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16. Abstract

The need for new instrumentation to sense, classify, and control increasing traffic flows has been evident for several years. In some cases, older technology (ACRS for example has proven inadequate for projects such as counting vehicles crossing rural bridges, owing to the adverse conditions in which the instrumentation must operate. Currently available counting and/or classification systems generally require deployment on or under the road surface and are subject to many hazards. What is needed is a simple, accurate, and inexpensive system that can be deployed at the side of roadways and easily be moved from location to location. The purpose of this study was to explore acoustics and modern signal processing as a technique for counting and possibly classifying traffic on rural, state, and interstate highway systems.

Objectives:

I. Develop an alternative to the commonly used rubber hose traffic counting system (ACR) for deployment on rural roadways.

II. Investigate the possibility of using acoustic signals from moving traffic as a basis for a new instrument for counting and possible classifying vehicles.

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FINAL REPORT

OF

STUDY CONTINUATION:

ACOUSTIC TRAFFIC DETECTION AND CLASSIFICATION SYSTEM

PHASE II

Study No. 2-10-89/2-1251

by

Robert H. Benson

Department of Engineering Technology

Texas A&M University

College Station, Texas

November 28, 1990

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

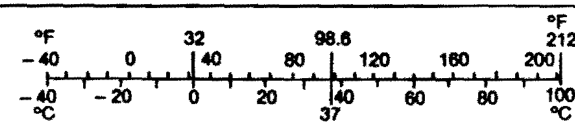
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

TABLE OF CONTENTS

PROBLEM STATEMENT

The need for new instrumentation to sense, classify, and control increasing traffic flows has been evident for several years. In some cases, older technology (ACRs for example) has proven inadequate for projects such as counting vehicles crossing rural bridges owing to the adverse conditions in which the instrumentation must operate. Currently available counting and/or classification systems generally require deployment on or under the road surface and are subject to many hazards. What is needed is a simple, accurate, and inexpensive system that can be deployed at the side of roadways and easily be moved from location to location. The purpose of this study was to explore acoustics and modern signal processing as a technique for counting and possibly classifying traffic on rural, state, and interstate highway systems.

BACKGROUND AND SIGNIFICANCE OF WORK

Acoustic signals provide a rich source of information about events in the environment which produce sounds. However, extracting useful information is difficult because the signals are associated with heavy noise. If a system employing acoustic or other forms of detection can be developed, these technologies will play an important role in the science of traffic surveillance and management.

Traffic moving along roadways produces sound, heat, and reflects light. These signals can be exploited in a variety of ways to render information about the characteristics of individual vehicles which are a part of the traffic flow. In some cases, velocity, acceleration, and class can be determined from examining digitally produced power spectra (frequency domain representation of a digitized sound wave) of vehicles as they pass a point along the roadway. This investigation involved the study of acoustic and infrared sensors as possible bases for new instrumentation for the science of traffic management and control.

The project was undertaken in two phases. Phase I involved the development of a prototype sensor unit, which is to be deployed near bridges in rural settings. The sensor is an inexpensive VOX operated audio tape recorder and microphone system. Phase I also included the development of a device to properly set the VOX level and procedures and guidelines for properly deploying the sensor.

Phase II continued the work begun during Phase I. Building on knowledge gained as a result of Phase I, we developed an infrared-based instrument intended to replace the commonly used ACR. We also investigated a signal processing approach to counting and classifying traffic sounds.

OBJECTIVES OF THIS STUDY

Objective I: Develop an alternative to the commonly used rubber hose traffic counting system (ACR) for deployment on rural roadways.

Objective II: Investigate the possibility of using acoustic signals from moving traffic as a basis for a new instrument for counting and possibly classifying vehicles.

Development of an Alternative to ACR: Initially, we considered using a acoustic filter system and a VOX trigger for the input to a traffic counting system. After studing dozens of spectra for pre-recorded traffic sounds, we determined that the sound signatures would be impossible to sort out with simple circuitry. We then took the approach of using the infrared signal from hot vehicle engines as a basis. An instrument was subsequently designed and prototyped following this principle. The following sections were written by Mr. Richard Long and Mr. Keith Jones. Both individuals were students in the Engineering Technology Program at Texas A&M University.

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Design, Prototype, and Testing: The conventional traffic counter is triggered when a vehicle's wheels compress a rubber hose positioned across the surface of a road. Unpaved road surfaces, such those found in rural areas, often cause the conventional traffic counter to count multiple times with only a single event. Additionally, the rough surface tends to cause early failure of the an infrared sensor to detect the presence of a moving vehicles. A infrared traffic counter can provide a reliable method of counting traffic crossing rural bridges across the state.

During the Spring 1990, a prototype infrared traffic counter was designed, fabricated, and tested. The following section contains a history of the design and development of the prototype infrared traffic counter. This section includes information about the various circuit, circuit functions, system testing, and suggested user operation. Also provided is the necessary information to build a replica of the original prototype.

Sensor Circuit Board: The sensor circuit board used a Heathkit infrared module. The module is composed of eight infrared sensors arranged in an array configuration and each sensor is alternately polarized (+ - + - + - + -). The output of each sensor is fed to a balanced detector circuit. This circuit detects changes in the output level from each sensor. If one or two sensors detect heat with respect to the background while the remaining sensors do not detect heat with respect to the background, then an imbalance develops between the sensors. An output signal is produced by the balanced detector S1 and S2 (Fig. 1). The signals

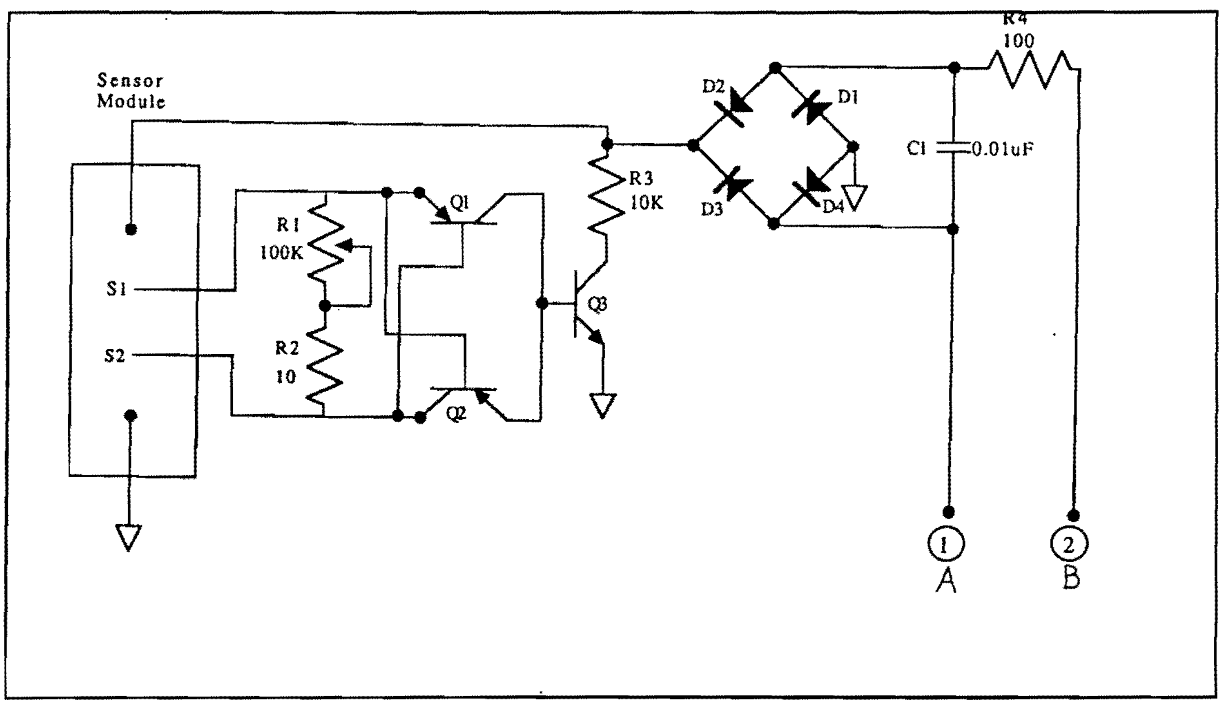


Figure 1. Sensor circuit.

S1 and S2 are opposite in phase. When S1 goes positive, S2 goes negative; and when S1 goes negative, S2 goes positive. The signals from S1 and S2 are applied between the emitter and base of transistors Q1 and Q2. One of these transistors will be turned on, depending on the polarity of the input signal. The outputs of these transistors turn on transistor Q3, which allows current to flow through D4 and produce a +0.42 voltage at point A. The bridge rectifier acts essentially like a gateway allowing current to flow through and forward bias all diodes when transistor Q3 is turned on.

Trigger Circuit Board point A will be approximately +0.42 volts with a signal present (infrared module activated). Resistor R2 and potentiometer R1 set the sensitivity of the received signal. By decreasing R1's resistance, the sensitivity of the infrared traffic counter will be decreased. This is important because the smaller this resistance the less sensitive the device is to smaller (less than the size of a vehicle) moving objects. Capacitor C1 is used to bypass RFN (radio frequency noise, 500 KHz - 300 GHz) to ground. The leads at points A and B can be interchanged and the sensor continues to work properly owning since the bridge rectifier's output between points A and B is always positive.

<u>Trigger Circuit Board:</u> The signal from the sensor circuit board is coupled to pin 5 of the operational amplifier LM324N found on the trigger circuit board (Fig. 2). Upon a signal from the sensor, the output at pin 7 goes high. This high state is achieved because the reference voltage at pin 6 (set by the voltage divider network of R5 and R6), is less than the signal at pin 5. The operational amplifier is configured as a comparator. When the signal from the sensor circuit board at pin 5 becomes greater than the reference voltage at pin 6, the operational amplifier saturates, thus causing the output at pin 7 to go high. This high state causes flip-flop IC CD4013BCN to change states and produce a high state at pin 13 and a low state at pin 12. The transition from high state to low state at pin 12 triggers a 555 timer which, in turn, triggers a binary ripple counter. Discussion of this process will be provided later.

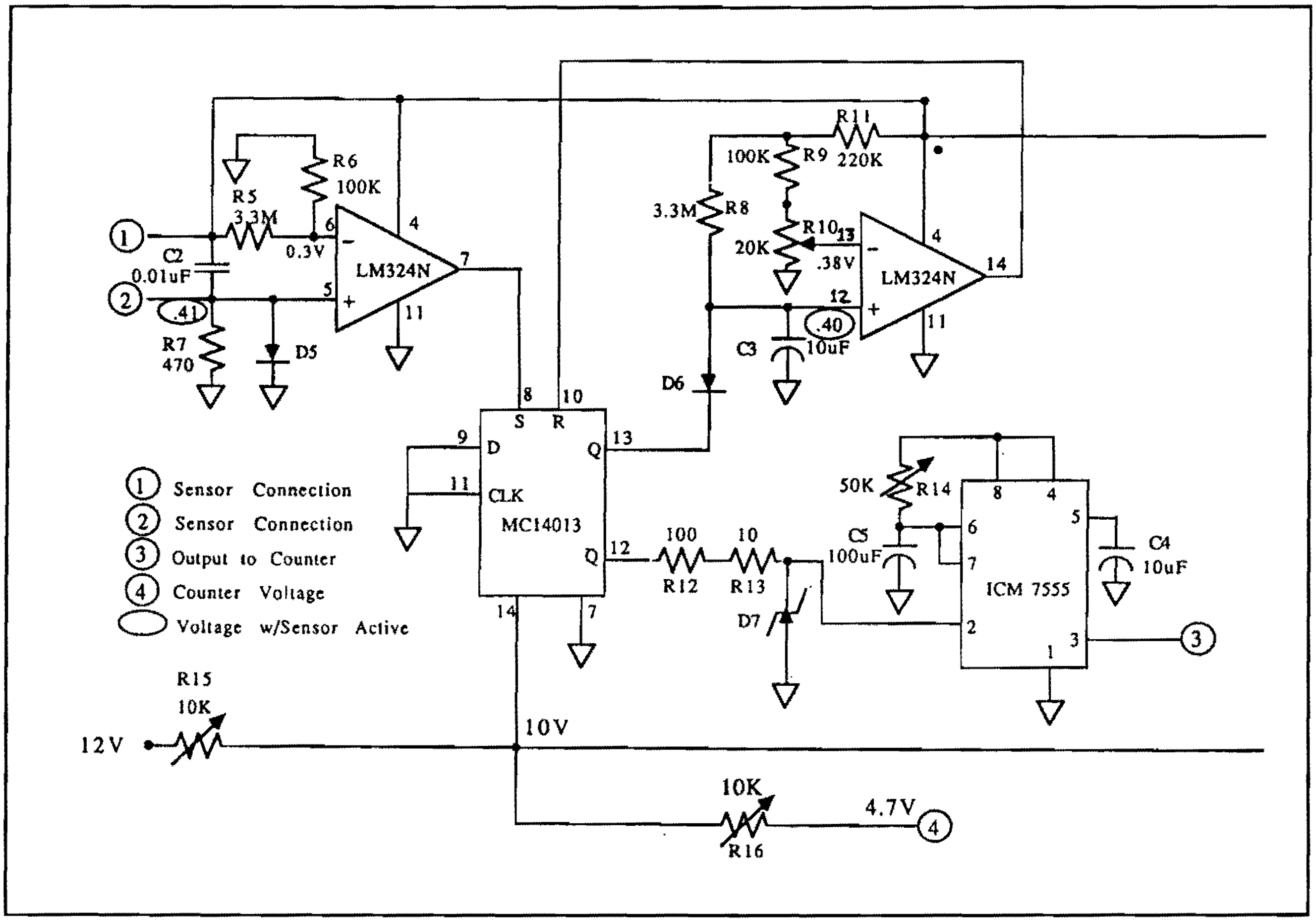


Figure 2. Trigger circuit.

The high state produced at Pin 13 of the flip-flop is coupled to pin 12 of the operational LM324N. However, owing to the high input impedance of the operational amplifier, current flows through capacitor C3 to ground and begins to charge the capacitor. When the capacitor charges to a voltage slightly greater than the reference voltage at Pin 13, the operational amplifier saturates causing Pin 14 to go to a high state. This high state resets the flip-flop. The output Pin 13 changes from a high state to a low state and pin 12 changes from a low state to a high state. When this process is complete, one event has been detected.

At this point, the capacitor at Pin 12 of the operational amplifier begins to discharge causing the voltage at pin 12 to become smaller than the voltage at Pin 13. When this occurs, the operational amplifier's output goes to a low state deactivating the reset pin 10 of the flip-flop. When the next vehicle passes through the path of the infrared sensor, Pin 7 of the operational amplifier goes high, setting the flip-flop and the process repeats.

The process described above occurs almost instantaneously. If a long vehicle, such as a tractor-trailer, passes through the coverage area of the infrared sensor, Pin 7 of the operational amplifier will cause the flip-flop to change states (Pin 13 becomes high, Pin 12 becomes low). However, the output Pin 13 will cause capacitor C3 to charge to a value much greater than the reference voltage at Pin 13 of the operational amplifier. This causes the output Pin 14 of the operational amplifier to remain in a high state for a longer period of time. The occurrence causes the flip-flop's set and reset pins, Pins 8 and 10 respectively, to be activated simultaneously. When this occurs the flip-flop will remain in the most recent state until the long vehicle passes completely through the infrared sensor's field. Once the vehicle passes through the infrared sensor's field, the set Pin 8 of the flip-flop becomes low while the reset Pin 10 remains high. This occurrence causes Pin 13 of the flip-flop to change to a low state and Pin 12 to change to a high state. This action will not produce a false count because flip-flop pin 12 must change from a high state (which it is presently in) to a low state. The high state will never occur until set Pin 8 of the flip-flop is reactivated by a high state from Pin 7 of the operational amplifier. Capacitor C2 bypasses any RF noise to ground. Diode D5 protects the trigger board circuitry from surges by providing a direct path for current to ground.

The flip-flop output Pin 12 produces a signal which is used by a binary ripple counter to count events. The output produced at Pin 12 is approximately +6.3 volts. TTL digital circuitry is used in the binary ripple counter portion of the infrared traffic counter. Consequently, the voltage level of +6.3 volts produced by the flip-flop is too high for the inputs to the TTL IC's. To solve this problem R12, R13, and D7 (1N750A716 4.7 volt zenor) are connected between flip-flop output pin 12 and ground. These resistors and zenor diode act as a simple voltage regulator to reduce the output voltage to the required level.

The 0 - +4.7 volts pulse produced from the output of the zenor diode is coupled to Pin 2 of the ICM 7555 (low power 555 timer IC). The 555 is configured as a monostable multivibrator (pulse generator). The function of the 555 is to eliminate double triggering. Initial data verified that the sensor module will at times cause flip-flop output Pin 12 to go from a high to a low state twice during the passing of a single vehicle. To solve this problem the 555 is configured so that it will produce a single pulse with each event. If a second instantaneous pulse occurs the 555 will not be triggered because capacitor C5 and resistor R14 are set so that they provide a 555 output pulse width longer than the double high to low transitions produced at the flip-flop output in 12.

The time delay graph (Fig. 2) was used to find the proper value of capacitor C5 and resistor R14 required to eliminate the double counting. R14 is a potentiometer. Adjustment of this potentiometer will vary the 555 output signal pulse width. Increasing R14's resistance will eliminate double counting, but will decrease the counter's ability to detect vehicles traveling in close proximity to one another. Figure 3. illustrates the operation of the circuit in the time domain.

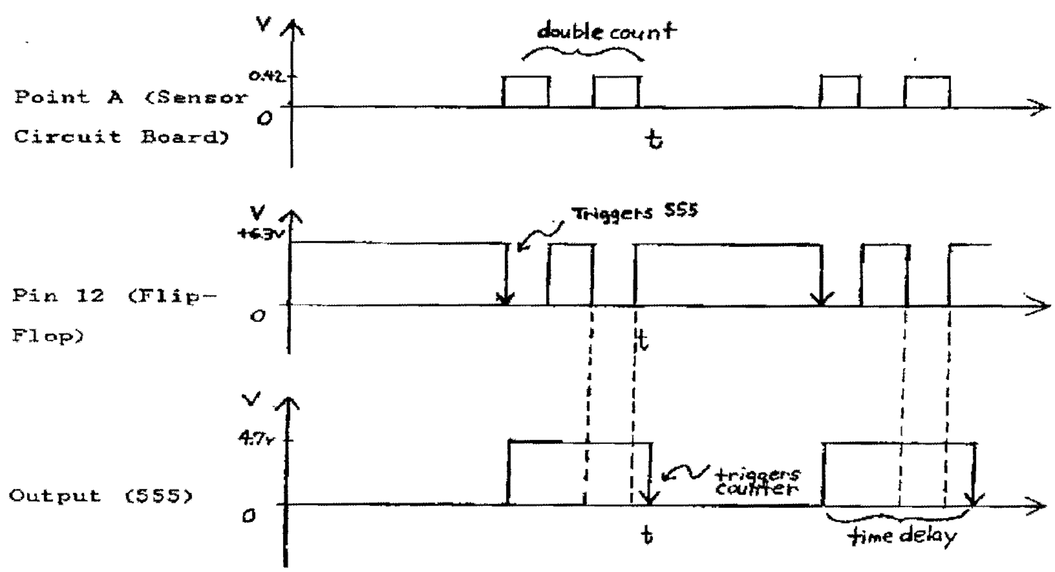


Figure 3. Timing diagram.

Counter Circuit Board: The output pulse produced by the 555 is coupled to Pin 14 of the first SN74LS90N Decade Counter (see Fig 4). Four SN74LS90N ICs are used to produce a counter capable of counting to a maximum of 9,999 events. Four 7490's are cascaded together to form the complete counter. The inputs to the second, third, and fourth decades come from Pin 11 (Q8) of the previous decade. When Pin 8 of one decade changes form high to low, it triggers the count for the next higher-order decade.

Output Pins 12 (Q1), 9 (Q4), 8 (Q6), and 11 (Q2) of the 7490 are fed to input Pins 7, 1, 2, and 6 of the SN74LS48N (BCD to 7-Segment Decoder-Driver) respectively. The 7448 decodes the binary coded decimal values into seven high and/or low voltage levels for driving the display. These seven decoded voltage levels display a decimal numerical value on a MAN74A724E common cathode seven-segment display.

Since four seven-segment displays are used in this design, the parallel combination of four 47 ohm resistors were replaced with a single 12 ohm resistor. This resistor (R17) is connected from Pin 12 of the seven-segment displays to ground.

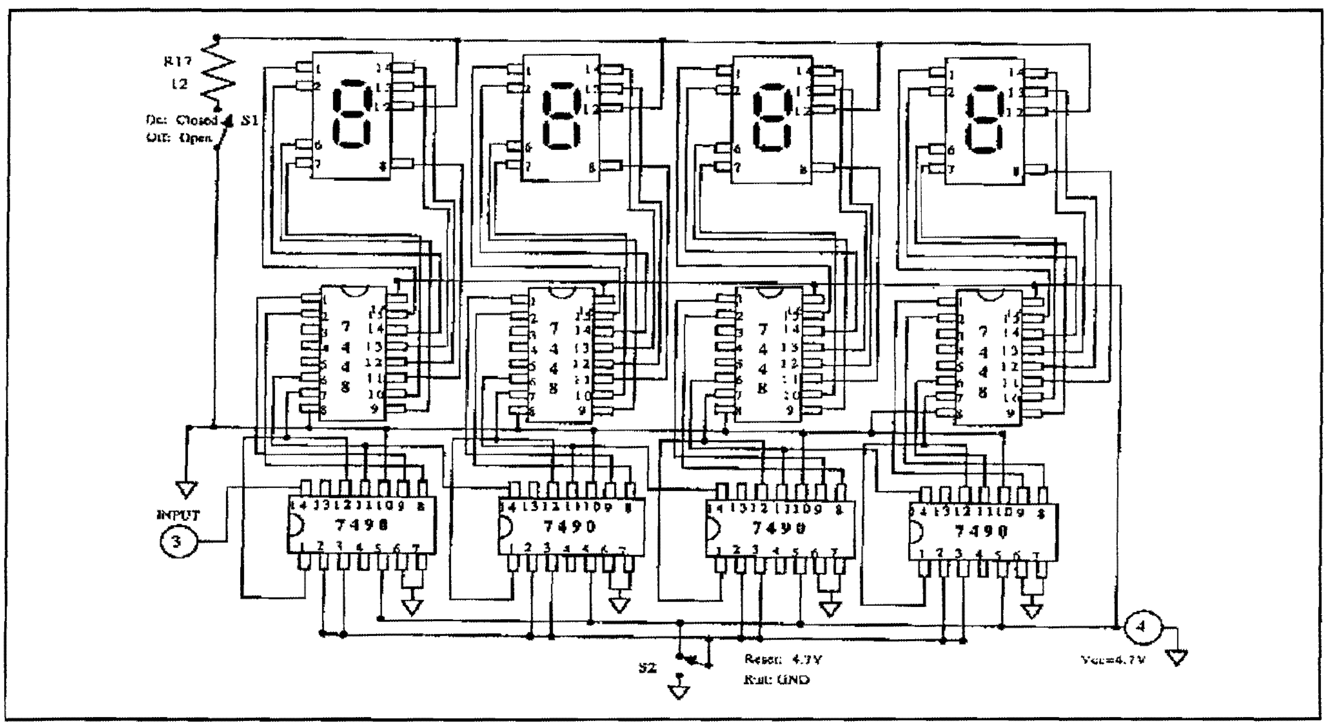


Figure 4. Counter circuit.

Infrared Traffic Counter Testing: During the design and development of the infrared traffic counter, the counter circuit board and trigger circuit board were individually designed and tested. After successful completion of individual circuit board design and testing, both circuit boards were interfaced and testing was again performed. The following section describes many of the testing procedures used. Also included in the following section are descriptions of various problems encountered during the design process and methods used to solve them.

Counter Circuit Board Testing: The counter circuit board was designed first. The SN74LS90N was connected for BCD counting. A SPDT (single pole double throw) switch was used to simulate a +5 to 0 volt clock pulse. The outputs were checked to see if the 7490 produced a binary coded decimal count. This process was repeated for all four 7490 ICs. Next, the outputs of the 7490s were connected to the corresponding input pins of four SN74LS48N ICs. The 7448s were then checked to see that the proper decoding necessary to drive the seven-segment displays was produced. Finally, four MAN74A724 seven-segment displays were connected to the outputs of all four 7448s. Problems were encountered at this stage owing to the use of common anode displays. Since a 7448 high output represents on, the common anode diodes in the seven-segment display were reverse biased. Once this problem was solved, and all three types of ICs were interconnected, a complete counter circuit test was performed. A 5 volt peak - 1 Hz clock pulse signal to the input Pin 14 of the 7490 was used. A visual inspection of the counting sequence generated on the four seven-segment displays was undertaken.

Trigger Circuit Board Testing: Testing of the trigger circuit board was done in the same manner as was previously done for the counter circuit board. Circuitry used in the this board was tested stage by stage until a complete working circuit was obtained. The LM324N operational amplifier was first connected in the comparator circuit. Tests were then performed to determine if the operational amplifiers in the LM324N ICs functioned properly in the comparator circuit configuration. The CD4013BCN SR flip-flop was then connected and tested. Only minor problems were encountered. The first problem was that the comparator circuit connected to the reset pin of the flip-flop did not reach a high state. This problem was solved by adjusting potentiometer R10 until a slightly smaller reference voltage was obtained.

A second problem was determining the capacitor value required at Pin 12 of the LM324N IC. Capacitor C3 controls the amount of time between the flip-flop being set and reset. Testing confirmed that a 10 micro farad capacitor provides an instantaneous, reliable reset of the SR flip-flop.

During the initial stages of the design, an NPN transistor was connected to the inverting output Pin 12 of the flip-flop. The transistor was used as a switch to produce a high to low transition to trigger the binary ripple counter. When using the transistor in this configuration, the minimum voltage capable of running the trigger circuit board was approximately 15 volts. When attempts were made to run the trigger circuit board at lower voltage levels, the inverting output Pin 12 of the flip-flop would not go from high to low. Calculations and further testing led to the conclusion that the transistor sinked too much drive current from the flip-flop, thus causing the flip-flop to be ineffective at lower voltage levels. At lower voltage levels the flip-flop could not provide the necessary power to drive the transistor. Testing verified that a low power 1N750A716 4.7 volt zenor diode could be used to force regulation of the output voltage produced by Pin 12 of the flip-flop. The zenor uses less power and therefore allows the flip-flop to drive the 555 and TTL binary ripple counter at voltage lower than 16 volts.

After testing of the trigger circuit board was completed, the trigger circuit board was interfaced with the sensor circuit board. Data collected during system tests verified that the sensor module causes double triggering to occur across the output of the zenor diode. To correct this problem, a ICM 7555 (low power 555 timer IC) was used.

Sensor Circuit Board: The infrared sensor circuit was obtained from Heathkit, Inc. Initially, no modifications were made to the circuitry. Field experiments (see Fig. 5) performed in the Research Park at Texas A&M University provided data indicating that the infrared sensor module detects movement other than that of vehicles. Testing resulted in the following conclusions.

1. When the sensitivity control knob of the potentiometer is turned counterclockwise, the sensitivity of the infrared sensor is increased.

2. When the sensitivity control knob of the potentiometer is turned counterclockwise, the infrared traffic counter will respond to much smaller thermal changes in its coverage area.

3. At the maximum counterclockwise sensitivity setting, movements of swaying trees and shrubs will cause enough thermal changes to activate the unit.

4. With the sensitivity control knob of the potentiometer turned clockwise, the unit will respond only to much greater thermal changes in its coverage area.

5. With the sensitivity control knob of the potentiometer turned completely clockwise, the unit will respond to movements of people and large animals such a horses and dogs.

Using the information above and by knowing that the resistance of the 500k ohm potentiometer is zero ohms in the fully rotated clockwise position, appropriate modifications were made to the sensor circuit board. The modifications were intended to provide a traffic counter capable of exclusively detecting vehicles. Potentiometer R1 was replaced with 100k ohm potentiometer. Implementing these changes in the infrared circuit board increased the sensitivity of the traffic counter, but not to the extent that it was able to be triggered by the movement of people and large animals. These changes did however prevent the traffic counter from counting events such as the passage of smaller animals.

Infrared Traffic Counter Installation: Securely fasten the main housing to a permanent fixture such as a tree or pipe. Connect the sensor circuit board housing to the main housing by inserting the bullet connector tagged A into the identically tagged female connector of the main housing. Repeat this process for the other connector. Next, connect the sensor circuit board housing to a pipe and position the unit at the side a road. For optimal results, position the sensor circuit board unit near a one lane bridge and elevate it to approximately one foot above ground level.

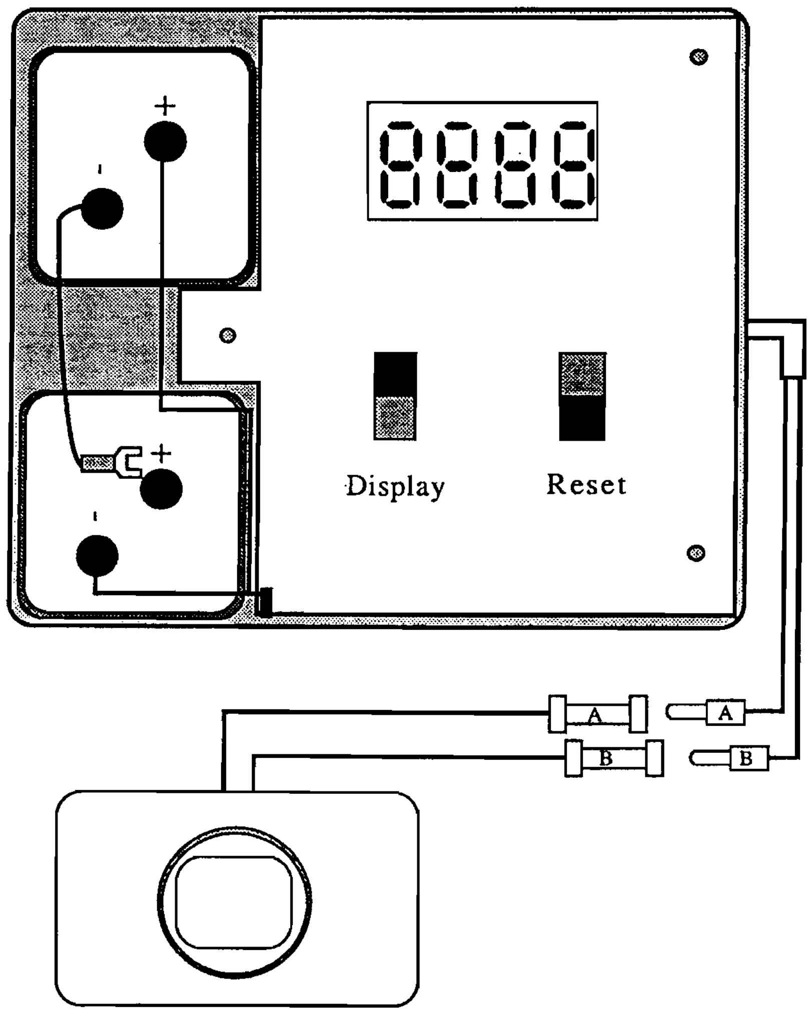


Figure 5. IR Traffic counter face plate.

Infrared Traffic Counter Operation: Open the lid of the main housing. Make sure the switch labeled RESET is positioned so that it is nearest the RESET instruction tag. There should be two six-volt batteries located on one side of the box. Using the battery connection wire, securely fasten the wire connectors (spade lugs) to the battery posts.

Make sure the connection is between the unused negative post of one battery and the unused positive post of the other battery. Next, wait approximately one minute and thirty seconds for system warm up. After warm up, slide the RESET switch to the position farthest away from the RESET instruction tag. The infrared traffic counter is now ready for operation. To visually observe a count of the number of events detected by the counter, position the DISPLAY switch to the position farthest away from the DISPLAY instruction tag. When the infrared traffic counter is left unattended for any extended period of time, it is important to make sure the DISPLAY switch is off (positioned such that it is nearest the DISPLAY instruction tag). Doing this will allow the batteries to last longer and the traffic counter to function properly for a longer period of time.

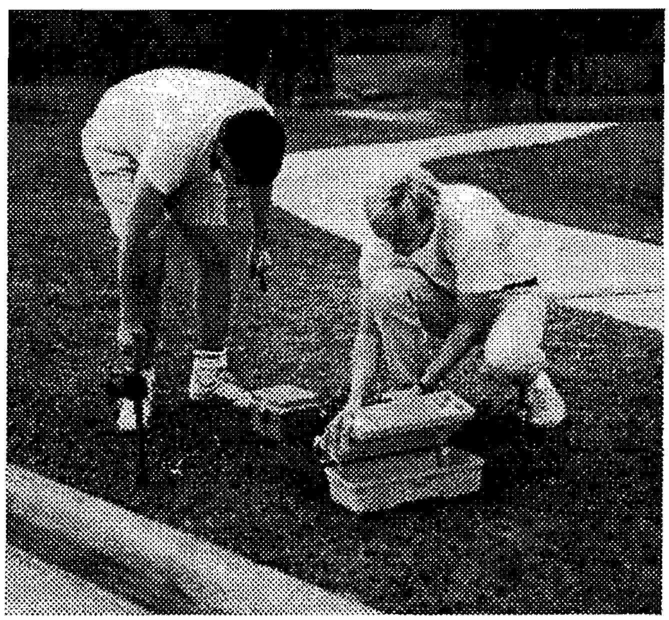


Figure 6. Richard Long and Keith Jones deploying unit.

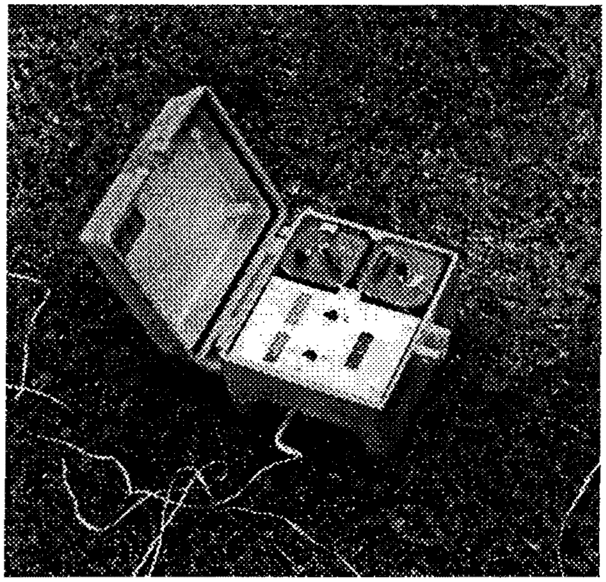


Figure 7. Prototype counter.

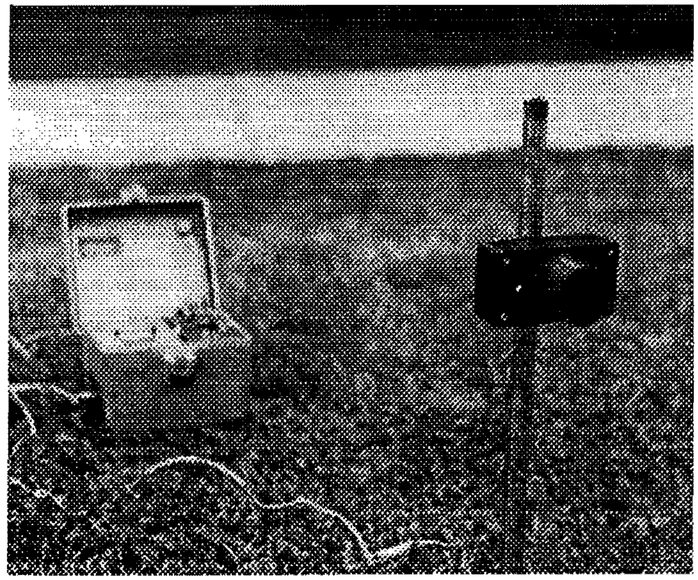


Figure 8. Counter with IR sensor.

SPECIFICATIONS

Range	60 ft.
Detection Pattern	Approx. 8 ft by 60 ft.
Detector	Passive infrared.
Sensitivity	Adjustable.
Operating temperature	0 to 120 degrees F.
Power requirements	12 VDC, 4-watts.
Trigger Delay	1.0 second.
Net weight	Approx. 5 lbs.

Parts List

Sensor Circuit Board

	QTY	DESCRIPTION	PART
Transistors	1	2N5305 NPN	Q3
	2	2N3906 PNP	Q1, Q2
Resistors 1/4 watt	1	10 ohm	R2
	1	100 ohm	R4
	1	10K ohm	R3
	1	100K ohm	R1
Capacitor	1	0.01 uF ceramic	C1
Diodes	4	1N4149	D1, D2, D3, D4
SENSOR	1	Heathkit infrared sensor. Part# 150-265 Phone (616)928-3571	Sensor Module
Circuit Board	1	Dimensions: 2 1/4" by 3 1/2"	
Miscellaneous	1	Roll double-stick foam tape	
	1	Roll of small gauge conductor cable	

Parts List

Trigger Circuit Board

	QTY	DESCRIPTION	PART
Integrated	1	LM324N	
Circuits		Op-amp IC package	
	1	CD4013BCN Flip-Flop	
	1	ICM 7555 Low power	
		555 timer	
Resistors 1/4 watt	1	10 ohm	R13
	1	100 ohm	R12
	1	470 ohm	R7
	2	100K ohm	R6
	1	220K ohm	R11
	1	3.3M	R5
	2	10K Pots	R15, R16
	1	20K Pot	R10
	1	50K Pot	R14
Capacitor	1	0.01 uF ceramic	C2
	2	10uF 50V	C3, C4
		(electrolytic)	
	1	100uF 35V	C5
		(electrolytic)	

Parts List

Counter Circuit Board

	QTY	Description	
Integrated Circuits(IC's)	4	SN74LS90N Ripple Counter	
	4	SN74LS48N BCD to 7	
Segment			
		Decoder Driver	
	4	MAN74A724E 7 Segment Display	
Resistors	1	12 ohm R17	
Miscellaneous	8	14-pin IC socket	
	4	16-pin IC socket	
	1	SPST slide switch S1	
	1	SPDT slide switch S2	
	1	1 1/4" by 2" circuit board	
	1	5 1/2" by 3 1/2" circuit board	
	4	1" metal spacer	
	2	1/2" plastic spacer	
Diodes	2	1N4149	D5, D6
	1	1N750A716 4.7V low power zener	D7
Miscellaneous	2	14-pin IC socket	
	1	8-pin IC socket	
	3	3/4" Metal spacer	
	1	2" by 5 1/2" circuit board	

Acoustic Signals for Detecting and Classifying Traffic: At the beginning of this project, we hoped to be able to develop a systematic approach to exploiting subtle characteristics in the sounds produced by traffic moving along roadways. First indications were promising. Samples of traffic sounds were recorded near College Station, Texas in 1988. These signals were converted to sound spectrographs using instrumentation in the Bioacoustics Laboratory at Texas A&M University. These early samples were remarkably free of background noise, were of low traffic densities, and were of vehicles with distinctive sound signatures. We found attempts to implement this concept as challenging as it is fascinating. However, our success with this approach was limited and it has not proved to be a useful technique.

The first stage in the investigation was to record a longer series of traffic sound samples. This was completed during the fall of 1989. These recordings were converted to digital form using a KAY model 5500 sonagraph. This instrument employs two AT&T high-speed digital signal processors allowing frequencies up to 36,000 Hz to be displayed in real time. We studied sound signatures from dozens of passing vehicles and searched for patterns upon which to base a counting and classification system. A visual examination of many spectrograms revealed the expected Doppler shift pattern associated with passing vehicles (Fig. 9). The Doppler shift curves always run from higher frequencies to lower frequencies. We were not able to see the Doppler shift pattern in some of the events we knew to be passing vehicles. Nonetheless, we felt that our best chance of success lay in exploiting the Doppler shift.

Even though the KAY 5500 is ideal for investigatory work, it does not provide output in the frequency domain. Sound signals transformed to the frequency domain and stored in computer memory are necessary for later digital processing. We studied product literature for suitable hardware which is compatible with the IBM PC computers in the Bioacoustics Laboratory. We decided upon the Microstar Laboratories DAP 2400/6 digital signal processor because of its advertised speed and versatility.

The DAP 2400 is a more or less complete data acquisition system which occupies one expansion slot in a PC. It combines analog

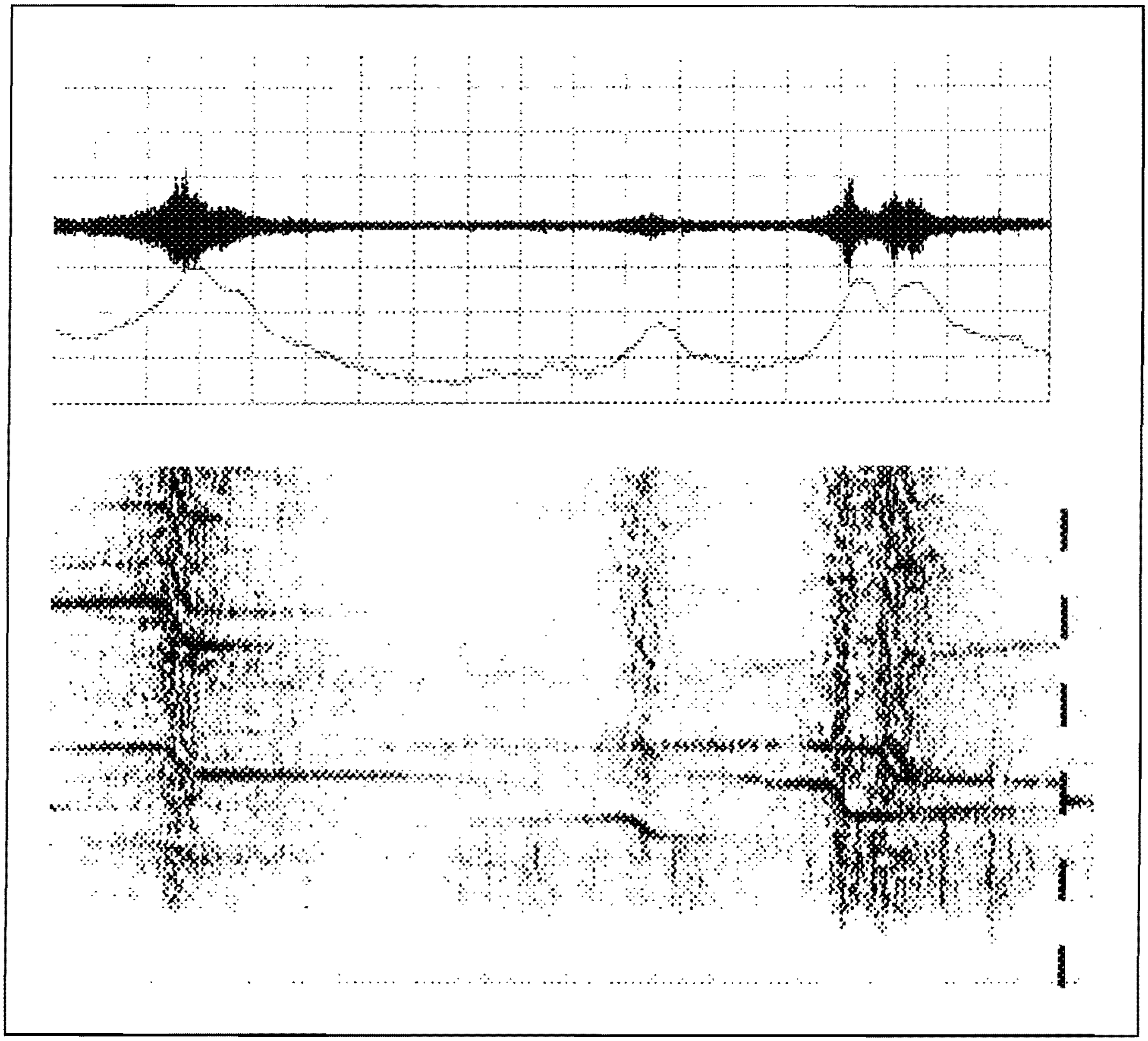
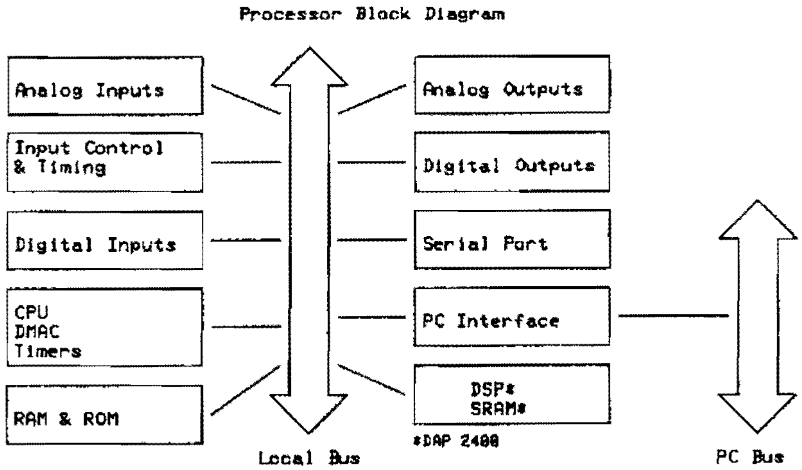
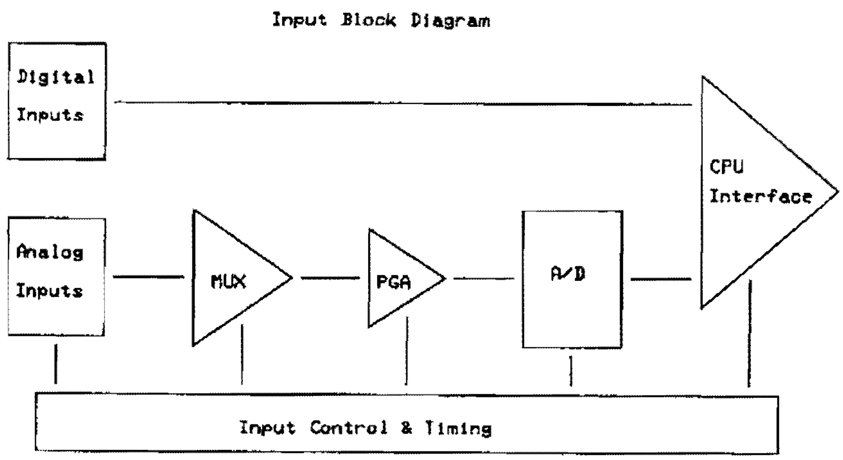


Figure 9. Spectrogram of moving traffic.

data acquisition hardware with a 16-bit microprocessor, a large buffer memory, and a real-time multitasking operating system called DAPL. The Data Acquisition Processor handles all the low-level details of data acquisition while performing computations in real-time. This frees the PC for user defined processing with the microcomputer hardware. The unit performs computations ranging from averaging and peak detection to digital filtering and fast Fourier transforms. These computations are implemented on a Motorola 56000 based digital signal processor. Figure 10 shows a block diagram of the Data Acquisition Processor, and a block diagram of the input section.



Data Acquisition Processor



Input Section

Figure 10. These are Figures 1 & 2 from the Microstar manual.

After several months of development, we were unable to design and code software which was significantly better at counting highway traffic than the infrared device described earlier. We presently believe that exploiting the acoustic signal from traffic would involve the development of complex and costly instrumentation equivalent to the classified systems used by the United States Navy in the submarine service.

One reason this concept fails is that many vehicles exhibit no easily recognizable frequency domain pattern. Although the Doppler shift is surely present in the signal, it is hidden in heavy noise.

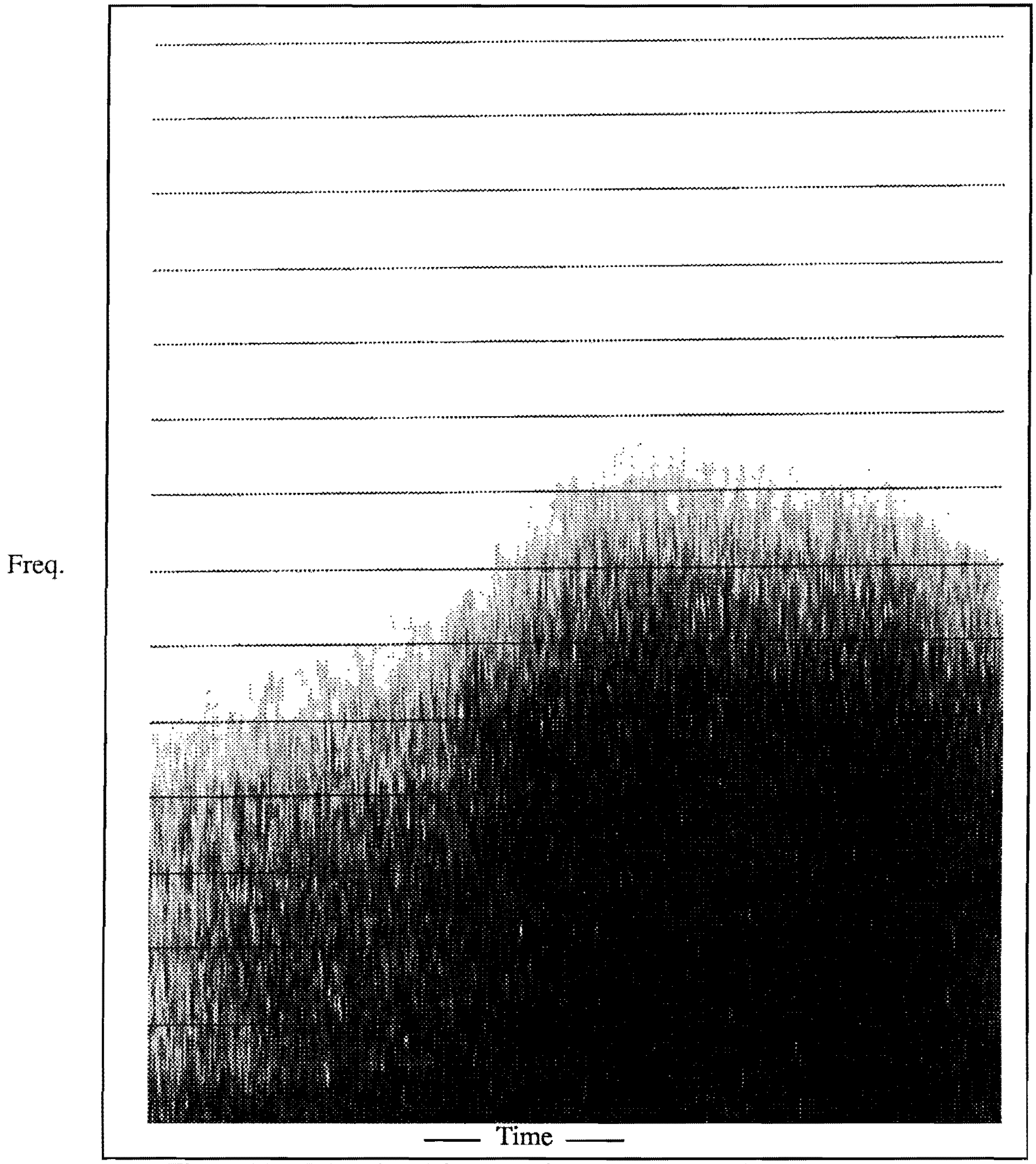


Figure 11. Noise signal from passing car. No Doppler pattern.

As an example, consider Figure 11 which is the sonagram of a passenger car at about 65 mph and a distance of 30 feet. Notice that the Doppler shift pattern is completely hidden in this example.

Two traditional methods of extracting the desired signal from the noise are: (1) use many repetitions of the sound, superimpose these and the random noise cancels out revealing the signal; (2)

have a clean copy of the expected signature with which to perform a cross correlation analysis thus improving the signal to noise ratio. Unlike a sonar operator listening to many repetitions of other subs with known signatures, neither of these methods are available for traffic classification. As a vehicle passes, we have only one repetition. Furthermore, with the exception of the Doppler shift, the details of the sound signature for each vehicle are different.

We did develop software capable of responding to the Doppler shift. However, it is not capable of dealing with signals hidden in noise or more complex signals associated with the simultaneous passage of multiple vehicles. A description of the program follows.

We connected the output of a Marantz PMD 200 cassette recorder to the single-ended S0 channel of the Microstar DAP 2400/6. This input channel is connected to a sample and hold circuit and sounds from the recorder are subsequently converted to 12-bit digital form and are continually fed into software pipe P1. The entire process is controlled by a Microsoft QuickBasic program listed at the end of this section. Please refer to this listing during the following software description.

We decided to restrict the range of the sound signal to a maximum of 500 Hz. Investigation using the KAY 5500 revealed that the Doppler shift pattern was most evident in this frequency band. Consequently, we chose the sampling rate to be 1250 Hz. Actually, we sampled at 12,500 Hz and then averaged every 10 samples to achieve the desired 1250 Hz. The Nyquist folding frequency for this sampling rate is 625 Hz which allowed for a liberal guard band.

We implemented a 40-tap low-pass digital filter and applied this filter to the data in pipe P1. The vec$ string in the Microsoft QuickBasic program contains the values of the taps. This filter assures that the values read from pipe P1 and into pipe P2 are restricted to the frequency band of interest. Pipe P2 is copied into pipes P3 and P4 for additional processing.

P3 is continually monitored to determine if the values in the pipe exceed a user defined level. If this level (corresponding to the loudness of the sound in the frequency band) is exceeded, the next 4096 averaged samples are collected from pipe P4 and passed to pipe P5. Using values in P5, a 256-point fast Fourier transform FFT and power spectrum calculation is performed and passed to pipe P_real. P_real is a long-integer pipe and is copied into short pipe P6.

To smooth the power spectrum, an eight-value running average is performed on pipe P6 and passed to pipe P7. The largest peak within the range from index number 20 to index number 110 is found and the index is moved to pipe p9. Since the power spectra are each 128 values long, 16 frames are investigated and 16 indices are passed to pipe P9. At this point the PC processor takes over and reads the 16 indices from P9 thus clearing P9. The DAP 2400 then continues searching and filling pipe P9 with addition groups of 16 values.

The PC does a regression analysis and calculates the slope of the best line through the 16 indices. It should be noted that the indices of the peaks are directly proportional to the frequencies of the peaks. Frames are ordered in time. The expected result is that the peak will start at a higher frequency and mover to a lower frequency (index) as times passes. This frequency (index) change from high to low is a result to the Doppler shift. If this does occur, the slope of the best line through the indices will be negative. A negative slope is counted as the passage of a vehicle.

We found that this system had an error rate of 19 percent. During a 15-minute segment of recorded traffic sounds, the system described here counted 58 vehicles. The true count was 72 vehicles. This means that the system was grossly undercounting events.

PROGRAM TO DETECT DOPPLER SHIFT IN TRAFFIC SOUNDS.

```
\**********************************************************
\*
\*     TTISLOPE
\*
\*   Written by Robert Benson  . . . . 02 Aug 90
\*
\*   Last Revision  . . . . . . . . . . 10 Sep 90
\*
\*   PROGRAM DESCRIPTION
```

```
'*
'*   This program attempts to count highway traffic
'*   use digital signal processing
'*
'*
'**************************************************************

      dim array(16)

      'This vector vec$ contains taps for a sharp-cutoff
      ' low-pass filter

      vec$ = "vector ttivec = (0,-1,0,7,-23,46,-65,"+_
           "59,0,-126,307,-489,576,-447,0,807,-1918,"_
"3173,-4337,5163,27306,5163,-4337,3173,"_-
"1918,807,0,-447,576,-489,307,-126,0,59,-65,"_
           "46,-23,7,0,-1,0)"

      call ttiinit    'Set up DSP board
      call ttistart   'Start DSP board

        print#1,"pipe p1,p2,p3,p4,p5,p6,p7,p8,p9,p_real long"
        print#1,"trigger t1"
        print#1, vec$
        print#1,"idefine a 1"
        print#1,"set 0 s0"
        print#1,"time 80"
        print#1,"average (channel 0,10,p1)"
        print#1,"end"

        print#1,"pdefine b"
        print#1,"rfilter(p1, ttivec, p2)"
        print#1,"copy (p2,p3,p4)"
        print#1,"limit (p3,outside, -1000, 1000,t1)"
        print#1,"wait(p4,t1,0,4096,p5)"
        print#1,"fft(4, 7, 2, p5, p_real)"
        print#1,"copy(p_real, p6)
        print#1,"raverage(p6,8,p7)"
        print#1,"findmax(p7,128,inside,20,110,p8,p9)"
        print#1,"format (p9)"
        print#1,"end"

      call ttierro 'Call for error checking

lbl:
      print#1,"start a,b"

      for i% = 1 to 16
      input#2,v
      array(i%) = v
      sumv = sumv + v
      next i%
      vave = sumv/16
      sumv = 0

      for i% = 1 to 16
      array(i%) = array(i%)/vave
```

```
      next i%
      vave = 0


      for i% = 1 to 16
      sumxy = sumxy + i% * array(i%)
      sumy  = sumy  + array(i%)
      next i%

      trys = trys + 1
      slope = (16*sumxy - 136*sumy)/.5440
      if slope<0 then car=car+1
      print using"####.###  ###  ###";slope,trys, car

      sumxy = 0 : sumy = 0

      if inkey$<>""then goto e1
      goto lb1

e1:
      call ttiterm ' 22000
      end

'*************************************************************
'*
'*      ttiinit.sub
'*
'*    Written by Robert Benson  . . . . 02 Aug 90
'*
'*    Last Revision   . . . . . . . . . 02 Aug 90
'*
'*    PROGRAM DESCRIPTION
'*
'*    This subroutine initiates the DAPL processer
'*
'*    ::::::::::::::::::::::::::
'*    :: FORMAL PARAMETER LIST ::
'*    ::::::::::::::::::::::::::
'*
'*    returns no parameters
'*
'*************************************************************


SUB ttiinit STATIC

      OPEN "ACCEL" FOR OUTPUT AS #1
      PRINT #1,"reset"
      ZZ! = TIMER

ttiinitlb1:
      IF (ZZ!+1) > TIMER THEN goto ttiinitlb1
      PRINT #1,"hello"
      OPEN "ACCEL" FOR INPUT AS #2
      IOCTL 1,"S,M44"
      GOSUB ttiinitlb2
```

```
EXIT SUB

ttiinitlb2:
     `  flush input subroutine
     `
     IF IOCTL$(2) = "0" THEN return
     ZZ$=INPUT$(1,#2)
     GOTO ttiinitlb2

END SUB


     \**************************************************
        \*
     \*   TTITERM.SUB
     \*   Written by Robert Benson .....03 Aug 90
     \*   Last Revision            .....03 Aug 90
     \*   Program description
     \*   This subroutine terminates the DAPL processor
     \*
     \*   ::::::::::::::::::::::::::
     \*   :: Former parameter list ::
     \*   ::::::::::::::::::::::::::
     \*
     \*   Returns no parameters
     \*
     \**************************************************

     SUB ttiterm STATIC

          IOCTL 1,"R"
          CLOSE
     END SUB

     \**************************************************
     \*
     \*   TTISTART.SUB
     \*   Written by Robert Benson  .......03 Aug 90
     \*   Last revision             .......03 Aug 90
     \*   Program description
     \*   This subroutine starts the DAPL processor
     \*
     \*
     \*   :::::::::::::::::::::::::::::
     \*   ::  Formal parameter list  ::
     \*   :::::::::::::::::::::::::::::
     \*
     \*   Returns no parameter
     \*
     \**************************************************

SUB ttistart STATIC


      PRINT #1,"reset"
      ZZ! = TIMER
```

```
ttistart1:
        IF (ZZ!+1) > TIMER THEN goto ttistart1
     GOSUB ttistart2

     EXIT SUB


ttistart2:

     '  flush input subroutine
        '
     IF IOCTL$(2) = "0" then return
     ZZ$=INPUT$(1,#2)
     GOTO ttistart2

     END SUB

      '***************************************************
      '*
      '*    TTIERRO.SUB
      '*    Written by Robert Benson ......03 Aug 90
      '*    Last revision
      '*    Program description
      '*    This subroutine detects errors in the DAPL
      '*    processor
      '*
      '*    ::::::::::::::::::::::::::
      '*    :: Former parameter list ::
      '*    ::::::::::::::::::::::::::
      '*    Returns no parameters
      '*
      '*
      '***************************************************



     SUB ttierro STATIC

     '  error detection subroutine
     '
     PRINT #1, "display errorq"
     INPUT #2,ZZ%
     IF ZZ% <> 0 THEN PRINT "Error detected in DAPL"_
          " commands";zz%: STOP
     EXIT SUB

     END SUB


     '***************************************************
     '*
     '*    TTIFLUSH.SUB
     '*    Written by Robert Benson  .....03 Aug 90
     '*    Last revision             .....03 Aug 90
```

```
'*   Program description
'*   This  subroutine makes flush input to the DAPL
'*    procesor
'*
'*   ::::::::::::::::::::::::::::
'*   :: Formal parameter list ::
'*   ::::::::::::::::::::::::::::
'*
'*   Returns no parameters
'*
'*******************************************************


     SUB ttiflush STATIC

ttiflushlb1:
     IF IOCTL$(2) = ''0'' THEN return
     ZZ$=INPUT$(1,#2)
     GOTO ttiflushlb1

     END SUB
```

CONCLUSIONS

The infrared counter prototype described in this report offers promise as a good alternative to the common ACR in certain special circumstances. We believe that active ultrasound would also be a promising basis upon which to develop a new system but need to be proven. We do not believe that counting are classifying traffic by sound signatures alone is a feasible approach owning to the varied sound signature arising from a host of vehicle types and ages, high noise levels, and the inability to capture repeated examples of sound from individual vehicles.