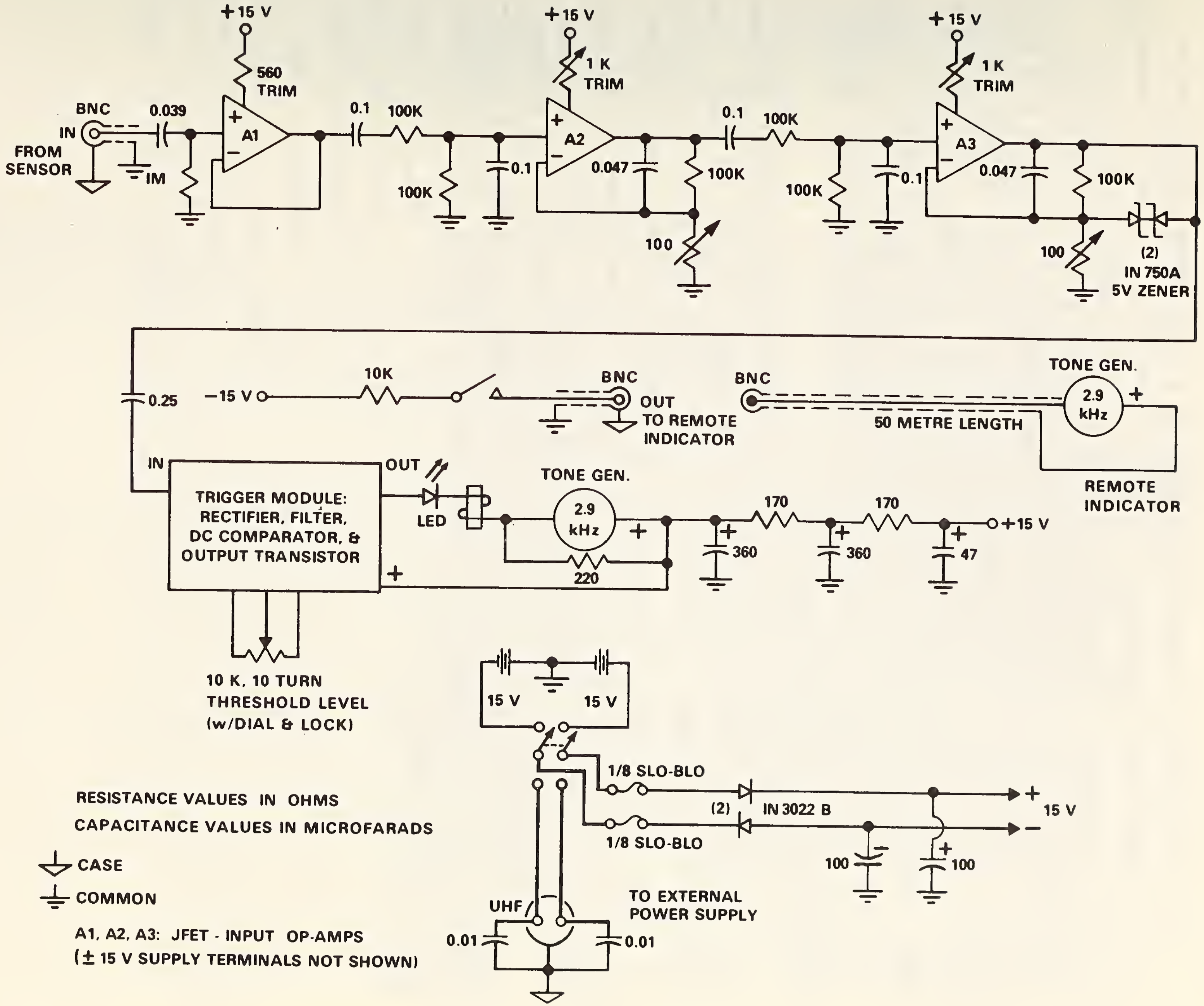


FIGURE 11. Schematic diagram of seismic switch

The tuned amplifier stages were followed by a zener-diode limiter and by a circuit module which combined the functions of rectifier, filter, dc comparator, and output transistor. This module was used to drive a series combination of a light-emitting diode, a 3 kHz tone generator (alarm) and the coil of a relay which was used in tests to drive a second tone generator at the end of a 50 m cable to indicate when triggering had occurred to observers at the design goal distance. This relay was also suited to either power or trigger a lane-marker light. The threshold level at which triggering occurred could be adjusted by a 10-turn potentiometer (with counter-type lockable dial) which set the reference voltage for the dc comparator; this control was adjusted to obtain the desired detection range with minimum false alarm rate.

To increase the gain (for use with piezoelectric polymer sensors), trimpots were added to adjust the gain of both gain stages, and also as offset-trimmers for these stages. Since unity dc gain was not used due to the very low passband frequencies, offset-trimming was needed to prevent saturation due to the larger output offset at these higher gains. The performance figures given above are for the minimum gain settings of the gain trimpots.

A major problem in the development of the seismic switch was the suppression of turn-off transients which tended to re-trigger the circuit. A combination of power supply decoupling and the shielding of internal input and output leads was found effective.

RESULTS

Using the combination of a ceramic sensor (bonded to the asphalt pavement and shielded as it was during the vibration studies) and the electronic switch with the characteristics described above, set up as shown in figure 12, triggering could be made to reliably occur for single vehicles at or beyond the 50 m distance, a large percentage of which had speeds obviously below 50 km/h (30 mph). After a proper threshold level was established, there were almost no vehicle passbys that failed to trigger at this distance, none that failed to trigger at close to this distance, and very few false alarms. These tests were all made on the NBS grounds, and therefore did not indicate what the false alarm rate would be due to opposite-lane vehicles separated from the sensor by a median strip; that such false alarms can be expected to be quite high, however, is indicated by figure 10, but time did not permit verification of this.

Time also did not permit a statistical study of trigger success and false-alarm rate. The variables of threshold level and road, vehicle, and switch characteristics, combined with the need for single-vehicle passbys, would have necessitated an extremely lengthy study to produce meaningful data, one quite beyond the scope of the investigation, and probably of little value from a practical viewpoint considering the latitude in triggering distance (between minimum and goal). The almost complete success obtained at this one location, however, indicates that acceptable results can almost certainly be obtained at most highway locations, exclusive of false-alarms due to opposite-lane traffic or to unusual seismic background noise.

While the effect of water on the road was not investigated, there is little likelihood that seismic vibrations at such low frequencies (as opposed to airborne noise at higher frequencies) could be altered by even a measurable amount by surface water, let alone by an amount significant in comparison with the effect of small changes in other variables (such as vehicle weight or tire balance).

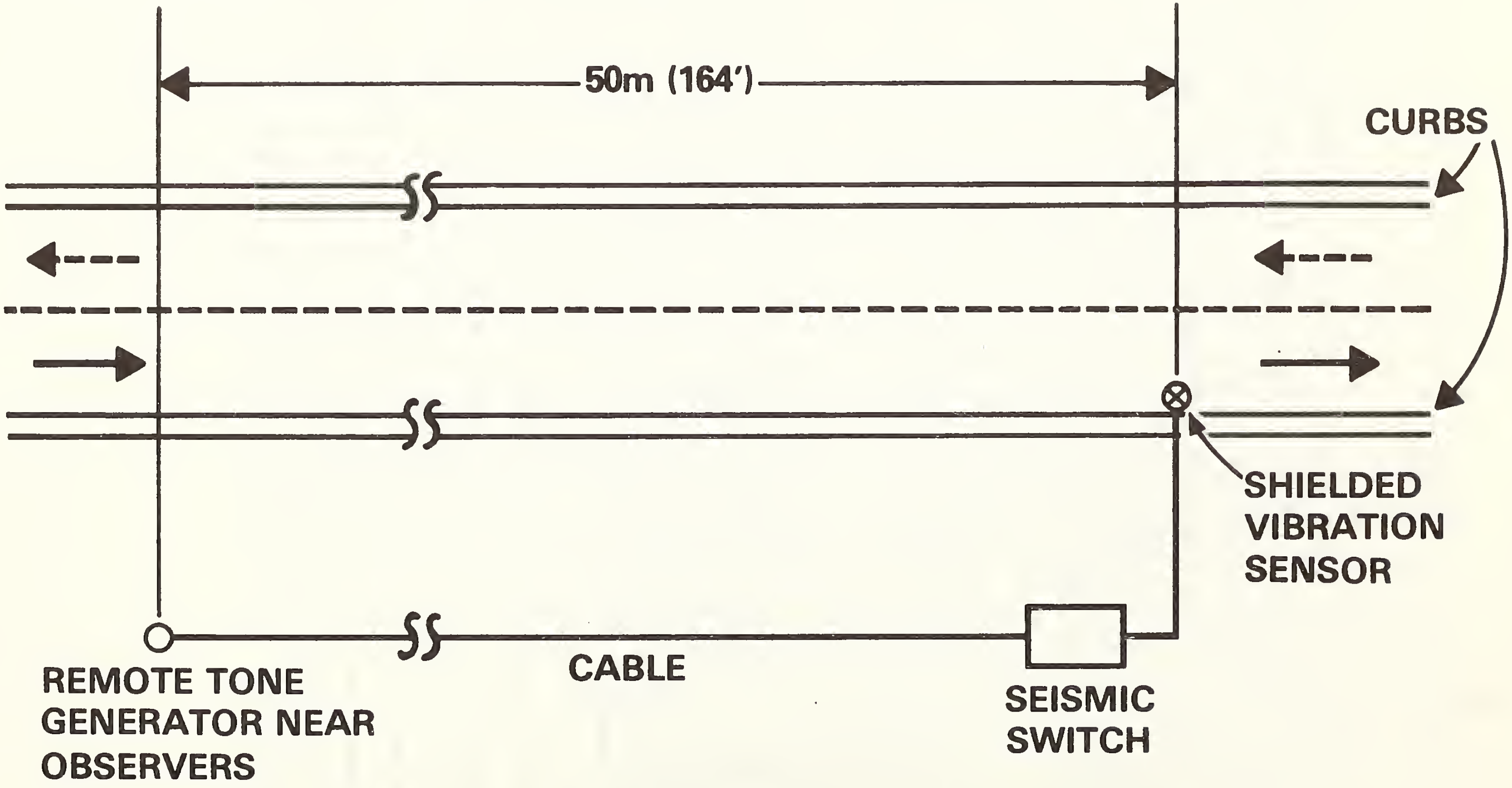


FIGURE 12. Set-up for testing seismic switch. Test utilized single-vehicle passbys (going from left to right in figure).

Attempts at using the switch with piezoelectric polymer sensors were largely unsuccessful, even with the increased gain previously mentioned. One sensor, however, a 7 1/2 cm (5 in) diameter simple sandwich, gave very promising results: triggering occurred with fair reliability at about 25-30 m (25 m is the minimum distance objective). However, a second polymer sensor essentially identical to this one could not be made to work. It is speculated that the variability exhibited by the polymer sensors was due largely to slight but significant differences in their bonding. The successful attempts are believed to have resulted from obtaining a "strain-gauge" action, where the pavement surface waves (Rayleigh waves, having a lateral as well as vertical motion) stretch the polymer film, rather than compress it, resulting in a far larger signal output due to the stress being applied through the cross-sectional area of the film, which is small compared with its face area. This mode of operation requires a taut film, however, which is difficult to reproducibly obtain by simple bonding techniques.

CONCLUSIONS

It has been conclusively demonstrated that seismic detection at a distance of 50 m (164 ft) of motor vehicles travelling 50 km/h (30 mph) is technically possible, and that it can be done using fairly simple equipment. Before practical use can be made of this concept, however, considerable additional work will be required.

RECOMMENDATIONS

While there are unanswered questions concerning such details as the dependence of seismic vehicle detection upon a number of variables, some of which are difficult if not impossible to quantify, the most important questions affecting the advisability of continued efforts in the detection area would now seem to be in other areas. Three of the more obvious of these questions are: (1) Can a lane-marker light be developed which is compatible with snowplows and yet providing, with reasonable power consumption sufficient light to be visible in competition with reflections from a wet pavement of headlights of oncoming vehicles (the situation in which lane markers are most desperately needed and possibly the only one that can really justify their cost)? (2) Can a battery supply (if power cables in the pavement are unacceptable) be developed for this light capable of lasting an economically acceptable length of time in the brutal environment of a highway pavement? (3) Is the whole idea economically feasible? Compared with these fundamental questions, the remaining doubts concerning seismic detectability are of minor importance. Keeping this perspective in mind, the following investigations would be desirable if the overall feasibility of the marker-light concept is deemed sufficient to warrant the necessary costs:

1. To obtain minimum-cost sensors, piezoelectric polymers should be developed for this application. That this is not an easy task is demonstrated by the substantial but largely unsuccessful efforts made under this program. That it is a realistic task, however, is demonstrated by the occasional (though unreproducible) success.

2. The minimum requirements for wind (etc.) shielding should be determined. This is also a difficult task, because of its ill-defined requirements and hard-to-measure variables.

3. If greater confidence in detectability on different roads is desired, a methodical study should be made of the amplitude and shape of pavement vibration spectra vs. distance, preferably using a recorder with a large number of channels, with good matching between sensors and between channels. This should be done at many locations on every type of road.

4. A similar quantitative investigation of pavement vibration spectra from opposite-lane traffic should be made at the same locations as in (3). In addition, the false-alarm rate at these locations could possibly be determined using the feasibility-model switch.

5. A low-cost low-power switch circuit should be developed suitable for (at least) a limited production run, in order to be able to demonstrate the electrically-illuminated lane marker concept using a sufficient number of lights for a realistic evaluation. While the 15 Hz tuning has proven successful, additional experimentation with passband characteristics is highly desirable prior to quantity production. Minimization of the false alarm rate at some locations may require different characteristics.

6. The most likely cause of false alarms -- opposite lane traffic vibrations -- could possibly be discriminated against by development of a directional sensor. The lateral component of the surface (Rayleigh) waves could be utilized for directionality by (a) laterally mounting an accelerometer-type sensor (such as the ceramic type used in this investigation), i.e., with the active direction (perpendicular to the broad face of the disc) parallel to the pavement and to the direction of traffic, or (b) developing a strain-gauge type sensor (such as a piezoelectric polymer) in the form of a thin strip parallel to the direction of traffic and bonded to the pavement at both ends with provision for taking up slack and pre-stressing.

7. The effects of recessing sensors in the pavement should be determined. While desirable from the point of view of environmental protection and ease of packaging, different switch frequencies may be required for best operation.

In addition to its possible use in lane marking, the seismic switch has other possible uses, such as triggering the illumination of warning signs along the roadway at particularly dangerous locations. The flashing of an illuminated warning would obviously be much less likely to be overlooked than the present passive caution signs. The presence of slow-moving vehicles hidden from sight to following vehicles by hills or curves could be warned of in this way by the use of appropriate time delays in turning the sign on and off, and by the use of large switch hysteresis, i.e., a much lower threshold for turn-off than for turn-on. While there are other conceivable methods for detecting vehicles for such purposes, the seismic method has the advantages of eliminating or minimizing the use of cables, and of being inherently well-protected (especially if buried) against environmental deterioration of either the device itself or its performance (and also against vandalism). The development of sufficiently directional sensors may make attractive the seismic operation of demand-type traffic-control signals.

An obvious non-highway use would be for intrusion detection, since extreme sensitivity of the feasiblity model to footsteps has been observed; this is believed to have been investigated for the military. (Nearby pedestrian traffic would obviously pose a difficult false-alarm-rate problem for seismically switched lane-marker lights or other signals.)

APPENDIX - A SIMPLE DESCRIPTION OF PIEZOELECTRIC SENSORS

Piezoelectric materials are dielectrics in which there has been a net internal displacement of charge between opposing surfaces of the material. The charge displacement may be due to the alignment of polar molecules or to the injection of free charges into the material. This is accomplished by exposing the material to a strong electric field while it is heated sufficiently to allow polar molecules to rotate into alignment with the electric field or to allow charge to penetrate the surface. The molecules and charges are then immobilized by cooling the material before the electric field is removed. If electrodes on the (poled) surfaces are connected together, then charge will flow between the electrodes into surface layers at the boundaries between the electrodes and the poled material sufficient to terminate the surface field of the latter (since no electric field can penetrate the conductors). (With or without electrodes, ions in the air would be attracted to the electrodes or the poled surfaces, neutralizing the electric field even without electrode shorting).

If stress is applied to the poled material, the resultant strain will alter the induced surface charge. A voltage will then appear between the electrodes equal to the change in surface charge divided by the capacitance between the electrodes. If the electrodes are momentarily short circuited while a steady stress is applied, removal of the stress will alter the surface charge by an equal amount in the opposite direction, reversing the polarity of the resulting voltage. An alternating stress, as from a sound field, will therefore generate a corresponding alternating voltage across a high impedance electrical load, such as a voltage amplifier, attached to the electrodes, or will drive an alternating current through a low impedance load, such as a charge amplifier.

The piezoelectrics used in this investigation were lead zirconate titanate, a crystalline ceramic, and poly(vinylidene fluoride), a flexible plastic. The piezoelectric ceramic was obtained commercially as electroded and poled discs, so that it was only necessary to assemble a pair of discs together and attach a shielded cable, as shown in figure A-1. The electrically paralleled discs formed a fully shielded transducer since the grounded electrodes of the discs were on the outside and connected together at their edges by a layer of silver-filled conducting epoxy.

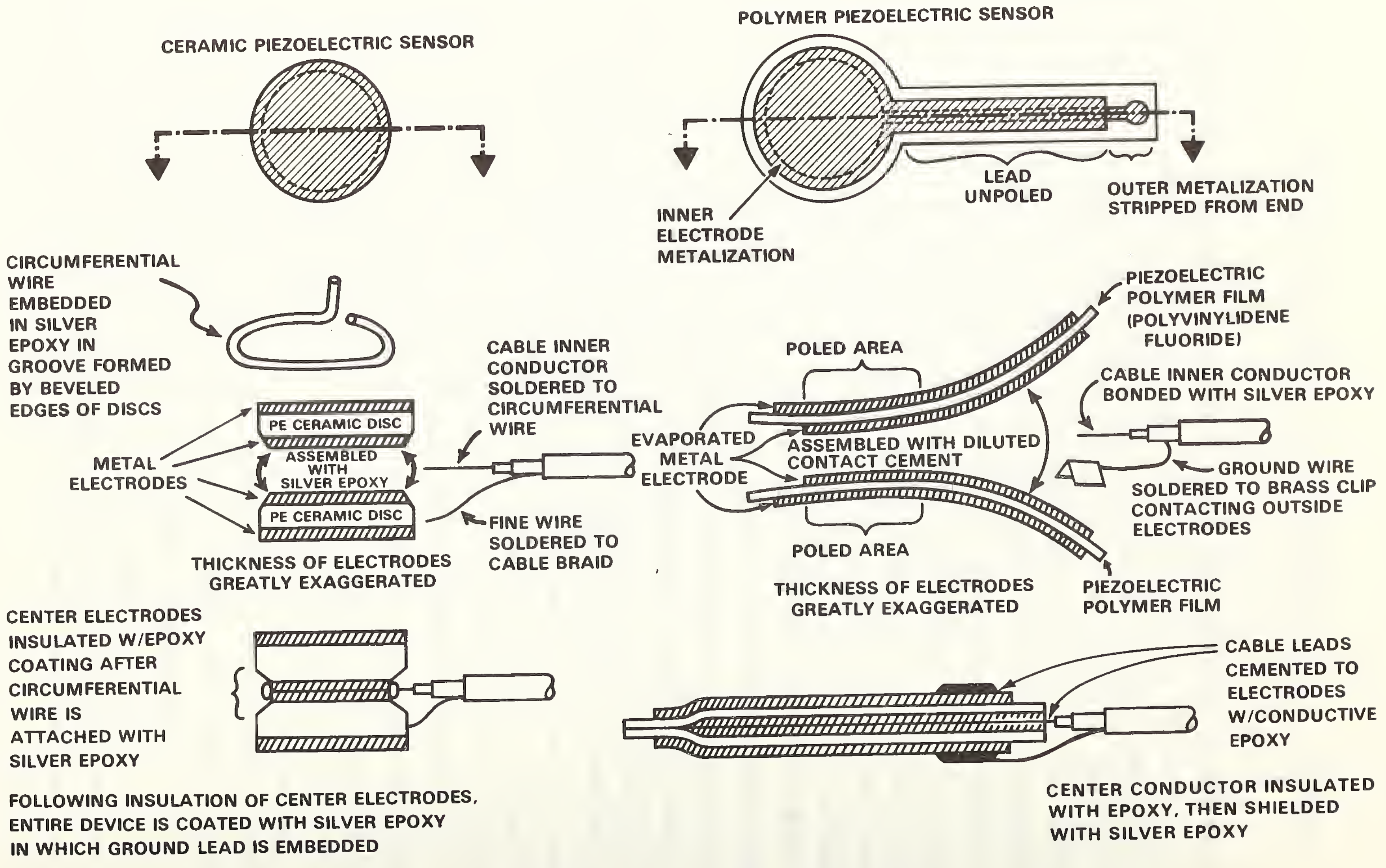


FIGURE A-1. Construction of piezoelectric sensors. Electrodes (metalization) shown shaded.

The piezoelectric polymers were electroded and poled at NBS using commercially available sheets of poly(vinylidene fluoride). They were assembled as self-shielding pairs, similar to the ceramic transducer. Details of a typical piezoelectric polymer fabrication procedure used at NBS have been given in a previous NBS report*.

The mode of operation for the ceramic sensor, and the usual mode for the polymer sensor, was as an accelerometer. Forces were developed through the sensor due to vertical acceleration by the vibrations transmitted to it from the road surface. Since the conversion of acceleration to force requires mass, the mass of the sensor was generally augmented by an added mass cemented to the top surface of the sensor. Because of the finite acoustic impedance presented by the pavement, and the finite acoustic impedance of the sensor, the force developed, and hence the output voltage, was not proportional to the added mass: a limit on the amount of usable mass was reached beyond which no further significant increase in output could be obtained.

An absolute measurement of road surface vibration was considered impractical for this project due to the calibration difficulties imposed by the combination of sensor mass and source (pavement) impedance.

*DeReggi, A. S., Piezoelectric Polymer Transducer for Impact Pressure Measurement, NBSIR 75-740, Final Report Covering Period December 15, 1973 to December 31, 1974: Section 2.2 "Transducer Construction", pp. 7-11. Available through NTIS.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The technical feasibility of detecting the approach of motor vehicles by seismic means was determined by the recording and analysis of road vibration, and verified by the construction of a seismic switch which was reliably triggered at a distance of 50 metres (164 ft) along the pavement by vehicles travelling at 50 km/h (30 mph).

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Ceramic transducers; motor vehicle sensing; piezoelectric polymers; road lane markers; road vibration; seismic detection: traffic noise

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