level measurements where there are several noise sources present.

A third potential problem relates to the way in which the trigger level portion of the regulation may be applied to switcher locomotives. The standard states that all switcher locomotives that operate in a particular railroad facility are deemed to be in compliance with this standard if the L_{90} trigger level on nearby receiving property does not exceed 65 dB. If this trigger level is exceeded, then presumably an inspector may require a 100-ft sound level measurement for each switcher locomotive in the railroad yard.

It is not too difficult to envision a situation in which one or more locomotives that meet the 100-ft sound level standard (70 dB at idle throttle setting) cause the trigger level of 65 dB to be exceeded because they are normally parked close to the receiving property measurement site. The obvious solution to any community noise problem caused by these locomotives is to move them further from the edge of the railroad yard, even though they meet the 100-ft standard. Yet the standard can be interpreted to require that all other switcher locomotives in the yard be tested at 100 ft and any exceeding the specified maximum be modified, even though those locomotives are not contributing to the trigger level at the receiving property measurement site.

Clearly, some discretionary judgment should be allowed both enforcement officials and railroad personnel in solving a noise problem such as this. A solution that reduces the L_{90} at the receiving property below the trigger level should be acceptable, even if it does not involve making 100-ft measurements of all other switcher locomotives in the yard.

CONCLUSIONS

Because elements of the new railroad noise emission regulations attempt to cover many complex situations, they can be implemented in a manner that is counterproductive to cost-efficient noise control. Proper training of both enforcement and railroad personnel will be required, along with the use of reasonable judgment on the part of these persons, in order that the intents of the noise act be carried out in an effective manner.

ACKNOWLEDGMENT

The preparation of this paper was supported by the Association of American Railroads.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Use of Microcomputers in Highway Noise Data Acquisition and Analysis

PHILIP J. GREALY, SIMON SLUTSKY, and WILLIAM R. McSHANE

ABSTRACT

A microcomputer-based noise data acquisition and analysis system has been designed that expands the capabilities currently available for monitoring highway traffic noise. The system was designed for research activities investigating the effects of pavement and tire design on highway noise levels, and it incorporates the state of the art in microcomputer interfacing equipment design. The system is designed to allow the high-speed collection and analysis of both A-weighted and 1/3 octave noise data for multiple microphone configurations. The components of the system are described, and a discussion of the hardware and software development, as well as the specific application the system is used for, is included. It is suggested that there are other applications that the system could be easily adapted to, and some insight into the effect that continued advancements in microelectronics may have on such a system is provided.

Conventional methods of acquiring highway noise data have made use of systems consisting of a series of microphones, sound level meters, and tape recorders. Collected data are then generally brought back to the laboratory for playback and analysis [see Figure 1 (1)]. This analysis is usually accomplished by using various types of filter systems coupled together with a computer. Although this method provides the necessary capabilities to carry out a detailed analysis of data, it requires large capital outlays for equipment and tends to be a time-consuming, labor-intensive, and thus costly activity.

With the advancements in the field of microelectronics in the past 5 to 10 years, the prospects of more compact and even portable equipment have been greatly improved. The evolution of the computer from vacuum tubes to transistors to integrated circuits

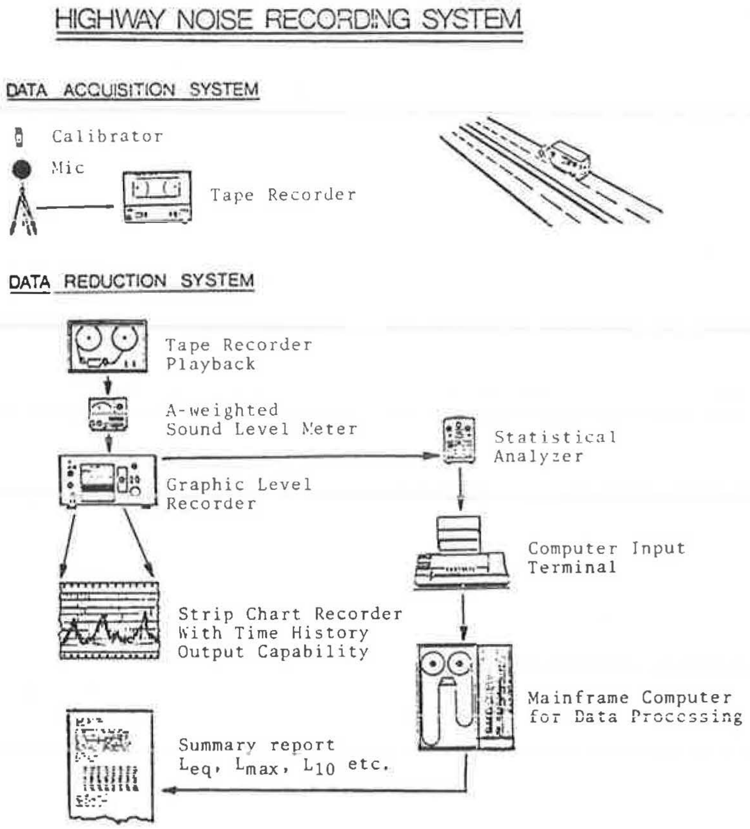


FIGURE 1 Typical highway noise data acquisition system *(1)*.

has created new possibilities in the instrumentation and data acquisition fields. The availability of microcomputers with 16K, 64K, and now as much as 256K of random access memory (RAM) has made it possible to modify the method in which noise data are collected and analyzed.

In the following sections the details of a microcomputer-based noise data acquisition system, which was designed to incorporate some of these technological advancements, are discussed.

DATA ACQUISITION REQUIREMENTS OF CURRENT RESEARCH ACTIVITY

The Transportation Training and Research Center of the Polytechnic Institute of New York (PINY) was awarded a contract by FHWA to develop and demonstrate a tire-pavement noise assessment procedure. From recently completed research (2), it has been found that at highway speeds, tire noise is a predominant source of highway noise; thus the type of pavement selected can make a significant difference [3 to 8 dB(A)] in the resulting highway noise level. In some areas such a reduction may in fact negate the need to construct extensive and expensive barriers. By providing the states with a means of assessing these differences in highway noise impacts due to variations in pavement designs, the pavement design engineer will have the ability to recommend the use of a "quieter" pavement in noise-sensitive areas.

As part of the demonstration program, it was necessary to develop, implement, and recommend a field measurement program that the states could exercise easily in collecting their own data. Although there are several other activities associated with the overall study, the data in this paper deal primarily with the approach taken to meet the data-collection needs.

In the initial development phases of this field measurement procedure, it was determined that to develop a procedure that could be used both easily and cost effectively by the states, efforts should be directed toward establishing an on-board data-collection method. Thereby, data collected could be incorporated into other agency inventory activities such as collection of pavement condition data, skid resistance measurements, and photologging--all necessary inputs to an effective pavement management system.

To justify the use of such a method, it was deemed necessary to conduct simultaneous measurements of both on-board and wayside microphones at various test sites, and from these measurements develop correlations between a vehicle-mounted on-board microphone and a microphone located at the roadside at the standard reference distance of 50 ft (see Figure 2).

Consequently, the investigators examined the possibility of designing a system capable of high-speed data acquisition from a multimicrophone configuration, with the ability of providing the following information for a test vehicle as it passes through a typical measurement trap:

1. A-weighted and 1/3 octave time history of the on-board microphone,
2. A-weighted and 1/3 octave time history of the microphone located 50 ft from the test vehicle, and
3. Position sensing and speed tracking of the vehicle.

To obtain this information at sufficient sampling rates (i.e., 1,000 samples per second), it was found both useful and necessary to have a data-collection

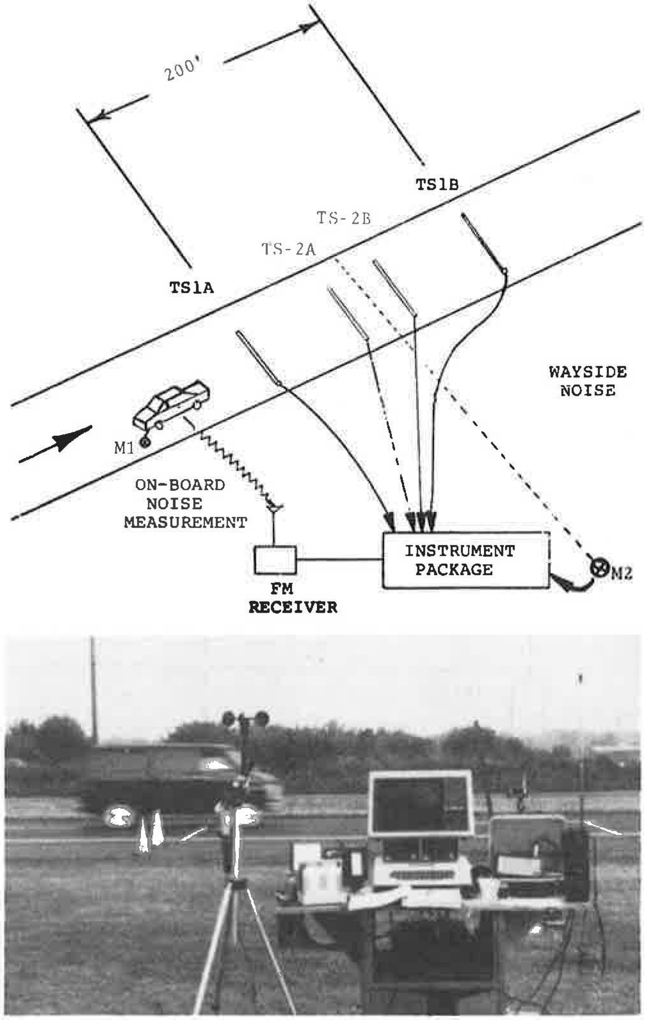


FIGURE 2 Equipment configuration used for passby on-board and wayside noise measurements.

system structured around a microcomputer. With this in mind, several possible equipment configurations were investigated. Due partially to the availability of certain in-house equipment, the conceptualization of the new system began with an APPLE II+ microcomputer and an IVIE Electronics IE-30A (3) real-time spectrum analyzer as the main components.

At the time the design of the system began, the APPLE II+ was found to be one of the most convenient microcomputers on the market, with a fairly broad base of hardware and software peripherals readily available. Two such peripherals that became integral parts of the system were a real-time clock and a 16-channel analog-to-digital (A/D) interface card.

Beyond component acquisition, the more complex problem of accessing and processing the various output signals of the different microphones and spectrum analyzers needed to be addressed. The most difficult of these tasks was the sampling of the 1/3 octave outputs of the IVIE IE-30A. To accomplish this, a combination of software and hardware development was necessary. The details of the hardware design specifications and software documentation are described elsewhere (4,5), but the general principles applied are described herein.

INTERFACING EQUIPMENT DESIGN

The IVIE/APPLE noise monitoring interfacing hardware consists of signal-conditioning units that can be classified into several groups. The first of these units, which is used with the various sound level meters and individual microphones systems, has the function of converting the wide-band, low-voltage audio signal from these systems into a slowly varying direct current (dc) voltage of between -5 to +5 V, which in turn can be input directly to the A/D interface card located inside the APPLE. The hardware for this purpose includes a voltage amplifier and an alternating current (ac) to RMS converter with a logarithmic output channel. This system provides a dynamic range of 50 dB, which can be adjusted to fit incremental ranges of acoustic levels from 50 to 140 dB for the individual microphones.

The second series of signal conditioners is designed specifically for the IVIE IE-30A's and is somewhat more complex. In general, however, they serve to sequentially sample both the 1/3 octave and A-weighted outputs from the IVIE and adjust them to fit into the appropriate voltage range for the A/D board of the APPLE. The output from the IVIE signal conditioner consists of a reference pulse followed by 29, 1/3 octave band samples that correspond to frequencies from 25 Hz to 16 kHz. The dynamic range of the third octave output from the system is 40 dB, whereas the A-weighted sound pressure level (SPL) has a dynamic range of 50 dB(A). This range is variable from 30 to 140 dB(A), depending on the reference setting of the IVIE.

CURRENT PINY WAYSIDE DATA ACQUISITION SYSTEM

Figure 2 shows the typical equipment configuration used by the research team. In general, the setup involves the placement of microphones on board the vehicle and at the roadside at 50 ft from the centerline of the vehicle's travel path. The instrumentation system referred to in this figure is shown in more detail in Figure 3, which is a block diagram of the equipment configuration. The individual components of this system are described in the following paragraphs.

As discussed previously, the heart of this system is an APPLE II+ microcomputer (64K RAM), which is used to monitor, store, and analyze several different channels of noise and speed data. The peripherals used in conjunction with the APPLE are

1. Four 5.25-in. disk drives,
2. One 16-channel A/D interface card,
3. One real-time clock interface card, and
4. One 12-in. monitor.

Note that the system can operate with a minimum of two disk drives; however, the use of the two additional drives allows the collected data to be sorted by vehicle type. Thus drive 1 is reserved to run the data-collection program while drives 2, 3, and 4 are used to store data collected for the vehicle categories of automobile, van, and truck, respectively. This in turn enables successive sampling of the various types of test vehicles without removing or changing storage disks.

In addition to these peripherals, there are several microphones and other components that complete the system:

1. One Bruel & Kjaer 2203 sound level meter;
2. Two IVIE-30A spectrum analyzers;
3. Four temporary roadway electronic sensing devices (tapeswitches);
4. A portable 800-w Honda gasoline-powered ac/dc electric generator;
5. Three short-range wireless FM transmitters;

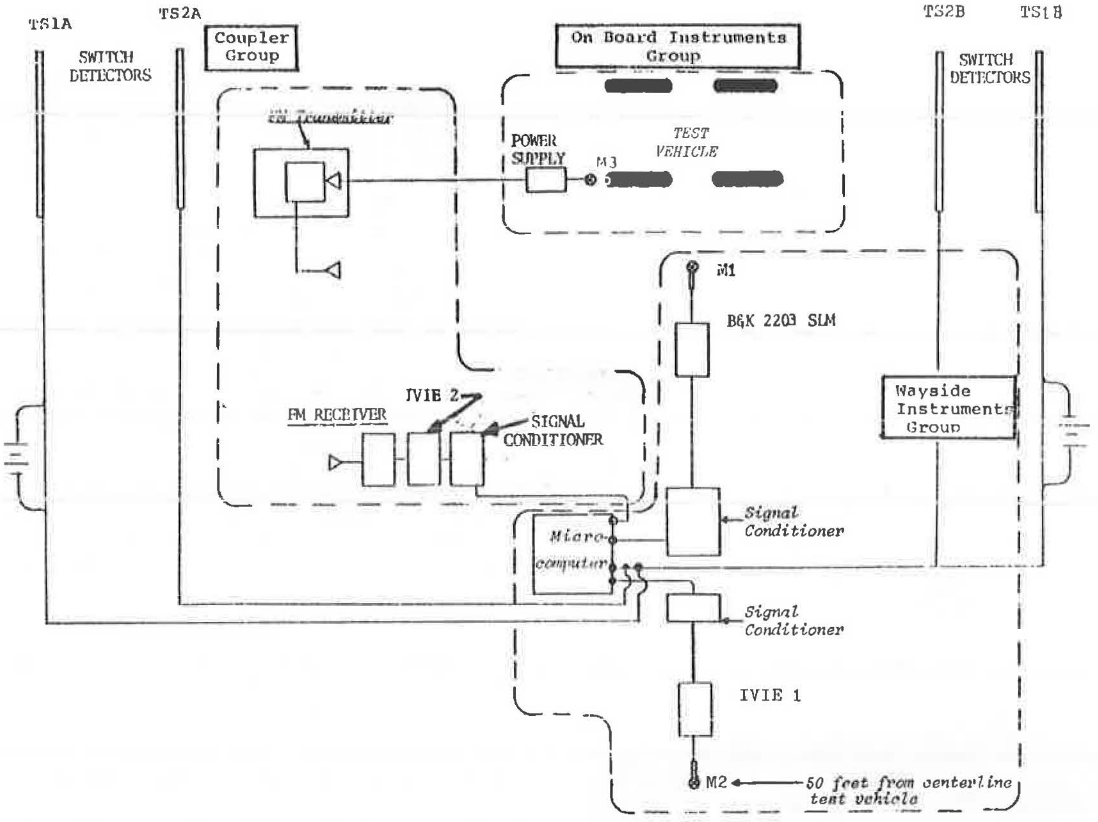


FIGURE 3 Block diagram of passby data acquisition instrumentation.

6. One FM receiver with a crystal matched to the transmitter;
7. Three test vehicles, including a passenger car, a van, and a truck; and
8. Three vehicle-mounted microphone systems (GenRad 0.5-in. condensor microphone with P-42 preamplifier and an 18-V power supply).

Of these components, those of particular interest are the FM telemetering system and the portable generator. The latter is noted because of its excellent power output, low exhaust noise levels, and compactness--factors that are essential for the types of measurements involved.

The telemetry system is also an essential component of the measurement system. The telemetering equipment consists of three short-range wireless FM transmitters coupled with a matched crystal FM receiver. The transmitters are mounted on each of the three test vehicles and are used to transmit the noise signals sensed directly behind the tire as a vehicle passes through the measurement trap.

The transmitted signal is picked up by the FM receiver located at the wayside. The output from the receiver is then transferred to the IVIE spectrum analyzer. The use of the system enables the on-board and wayside measurements to be recorded sequentially by the computer located at the roadside. There are, however, certain limiting factors associated with its use.

The first factor is the limited transmission range of approximately 150 ft. This limitation is partly overcome by placing the receiver at the midpoint of the measurement trap, thus expanding the effective trap distance to as much as 300 ft, which is adequate for these measurements.

The sound problem is the limited dynamic range of the telemetering system, which is on the order of 30 to 35 dB. The effect of this limited dynamic range is mitigated by the nature of the on-board signal, which experiences only minor fluctuations in levels over the entire measurement trap. Still, because the range of noise levels for the three vehicle types exhibits a greater variation, care must be taken in adjusting these levels to obtain a maximum useful dynamic range for the system.

In order to combine and coordinate the equipment into an interactive system capable of processing and storing the various events occurring during a vehicle passby through the measurement trap, an extensive software package was designed. The individual components of this package are discussed in the next section.

DATA ACQUISITION SOFTWARE

The data acquisition software consists of three main routines, including (a) test inventory data, (b) data collection and memory storage, and (c) disk data storage. The first routine, which is written in APPLESOFT BASIC, serves the purpose of inputting inventory information to be stored with the data collected for each run. This includes general information such as the vehicle, tire, and pavement types being tested, as well as the date, time, and meteorological information.

The second routine is actually the key part of the package and is written in APPLE-6502 assembly language. This routine serves the purpose of reading the starting and ending time of each run and storing the individual data samples in the memory of the microcomputer. After the data collection is completed, the program returns to a BASIC routine, which saves the data to disk for future analysis. The data are stored in the format shown in Figure 4.

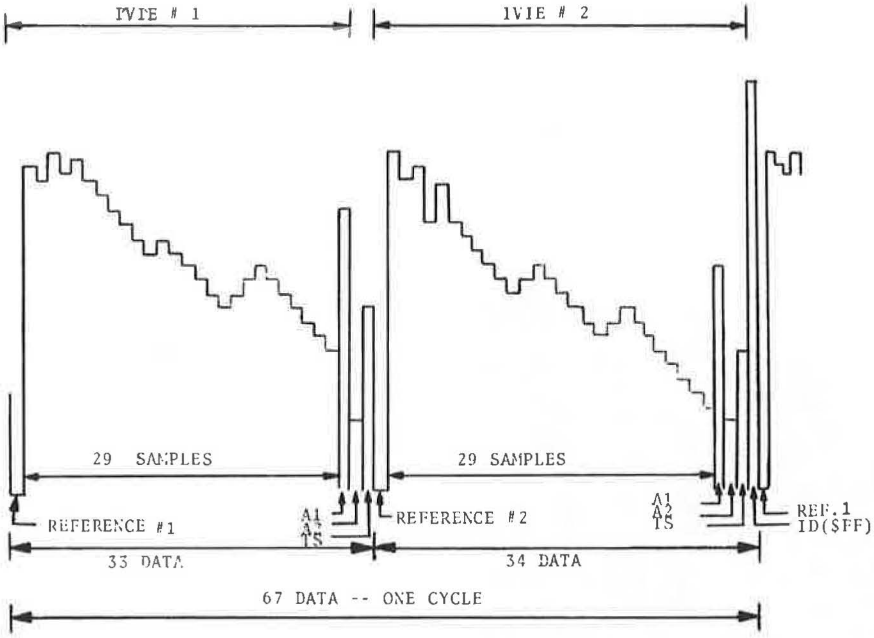


FIGURE 4 Data storage format.

The tapeswitch (TS-1A) referred to previously in Figure 2 serves to automatically trigger the assembly language software used to collect the data from the various instruments. Tapeswitches TS-2A and TS-2B isolate a smaller trap in the region where the peak is expected to occur. The last tapeswitch (TS-1B) terminates the acquisition of samples from the various microphones and enables the data to be written to disk.

As shown in Figure 4, a complete cycle consists of 67 pieces of data. The cycle begins with a reference signal from IVIE no. 1 followed by 29, 1/3 octave band samples that correspond to frequencies from 25 Hz to 16 kHz. This is followed by an A-weighted signal from the wayside nearfield microphone and an A-weighted signal from IVIE no. 1. An indication of the tapeswitch status follows, with the remainder of the cycle consisting of a repeat of identical information for the second IVIE. The last data value in the cycle is an identification signal that marks the end of the cycle. As many as 100 cycles can be collected and stored in memory during a typical run.

The sampling rate of the measurement system is limited by the processing rate of the IVIE IE-30A. It takes approximately 11.5 milliseconds to sample the 1/3 octave spectrum and A-weighted outputs from a single IVIE. However, when acquiring data from two IVIEs, as in the case here, the time to read the data from both can range from 23 to 34 milliseconds. This is due mainly to the internal clocks of the IVIEs, which may or may not be fully synchronized with one another. Nonetheless, for a typical trap distance of 200 ft, the number of cycles collected during a single 55 mph passby run is on the order of 75 cycles. With a cycle consisting of 67 data points, this corresponds to a total of 5,025 pieces of data for a single run.

ON-BOARD DATA ACQUISITION SYSTEM

The data-collection system previously described is for a combination of on-board and wayside noise measurements. Variations of this system exist for separate collection of either on-board or wayside measurements. For wayside-only measurements, the change requires no more than elimination of the transmitted on-board signal from the process. The on-board process is less trivial; it is described in detail in the following paragraphs.

Initially, the on-board measurement procedure consisted of a microphone mounted behind the tire, as shown in Figure 5. To reduce the effect of wind noise around the microphone, a specially designed windscreen was developed. Based on prior work conducted by Rosenheck and Hofmann (6), the use of a tear-drop-shaped windscreen was investigated. Be-

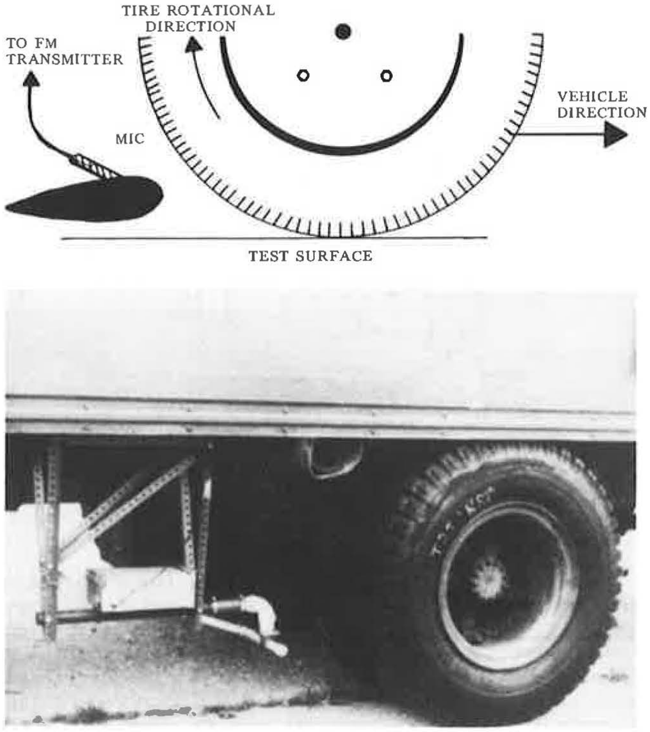


FIGURE 5 Typical mounting of on-board microphone system.

cause this type of windscreen is not commercially available, it was necessary to construct one in-house. Figure 6 shows one of these windscreens mounted directly behind a test tire. Based on the results of a simulated wind tunnel test, it was found that the use of this windscreen enabled consideration of measurements with frequencies as low as 200 Hz, which otherwise would have been submerged by the wind noise.

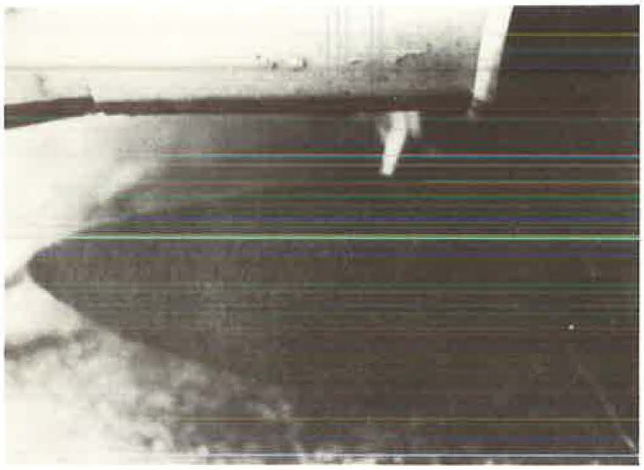


FIGURE 6 Windscreen used with on-board microphone.

Care was also taken in mounting the microphone on the vehicles to minimize vibrational effects. A rigid mounting system that consisted of polyvinal-chloride (PVC) piping was used. In addition to providing support for the microphone and preamplifier, the piping was lined with foam rubber and the microphone cable was run through it for added protection.

The remainder of the on-board system consists of the IVIE/APPLE interface system previously described coupled with a speed pick-up device that constantly inventories the vehicle speed during measurements (see Figure 7). Figure 8 shows the typical on-board instrumentation setup in the test van.

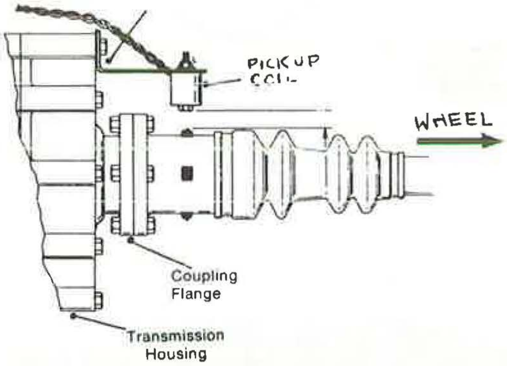


FIGURE 7 Placement of speed-sensing device.

After gaining some experience with the telemetering of noise signals with the FM transmission system, it became apparent that the possibility of testing two vehicles simultaneously was feasible. In this configuration, one test vehicle is equipped with (a) a microcomputer system, (b) two IVIEs, (c) a speed pick-up unit, and (d) two FM receivers with different crystals. The data from this first vehicle are fed directly through the IVIE and into the microcomputer system. The data from the second vehicle are transmitted to the first vehicle by the transmitters. One channel transmits the noise data and the other transmits the speed data for the second vehicle. When these data are received by the receivers in vehicle one, the speed data are input directly to the microcomputer, and the noise data are processed through the second IVIE and then stored in the microcomputer.

DESCRIPTION OF DATA ANALYSIS SOFTWARE SYSTEM

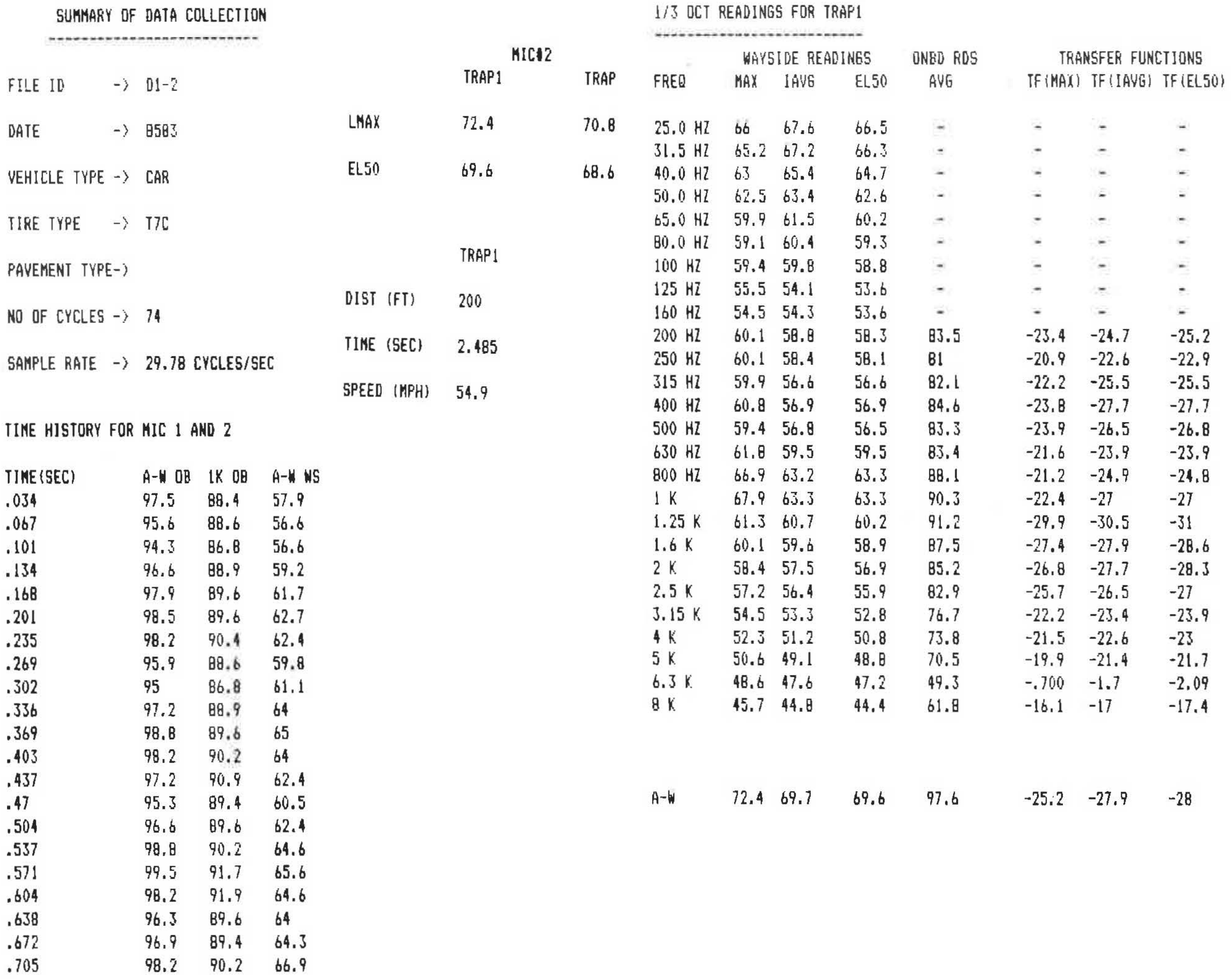
The data analysis software consists of various programs that serve such functions as recalling the raw data from disk, performing various statistical computations, and printing paper copies of these results. The details of each of these are described in the following paragraphs.

The Recall/Data program simply recalls the raw data from disk according to the format in which it was initially stored. The data are read back into memory where it can be used in any of a series of computations.

The Data/Analysis program is used in computing L_{eq} (L-equivalent), L_{max}, and average on-board and wayside levels for each frequency; it is also used in the preparation of time histories for the various microphones. This program has several variations, depending on whether the data are for wayside and on-board measurements or simply for on-board measurements. There are also several printing options available for printing hard-paper copies of these results. Figure 9 is a typical output of the available data. The printed record data include such items as the identification number, date, test conditions, and data sampling rate. The data outputs include a time history of the various microphones and an indication of L_{max} and L_{eq}. The last portion of this printout is a summary of the maximum and average levels by 1/3 octave for each microphone.

To summarize and compare the results of several individual runs for the same site and vehicle and tire combination, there is also an Analysis/Summary program that takes the results of these runs and computes the mean levels and variances for all runs. These results can then be used in further statistical analyses and presentation of results.

FIGURE 8 On-board instrumentation system.



```
     SUMMARY OF DATA COLLECTION
     --------------------------
                                                         MIC#2
                                                 TRAP1              TRAP
FILE ID      -> D1-2

DATE         -> 8583                     LMAX    72.4               70.8

VEHICLE TYPE -> CAR                      EL50    69.6               68.6

TIRE TYPE    -> T7C
                                                 TRAP1
PAVEMENT TYPE->
                                         DIST (FT)    200
NO OF CYCLES -> 74
                                         TIME (SEC)   2.485
SAMPLE RATE  -> 29.78 CYCLES/SEC
                                         SPEED (MPH)  54.9

TIME HISTORY FOR MIC 1 AND 2

TIME(SEC)          A-W OB  1K OB   A-W WS
.034               97.5    88.4    57.9
.067               95.6    88.6    56.6
.101               94.3    86.8    56.6
.134               96.6    88.9    59.2
.168               97.9    89.6    61.7
.201               98.5    89.6    62.7
.235               98.2    90.4    62.4
.269               95.9    88.6    59.8
.302               95      86.8    61.1
.336               97.2    88.9    64
.369               98.8    89.6    65
.403               98.2    90.2    64
.437               97.2    90.9    62.4
.47                95.3    89.4    60.5
.504               96.6    89.6    62.4
.537               98.8    90.2    64.6
.571               99.5    91.7    65.6
.604               98.2    91.9    64.6
.638               96.3    89.6    64
.672               96.9    89.4    64.3
.705               98.2    90.2    66.9
```

```
1/3 OCT READINGS FOR TRAP1
--------------------------
          WAYSIDE READINGS       ONBD RDS        TRANSFER FUNCTIONS
FREQ      MAX   IAVG    EL50     AVG         TF(MAX) TF(IAVG) TF(EL50)

25.0 HZ   66    67.6    66.5     -           -       -        -
31.5 HZ   65.2  67.2    66.3     -           -       -        -
40.0 HZ   63    65.4    64.7     -           -       -        -
50.0 HZ   62.5  63.4    62.6     -           -       -        -
65.0 HZ   59.9  61.5    60.2     -           -       -        -
80.0 HZ   59.1  60.4    59.3     -           -       -        -
100 HZ    59.4  59.8    58.8     -           -       -        -
125 HZ    55.5  54.1    53.6     -           -       -        -
160 HZ    54.5  54.3    53.6     -           -       -        -
200 HZ    60.1  58.8    58.3     83.5        -23.4   -24.7    -25.2
250 HZ    60.1  58.4    58.1     81          -20.9   -22.6    -22.9
315 HZ    59.9  56.6    56.6     82.1        -22.2   -25.5    -25.5
400 HZ    60.8  56.9    56.9     84.6        -23.8   -27.7    -27.7
500 HZ    59.4  56.8    56.5     83.3        -23.9   -26.5    -26.8
630 HZ    61.8  59.5    59.5     83.4        -21.6   -23.9    -23.9
800 HZ    66.9  63.2    63.3     88.1        -21.2   -24.9    -24.8
1 K       67.9  63.3    63.3     90.3        -22.4   -27      -27
1.25 K    61.3  60.7    60.2     91.2        -29.9   -30.5    -31
1.6 K     60.1  59.6    58.9     87.5        -27.4   -27.9    -28.6
2 K       58.4  57.5    56.9     85.2        -26.8   -27.7    -28.3
2.5 K     57.2  56.4    55.9     82.9        -25.7   -26.5    -27
3.15 K    54.5  53.3    52.8     76.7        -22.2   -23.4    -23.9
4 K       52.3  51.2    50.8     73.8        -21.5   -22.6    -23
5 K       50.6  49.1    48.8     70.5        -19.9   -21.4    -21.7
6.3 K     48.6  47.6    47.2     49.3        -.700   -1.7     -2.09
8 K       45.7  44.8    44.4     61.8        -16.1   -17      -17.4



A-W       72.4  69.7    69.6     97.6        -25.2   -27.9    -28
```

FIGURE 9 Sample printout of data analysis results.

AUTOMATION CONCEPTS

Although the use of the microcomputer eliminated the stage of playing back a recorded tape, it is still a somewhat time-consuming process to complete a detailed analysis of the raw data. To overcome the loss of time and personnel necessary for running the analysis, a procedure to automate this stage was developed. Considering that it can take up to 25 min on the microcomputer to analyze a typical run, and that a total of 35 runs are taken for each vehicle at each site, it was necessary to structure a program that would allow multiple runs to be analyzed without operator interaction; that is, to successively read and analyze the individual files and then save the results on disk. This was accomplished through software, with the resulting data processing time reduced by between 30 and 50 percent.

This automated method of reading successive files also proved to be useful when printing paper copies of the results. The operator only has to load a disk into the microcomputer, answer a few questions, and then return later with all files printed automatically.

CONCLUSIONS

By taking advantage of the recent technological advancements in microelectronics, a more cost-effective highway noise data acquisition system has been designed, tested, and implemented. With such a system the amount of useful data that can be feasibly collected and analyzed by highway engineers is greatly expanded.

Although the system described herein was designed specifically for the acquisition of highway noise data, it has the potential of being used for other applications. Some of these other uses could include noise-monitoring systems for airports, subway systems, and industrial applications, where the concern for noise levels is a sensitive issue.

In summary, the present system is limited by the amount of available storage and the number of channels of data that can be handled because it was designed around an 8-bit, 64K (RAM) microcomputer. However, since the time it was initially designed, other 16-bit microcomputers with 256K (RAM) or greater and additional A/D channels have become commercially available. By configuring the present system around one of these more advanced microcomputers, the capabilities will be greatly increased.

ACKNOWLEDGMENTS

The research reported on herein is being conducted under an FHWA contract, "Tire-Pavement Noise Accessment Procedure." Fred Romano is the FHWA technical monitor. The authors wish to acknowledge the inputs of many others associated with the design and implementation of the research reported on here. Special thanks are expressed to Loyal Chow, Patrick Hanley, James Goon, and Conrad Moses for their contributions to the design of the hardware and software systems presented here. Appreciation is also extended to Michael Leonard, Nassy Srour, and Horace Patterson for their assistance in the data-collection efforts.

REFERENCES

1. Guide on Evaluation and Attenuation of Traffic Noise. AASHTO, Washington, D.C., 1974.
2. J.C. Walker and R.D. Oakes. The Reduction of Tyre-Road Interaction Noise. Dunlop Corp., England, 1981.
3. IVIE IE-30A Audio Analysis System Owner's Manual. IVIE Electronics, Salt Lake City, Utah, March 1978.
4. L. Chow and P. Grealy. IVIE/APPLE Interfacing System. Polytechnic Institute of New York, Brooklyn, Sept. 1982.
5. P. Hanley and P. Grealy. Tire-Noise Data Processing Software--User's Manual. Polytechnic Institute of New York, Brooklyn, July 1983.
6. A.S. Rosenheck and R.F. Hofmann. Measurement of Automobile Tire Noise in a Moving Vehicle and Comparison with Drum Measurements. Proc., International Tire Noise Conference, Stockholm, Sweden, 1979.

This paper was produced as part of a program of research sponsored by FHWA, U.S. Department of Transportation. The results and views expressed are the product of this research and statements expressed in this paper are those of the authors and do not necessarily reflect those of the FHWA.

Publication of this paper sponsored by Committee on Instrumentation Principles and Applications.