MULTI-PARAMETER VEHICLE FLOW DETECTION AND ANALYSIS

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by

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ABSTRACT

A synopsis of known vehicle detecting principles and detectors is given. The requirements for an ideal detector and its placement are analyzed to produce pulse outputs suitable for multi-parameter detection. Test results of several existing single pulse output type detectors are presented. The measurement of traffic volume, speed, density and vehicle length by converting elapsed time is examined. Error or accuracy formulae are derived, and a review of analog and digital techniques directly applicable to multi-parameter traffic flow analysis is included.

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INTRODUCTION

The rapidly increasing traffic flow on streets and highways and the construction of high level facilities such as freeways and expressways has created a number of problems as well as opportunities for the traffic Engineer. Today many electronic devices are employed in the general study, survey and control of vehicular traffic flow.

One basic element is common to almost every field of application, namely; the vehicle sensing detector. Up to the present, detectors provide one single electrical pulse per vehicle and these pulses are utilized principally in vehicle counters and traffic signal controllers.

There is a wider demand for vehicle flow parameters other than a vehicle count alone. Hopkins (3) introduced the idea of the "five purpose" or multi-parameter detector in 1961. The most useful parameters are:

1) volume or flow in unit time,
2) speed,
3) density or lane occupancy,
4) vehicle size,
5) and vehicle position on the roadway.

Almost all references from (2) to (14) use some form of vehicle detection from computer input to expressway surveillance. "The list of potential parameters seem endless" writes Barnes (7) referring to vehicle weight, type of pavement, weather conditions, visibility, temperature and others.

The aim of this study can be summarized as follows:

a) To review all existing detection principles and detector types and prepare a critical evaluation of each.

b) To develop the principles of converting pulses generated by moving vehicles into data in a form that may be used for multi-parameter detection.

c) To introduce different designs for multi-parameter detection system, using analogue and digital techniques.

The conclusion of this work is that not one but many multi-parameter detector types may be realized. How simple or elaborate a design should be, must depend upon its field of application.

The author had many helpful suggestions from Professor Hugh A. MacDiarmid and from the staffs of the departments of Electrical Engineering and Physics for which he wishes to express his sincere thanks.

CHAPTER I

VEHICLE DETECTORS

I (a) Detector types and operating principles

Many physical phenomena has been tested and applied to the detection of moving vehicles. The principles of mechanics, acoustics, electric and magnetic forces, optics, radio-technics, even radioactivity have being applied in a multiplicity of vehicle detectors marketed today. It becomes an ever growing problem to make the right choice for a particular application. Basically these detectors provide one (sometimes two) pulse per vehicle and are input devices to anything from a simple counter or traffic signal controller to a general purpose computer.

These fields of applications are setting more or less stringent requirements. It has therefore become important to summarize the properties of detecting principles showing the possible uses, advantages and disadvantages of each type of vehicle detector.

Valuable contributions were made by Hewton (12) and Christensen (14) who conducted detector evaluating experiments as input devices for a general purpose computer in Toronto and pioneered the installation of the World's first in-line, real-time general purpose computer, led by Cass and Casciato (9).

Table 1 (Page 3) was prepared for a convenient and quick review of vehicle detectors, the classification being according to operating principle, installation, placement, or mounting. A more detailed summary is given in Appendix 1 (Page 72).

A symbol was suggested in connection with each type of detector in Table 1, which has not been used in the literature on the subject since vehicle detectors were introduced. The graphic symbols are distinctive, with arrows indicating mechanical pressure on all units using mechanical force for actuation. The first letter within the drawings indicates the type of detector and the last is always the letter D, meaning detector. (TD=tube detector: USD=ultrasonic detector etc.)

There is one property common to all detection principles in Table 1. An electric pulse of some shape and duration is discharged at the output terminals of each vehicle detector.

TABLE I.

CLASSIFICATION OF VEHICLE DETECTORS BY OPERATING PRINCIPLES – MOUNTING AND INSTALLATION.

OPERATING PRINCIPLE	SUGGESTED SYMBOLS	GROUND BASED DETECTORS			OVERHEAD DETECTORS
		UNDER PAVEMENT	IN PAVEMENT	ON PAVEMENT	
MECHANICAL	T ↓ D			RUBBER AIR TUBE	
	P ↓ D		PRESSURE PAD		
	S ↓ D	STRAIN GAUGE			
	C ↓ D			CONTACT STRIP OR CABLE	
MECHANO-ACOUSTIC	I ↓ D		IMPACT		
MAGNETIC	M.L.D.		METAL LOCATOR		
	M.F.D.	EARTH'S FIELD			
	M.B.D.		MAGNETIC BRIDGE		
OPTICAL	PH. D.			PHOTO-ELECTRIC	
	I R D				INFRA-RED
ACOUSTIC	USD				ULTRASONIC
RADIO-ACTIVE	G. C.			GEIGER COUNTER	
ELECTRO-MAGNETIC WAVES	R.D.				RADAR
	L. D.		LOOP	TEMPORARY LOOP	
ANY DETECTOR	D	GENERAL DETECTOR SYMBOL			

I (b) Errors of detection

In every measurement problem the question of accuracy is of importance. The final value shown by a measuring device is only accurate to a degree, which should be numerically stated as a percentage.

The accuracy of a detecting system must therefore be examined. For this purpose two detectors will be placed at a short distance apart. A vehicle passing over the detectors will generate two pulses. The time lapse between the pulses will be measured and the speed of the vehicle will be calculated.

The accuracy of the speed measurement due to detector spacing and the method of calculation will be examined.

The term, short detector spacing, must be qualified. Suppose that the speed of a vehicle is changing over the detection area either because of acceleration, or deceleration. Studies in references (1 & 10) show that the motion of automobiles, under such circumstances, may be approximated by the laws of uniformly accelerated or decelerated motion.

Since it is very difficult to reproduce all possible situations in vehicle motion the worst case is taken here, that is a vehicle uniformly accelerating from standstill. It may be shown that the relative error E increases as the speed approaches zero (refer to Figure 1). Comparison of the approximating chord speed vector v with the real speed tangent $V(t)$, at low and high speeds shows a diminishing difference at the higher speeds.

The S co-ordinate is divided into ΔS spacing intervals which corresponds to the distance between detectors. In a given experiment Δs remains constant.

The formula of uniformly accelerated motion is expressed by:

$$S = \tfrac{1}{2} a t^2 \qquad \text{-------------- 1.}$$

where S is the distance a body moves under uniform acceleration (a), as a function of time (t).

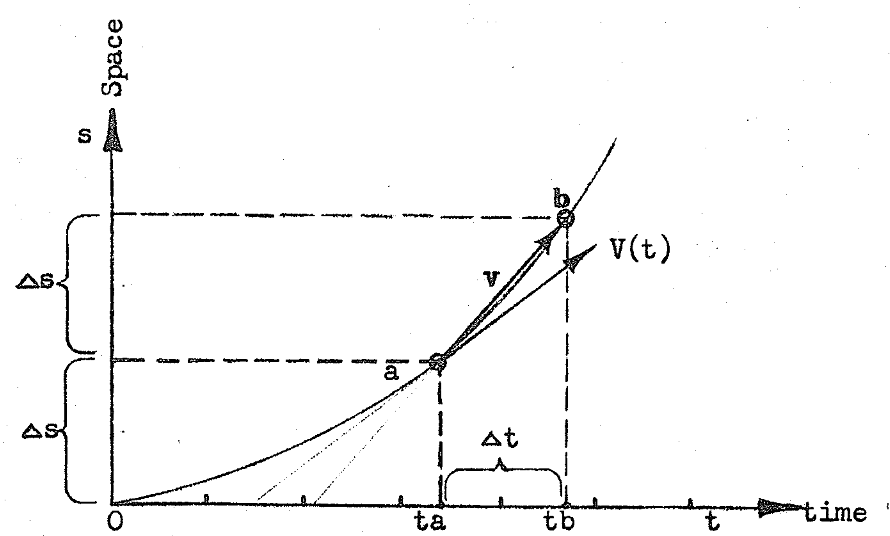


FIGURE 1

The curve of uniform accelerated motion. ΔS is constant detector spacing in a given experiment. v is approximated by $\Delta s/\Delta t$ and $V(t) = ds/dt$ is the correct speed.

It should be noted that the time interval diminishes as the speed increases.

The true speed is:

$$V = \frac{ds}{dt} \qquad \text{-------------------------2)}$$

The approximated speed is:

$$v = \frac{\Delta s}{\Delta t} \qquad \text{----------------------- 3)}$$

And the relative error is:

$$E = \frac{\Delta V}{V} = \frac{v - V}{V} \qquad \text{--------------------- 4)}$$

By differentiating equation 1, at the point "a"

$$V_a = a\,t_a \qquad \text{-------------------- 5)}$$

and expressing the approximate speed between "a" and "b"

$$v = \frac{\Delta s}{\Delta t} = \frac{\frac{1}{2} a t_b^2 - \frac{1}{2} a t_a^2}{t_b - t_a} = \frac{a(t_b + t_a)(t_b - t_a)}{2(t_b - t_a)} = \frac{a(2t_a + \Delta t)}{2}$$

$$v = \frac{1}{2} a (2t_a + \Delta t) \qquad \text{---------------------- 6)}$$

The speed difference is:

$$\Delta V = v - V = \cancel{a t_a} + \frac{1}{2} a \Delta t - \cancel{a t_a} \qquad \text{-------------------- 7)}$$

$$\Delta V = \frac{1}{2} a \Delta t$$

The expression of the relative error, using equations 5) and 7) is now:

$$E = \frac{\Delta V}{V} = \frac{\frac{1}{2} a \Delta t}{a\,t_a} = \frac{\Delta t}{2t_a} \qquad \text{---------------------- 8)}$$

This form of the relative error is not readily usable because it involves the time instant t_a. (It is related to the zero point of time scale). A more convenient formula for practical calculations is given if the relative error is expressed in terms of the real speed and acceleration. Substitute the speed difference from equation (7) into equation (4) then the error is

$$E = \frac{\Delta V}{V} = \frac{\frac{1}{2} a \Delta t}{V} = \frac{a \Delta t}{2V}$$

Thus the relative error is obtained in its final form, (Equation 9).

$$\boxed{E = \frac{a \Delta t}{2V}} \quad a=\text{constant} \qquad \text{------------------ } 9)$$

It was shown in Figure 1 and now by equation 9 that for constant acceleration (a), if Δt is small (the time interval between start and stop pulses) the error is small.

In summary of this section, equation (9) expresses the error of speed calculation due to a time lapse measurement technique resulting from the geometry of detector placement. The error formula so derived may be re-written and a relationship may be established to express the relative error as a function of detector distance. This is the designer's approach to the problem.

The user of detectors for speed measuring is faced with the following task:

Calculate a detector spacing to provide start and stop pulses for the measurement of elapsed time and secure predetermined accuracy in speed conversion using the approximate formula

$$v = \Delta s / \Delta t$$

Express $\Delta s = v \Delta t$ and substitute Δt from equation 9, and

$$\Delta S = v \frac{\varepsilon 2 V}{a} \qquad \text{------------------10)}$$

is obtained, where v is the approximate speed and V is the real speed. Now ($v \approx V$).

This gives the detector spacing ΔS as

$$\boxed{\Delta S = \frac{2 \varepsilon V^2}{a}} \qquad \text{----------------11)}$$

This formula is the design equation for detector placement.

The results of calculations using this design equation, are shown in Table 2 and Figure 2. A maximum error of 10% is usually specified. The acceleration of vehicles in one case is taken as a=2 MPH/Sec, and in the other a=4 MPH/Sec. They represent average and large accelerating values for passenger vehicles and were taken from the Traffic Engineering Handbook (1).

TABLE 2

To achieve a maximum error of 10% above the speed chosen, a detector spacing of $\triangle$S feet or less must be maintained

Maximum error 10%; E = 0.1			
V speed		S feet; detector spacing	
M.P.H.	feet/second	a=2 m.p.h./sec	a=4 m.p.h./sec.
1	1.466	0.1466	0.0733
2	2.93	0.586	0.29
3	4.4	1.32	0.66
4	5.85	2.34	1.17
5	7.33	3.66	1.83
6	8.8	5.28	2.64
7	10.26	7.18	3.59
8	11.73	9.38	4.69
9	13.2	11.88	5.94
10	14.66	14.66	7.33

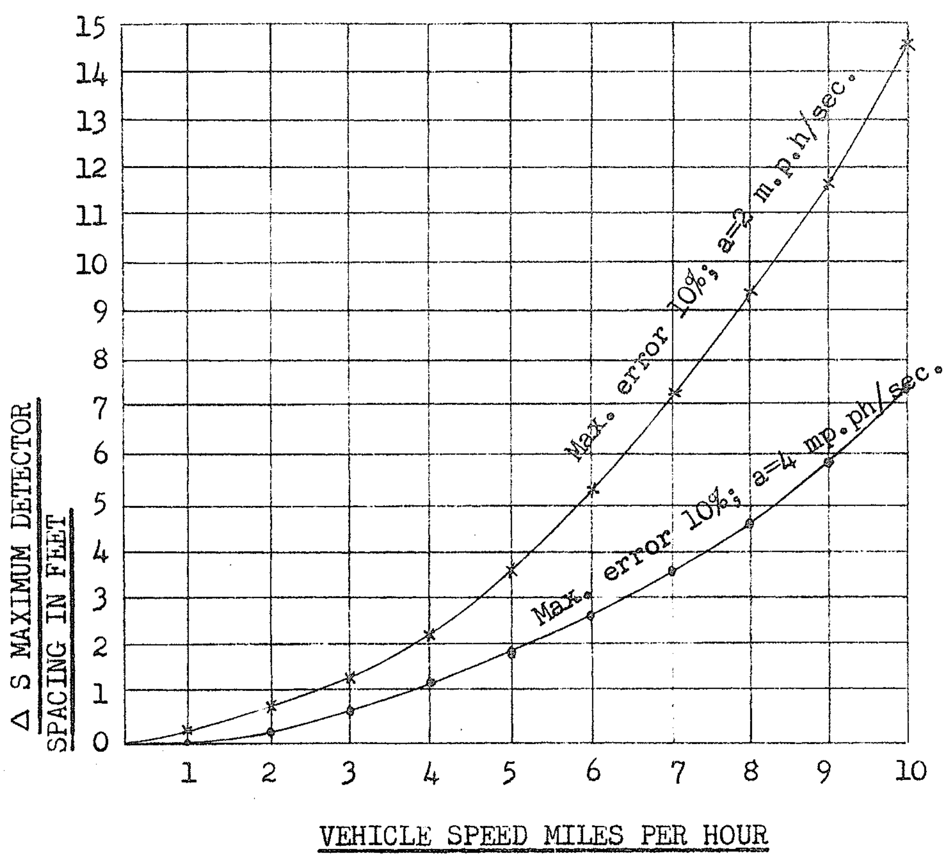


Figure 2

Curves and table of detector spacing calculation based upon a maximum of 10% error as a function of speed

It can be seen that for an accuracy of better than 90% and for large accelerating values a small detector spacing must be chosen. For example: To detect a speed of 5 MPH with better than 90% accuracy a detector spacing of 1.83 feet or less must be chosen. When the same accuracy or better is required at V=10 MPH or more, it may be achieved with a detector spacing at 7.33 feet or less.

The designer may substitute different error criteria into equation 11, which is general and may be used in other elapsed time detecting problems. The previous calculations included in Table 2 and Figure 2 are merely a demonstration of the use of this formula.

At this point attention is drawn to the contents of Table 2, (P.73). It was shown that for accurate speed measurement by the elapsed time method, particularly at low speeds, detector distances as small as one or two feet may be necessary. Some detector types are immediately ruled out for multi-parameter detection by this criterion. A detector in such an application must have a well defined line or area of detection and must provide sharp fast rising pulses regardless of vehicle shapes, lateral placement, frame or body height.

In the next section a discussion of pulse shapes is given, especially from the point of view of further error possibilities in measurements, introduced by the detecting apparatus.

I (c) Analysis of detector pulses

Time delays caused by detector circuits are so small compared to the millisecond rise time and time durations encountered in vehicle detection, that they will be neglected in this section.

With the exception of the pressure type detectors the energy of input pulses are not large enough to operate further stages without amplification. The pneumatic tube detector is simple, the area of detection is well defined and therefore it very closely approaches being an ideal detector. Unfortunately however it is vulnerable to damage by impact, snow plows, street sweepers, and it becomes brittle in cold weather and may be covered with snow or ice. Operated by the wheels of vehicles, it does not give a signal that is truly proportional to the vehicle length. For all these reasons the pressure type detectors are rejected for multi-parameter detection.

At the present time loop detectors provide the best compromise between the simple pressure type and all other detectors that require amplification. Figure 3 shows an arrangement of an ideal detector system, in which there are two lines of detection. Pulse shapes generated by loop or other similar detectors will be compared to the ideal one. The effects of rise time, triggering level, amplitude level changes and distortion will be analysed. First examine the pulses generated.

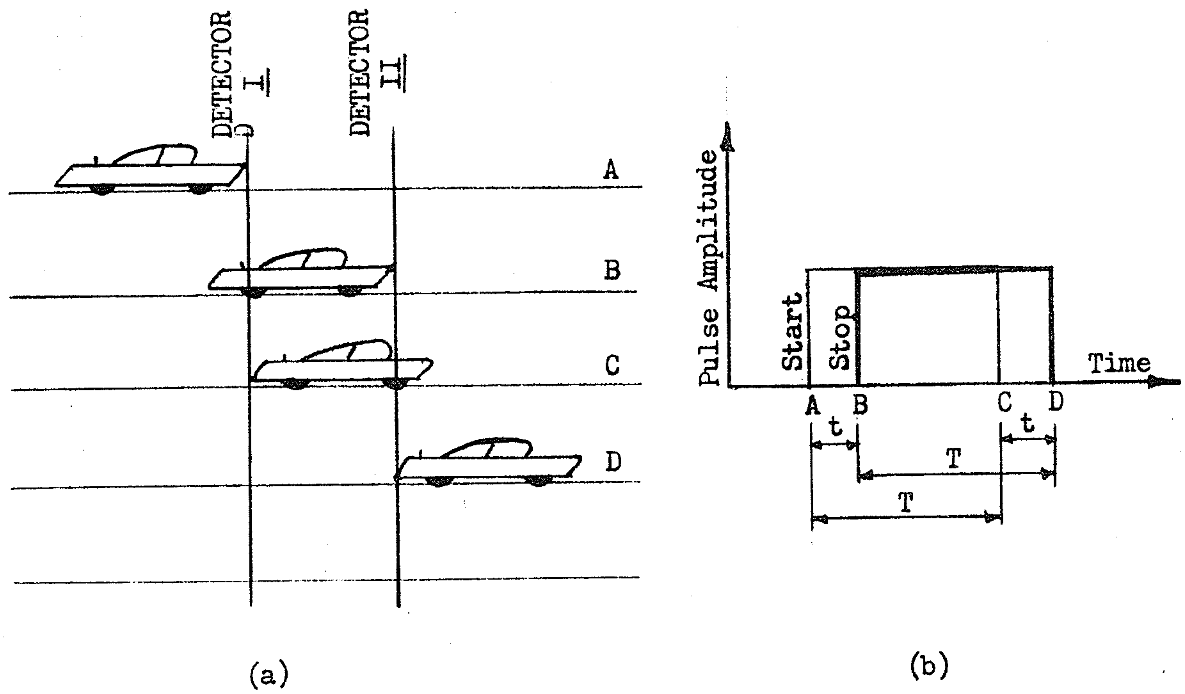


Figure 3

TYPICAL POINTS OF A VEHICLE PASSING TWO LINES OF DETECTION

a) shows a vehicle passing over two ideal detectors;

b) generates two ideal pulses.

Characteristic points of travel are marked as A,B,C and D. When a vehicle passes over two separate lines of detection, it will generate two overlaping ideal pulses. (Fig.3)

There are four characteristic points of the resulting pulses:

A.	Arrival at loop 1	Start)	Defines: t
B.	Arrival at loop 2	Stop)	
C.	Departure from loop 1	End of first T interval)	Defines: T
D.	Departure from loop 2	End of second T interval)	

These four points will give the required intervals for the derivation of different parameters in the next chapter (II).

An excellent example of the use of such pulses is given by Brainard, Trabold and Becker of the General Motors Research Laboratorys (14) who designed and built a data recording system for traffic flow analysis. This system uses photoelectric detectors, in an experiment in the New

York Tunnel (18). Each event (A.B.C.D.) is detected and time data is punched onto a tape in digital form. However there were no speed, density or other parameters calculated. The punched data may be fed into a General Purpose Computer for **numerical** analysis.

While the authors state "it is desirable to set the distance between detectors to be as short as possible" they used a spacing of 12 feet. After consideration of punch tape recording rate S_p, the number of characters required per event N, and the maximum vehicle speed, the optimum detector distance L_d was found by them to be:

$$L_d > \frac{V_m N}{S_p} \simeq 12 \text{ feet}$$

A twelve foot distance however will give less than 90% accuracy at speeds below 15 MPH according to equation 11, which was developed previously.

Actual detectors do not give ideal square pulses.

Loop detectors will be considered instead of ideal lines of detection in the following discussion. A closer look reveals that instead of ideal square pulses, a rise time and amplitude changes result from the loop detector pulses. Figure 4, shows that the loading and unloading of the loop coil by the moving vehicle gives a rise time of t_1 to t_2 and fall time t_3 to t_4 and may produce an amplitude A_1 with one type of vehicle and A_2 with another. The time axis and the vehicle length of Figure 4 are not to scale. In practical applications the rise and fall times (t_2-t_1) and (t_4-t_3) are much less than (t_3-t_2).

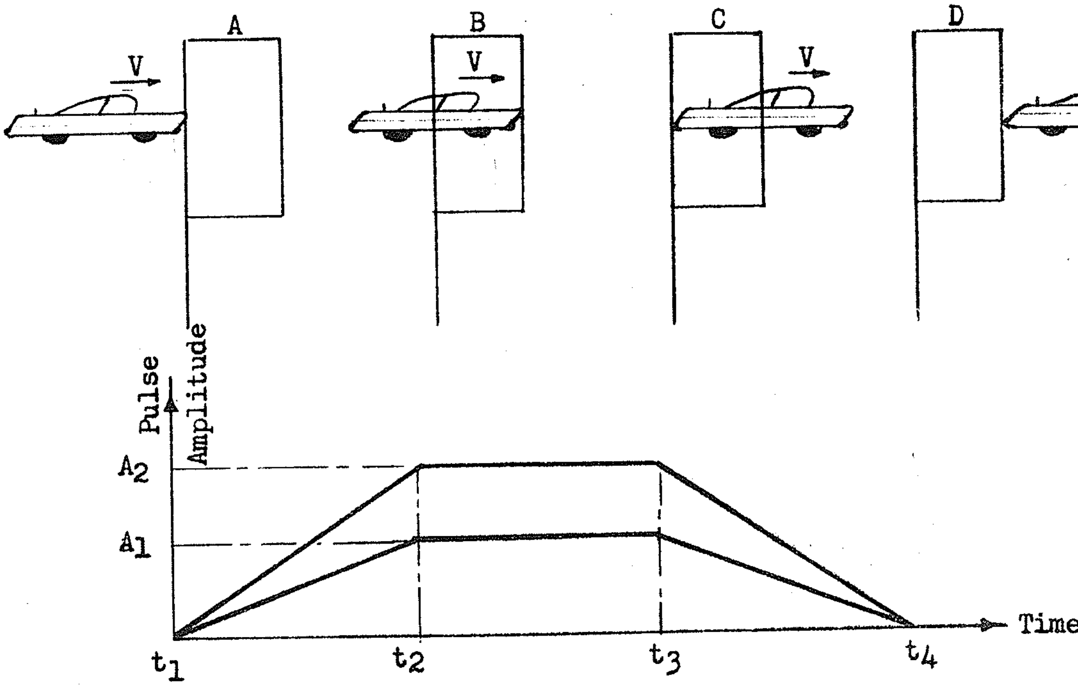


Figure 4

Demonstration of rise time and fall time of loop detector pulses.

Several experiments were conducted to analyze the affect of different vehicles on the pulse amplitudes. The experimental arrangements are shown in Figure 5.

A tube detector (D.T.) and a loop detector (L.D.) were installed 9 feet apart in such a manner that vehicles actuated the tube detector first. The tube detector actuated the triggering amplifier thus providing a start pulse for the two Y beams of the triggered time-base oscilloscope. A camera attached to the oscilloscope was also opened in synchronization with the tube detector pulse and thus a complete loop detector pulse was photographed, including the rising slope, each time a vehicle was detected. The second beam of the oscilloscope was modulated by a tone generator to provide a time scale for convenient time-scale reference.

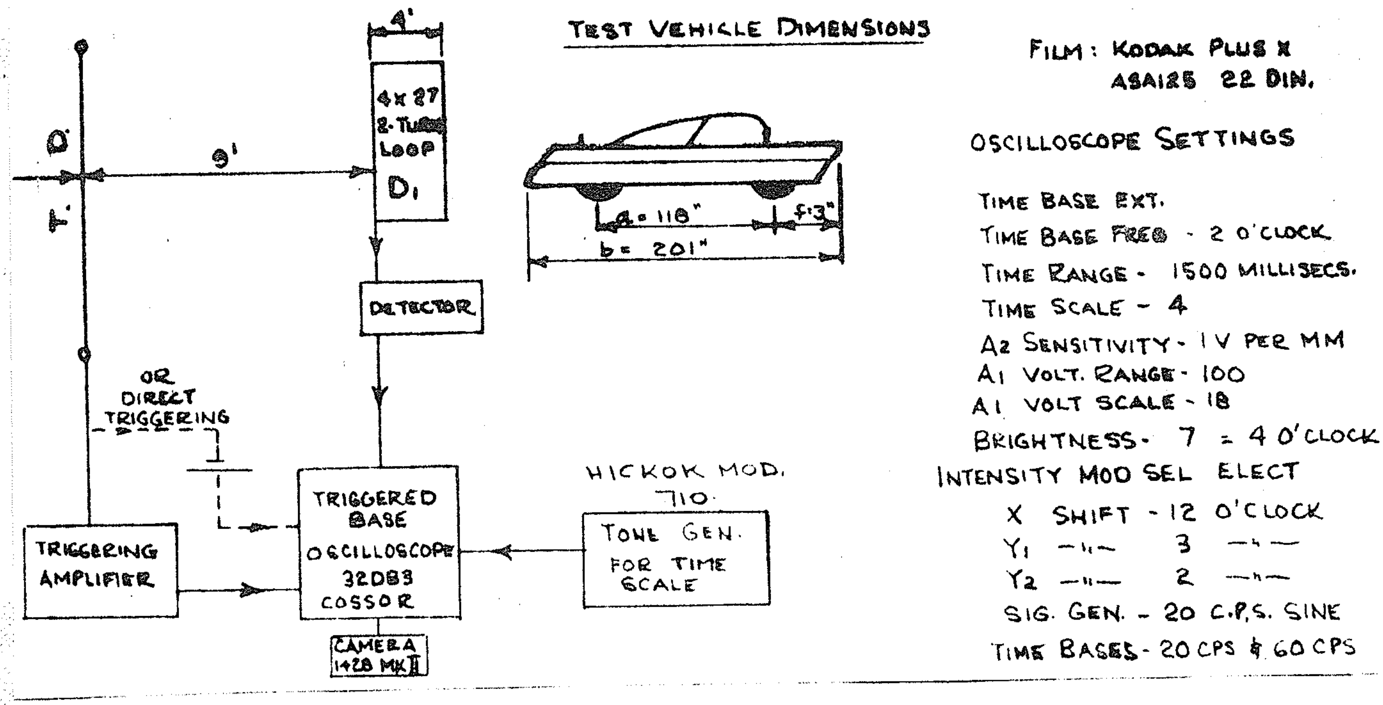


Figure 5

Experimental arrangement for detector pulse analysis

These experiments revealed that pulse heights with some of the detection circuits are dependent upon the height and size of the vehicle frame. The oscillograms taken show this and it will be discussed later.

In summary, pulse provided by real loop detectors are not ideal square waves and may have different amplitudes. An acceptable detection system must be so designed that a predetermined level of measuring accuracy is secured, regardless of the differences in pulse shapes. The accuracy in any given measurement is dependent upon the physical parameter being measured.

With the aid of Figure 6 the dependence of time intervals and traffic flow parameters on the pulse shapes was analyzed. Among the parameters listed in Chapter I the quantity (Q) of traffic flow or volume is the easiest to measure and it is completely independent of the pulse shape. The only criterion is a sufficient level of amplitude above the triggering level. If this condition is satisfied the volume of vehicles measured is completely accurate. (Coincidence of vehicles and other factors outside the detector may cause errors, but these are independent of the detecting principle and will not be discussed).

The effect of detector spacing ΔS on the accuracy of speed measurement was analyzed in Chapter I (b). The technique requires two detectors and the measurement of time lapse Δt. Figure 6 shows that Δt duration between two pulses is independent of the pulse shapes. The Δt interval may be obtained by simple amplitude level triggering as shown, and it is also independent, not only of the pulse shape, but of the triggering level. The only criteria regarding pulse shapes is that there must be indentical pulses provided by both loops, but some pulse distortion may be tolerated. Long term drift of the triggering level is also permissible as long as the two pulses representing one vehicle passage, are identical.

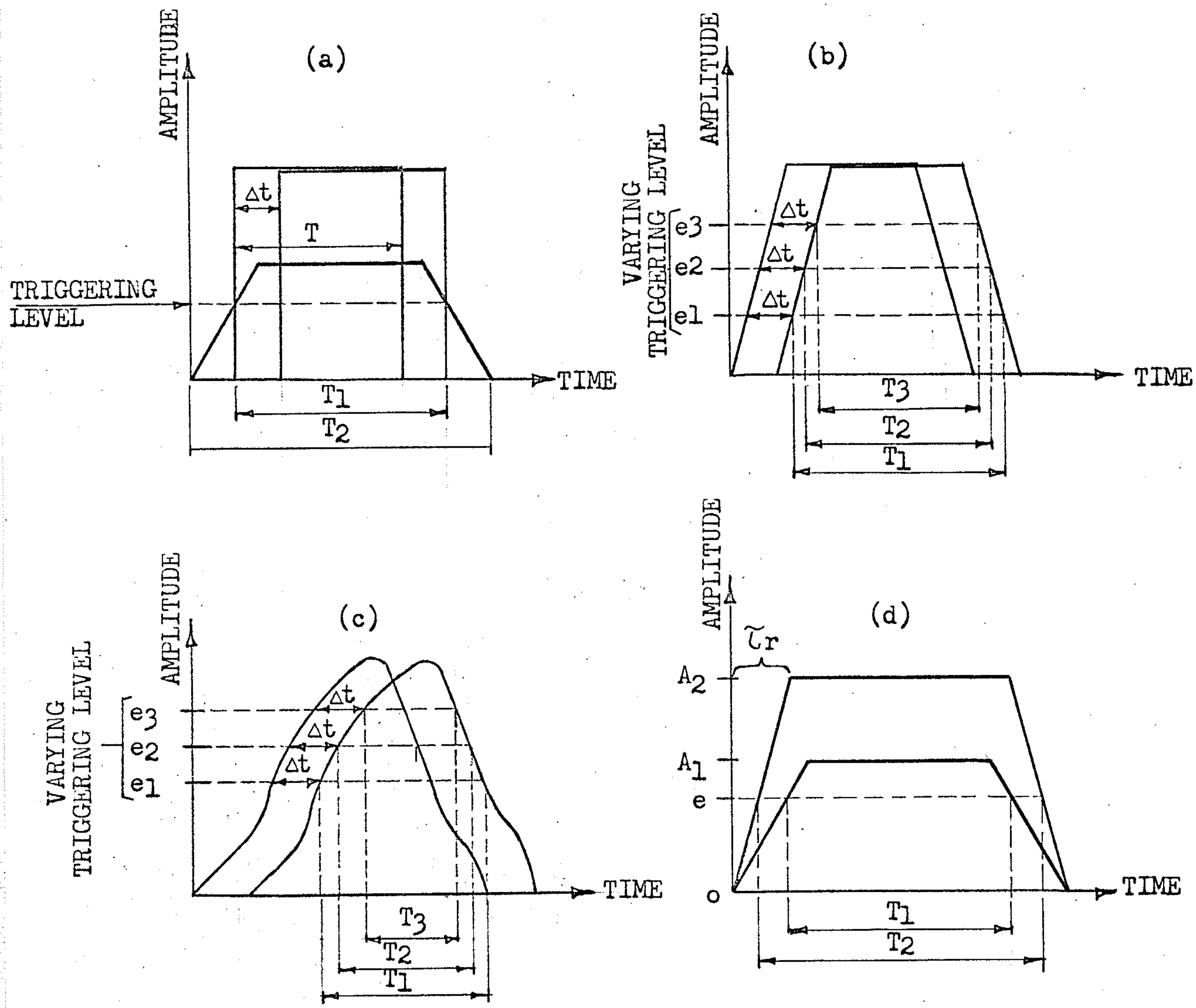


Figure 6

Effects of amplitude and pulse shape changes on the different time intervals used for measurements of traffic parameters.

One way of achieving uniformity is by using one single detecting circuit with two sensing loops. Then whatever changes occur in the detecting and amplifying system will affect both loops and both pulses in the same fashion.

Unfortunately the measurement of vehicle length "L" does not allow such freedom, since it involves measurement of the duration T of a single pulse. Changing triggering levels from the leading edge to the end of a pulse, (Fig.6d) may result in a different time interval T. While it is easy to stabilize the triggering level, it is more difficult to overcome the variation of amplitude levels that result from the differences in vehicle geometry, such as frame height and body structure.

This point brings to focus an earlier observation that a line of detection is more desirable than an area of detection. In the first case there is no rise time involved and with proper circuitry the output pulse has an almost ideal square shape.

I (d) Errors with varying amplitude levels and rise time

This section will analyze the accuracy of length measurement of moving vehicles. Rise time and amplitude changes due to varying body characteristics will be considered.

For the measurement of vehicle length the equation is $L = S\,T/t$ ...(27)

(The derivation of this formula will be given in the next section).

This equation is based on the assumption of an ideal pulse shape, with duration T.

A more realistic situation is shown in Figure 7.

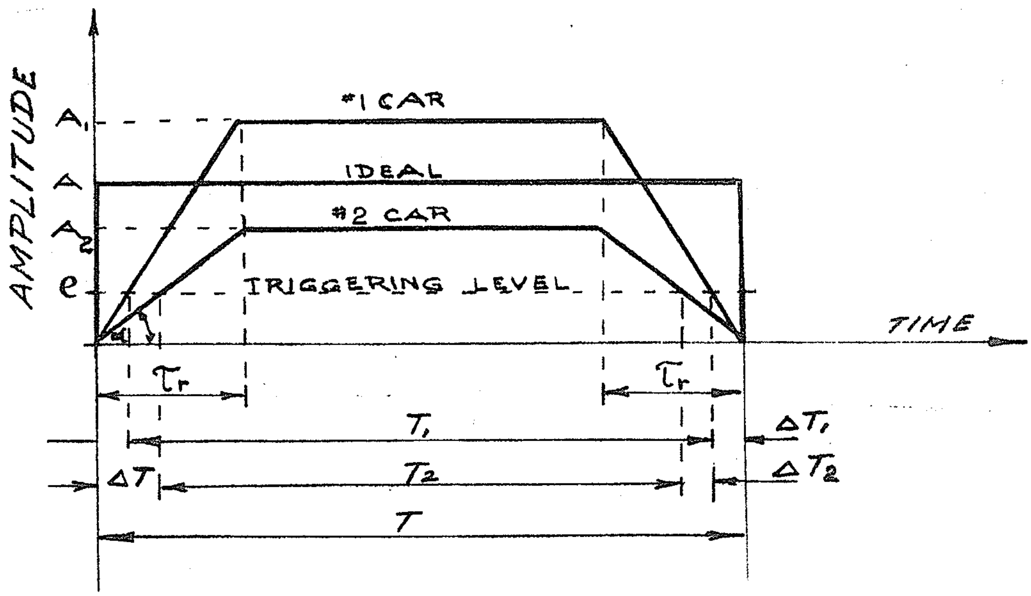


Figure 7

Comparison of low and high amplitude pulses, with an ideal pulse. The pulses are generated at the same speed by vehicles of the same length.

Shown are:

1) An ideal pulse having T duration and A amplitude.

2) An actual pulse having τ_r rise time, A_1 amplitude and T_1 duration due to e triggering level.

3) Another actual pulse having the same rise time but A_2 amplitude and T_2 duration. ($T_1 > T_2$)

4) In all three cases the vehicles, generating these pulses, have identical lengths (L) and speed (V) and produce the same rise times, yet there is an error in the measurement resulting from the recording of T_1, or T_2, instead of T.

By visual inspection it is seen that the larger error is caused by the smaller amplitude (A_2) signal.

The absolute error is $2 \Delta T = 2 (\Delta T_1 + \Delta T_2)$ and the relative error is:

$$E = \frac{2 \Delta T}{T} \quad \text{------------------12)}$$

In terms of the "pulse rise" angle α of Figure 7, ΔT can be expressed as:

$$\Delta T = \frac{e}{\tan \alpha} \quad \text{-----------------13)}$$

The combined form of these equations is:

$$E = \frac{2e}{T \tan \alpha} \quad \text{-----------------14)}$$

The tangent of the same angle may be expressed from the pulse height A and the rise time τ :

$$\tan \alpha = \frac{A}{\tau} \quad \text{----------------15)}$$

and the pulse duration T is:

$$T = \frac{L}{V} \quad \text{----------------16)}$$

(The proof of equation 16 will be given in the next section).

Substituting 15 and 16 into 14, the relative error due to rise time and varying amplitude is:

$$E = \frac{2e}{T \tan \alpha} = \frac{2e}{\frac{L}{V} \frac{A}{\tau}} \quad \text{-----------------17)}$$

The rise time may also be expressed in terms of speed (V), and loop width (W).

$$\tau = \frac{W}{V} \quad \text{----------------18)}$$

and the error is: $E = \dfrac{2e}{\frac{L}{\cancel{v}}\,\frac{A}{w}\,\cancel{v}}$

The speed term cancels, and the final form of the relative error function is:

$$\boxed{E = 2\,\frac{e}{A}\;\frac{w}{L}} \qquad \text{----------------19)}$$

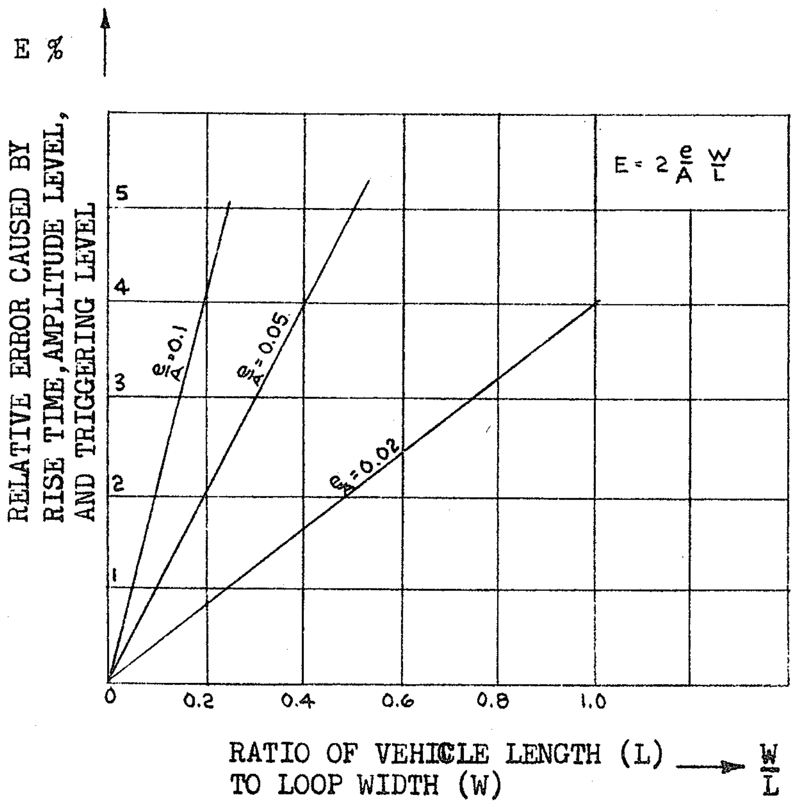
a) The formula proves the earlier statement that an ideal detector has a zone of detection of zero width, a condition which defines a line: if $w \longrightarrow 0$ than $E \longrightarrow 0$.

b) It shows that the ratio of triggering level (e) and amplitude (A) should be small, which requires large amplification <u>before triggering</u>.

c) It is evident that the relative error decreases with increasing vehicle lengths. The largest errors are encountered therefore with smaller vehicles.

A few results are calculated with the aid of equation 19 which in this form gives straight lines. E is error, e is triggering level, A is pulse amplitude, W is loop width and L is vehicle length.

The error in the measurement of vehicle length is therefore under control. For example, taking the shortest vehicles to be approximately ten feet in length, a loop width of 5 feet results in a ratio of $\frac{W}{L} = 0.5$. A triggering voltage of 0.1 volts with a pulse amplitude of 1 volt gives $\frac{e}{A} = 0.1$, then the maximum error is: $E_{max.} = 2 \times 0.1 \times 0.5 = 0.1$; ie. $E = 10\%$. A better result may be obtained by simply higher amplification before triggering. If $A = 10v$, the error becomes only 1%.



E : ERROR

e : Triggering pulse level in volts

A : Pulse amplitude in volts

W : Loop width in test

L : Length of vehicle in feet

Figure 8

Errors due to rise time and amplitude changes

I (e) Detector Tests

It was mentioned previously in section I (c), that actual measurements were performed on different types of loop detectors made by several manufacturers. The specified output of all detectors was one pulse per vehicle.

The experimental setup was as shown in Figure 5, and included a triggered time base oscilloscope with a camera unit. The measurements revealed some striking differences between the commercial units. Block diagrams and the operating principles will be given, without revealing confidential data.

All of the loop detectors utilize relative changes of loop inductance during the presence of vehicles inside the loop area. Amplitude, phase, frequency and impedance changes occur as a result of a change in the inductance. Different commercial units utilize this effect to generate one output pulse per vehicle.

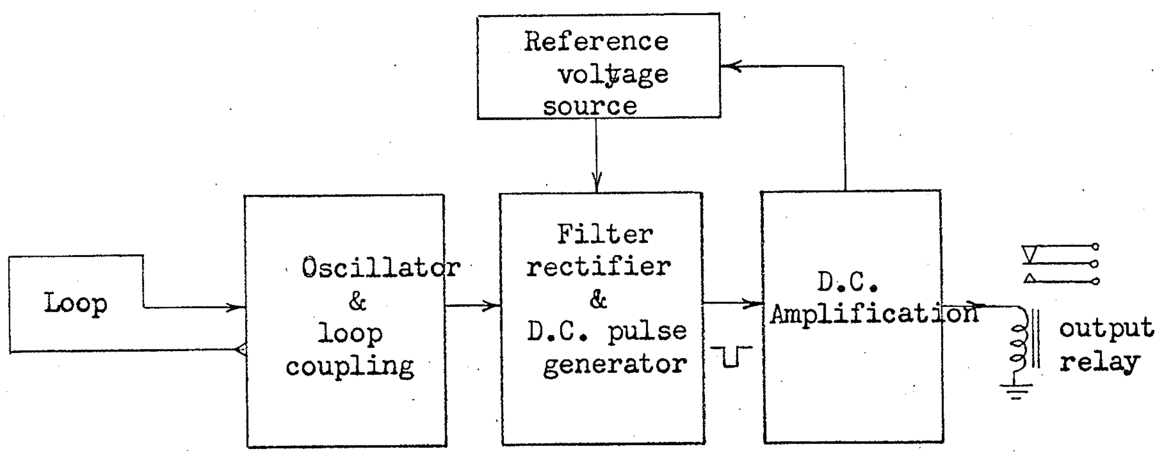


Figure 9

Block Diagram of Detector X. The Oscillator output is rectified, sudden changes in the amplitude level generate a negative going pulse.

Detector X (Figure 9)

Contains 6 transistors, 5 diodes and a built-in power supply. An oscillator circuit with inductive coupling to the sensing loop feeds the filter-rectifier stage which is followed by DC amplification.

The output transistor is normally cut off and is driven into conduction by an amplified pulse. The amplitude of the oscillator and the rectified signal level becomes smaller suddenly due to vehicle presence, thus generating a negative going pulse. Stability is secured by a reference voltage source and a feedback loop. This is a simple and effective detector.

Detector Y. (Figure 10)

Contains 9 transistors, 3 diodes and a separate power supply.

The loop is the inductance in the tank circuit of the oscillator. The frequency change caused by the passage or presence of a vehicle is detected by a tuned discriminator circuit and amplified, using AC coupling. A rectified signal feeds the output transistor and produces a fairly square d.c. pulse for the relay. The wide band AC coupling makes this unit insensitive to slow frequency drifting. It is also quite a simple and reliable unit.

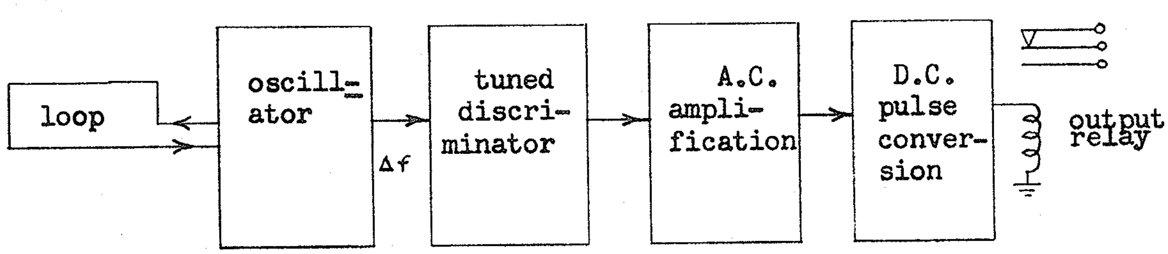


Figure 10

Block Diagram of Detector Y

The Loop is part of the Tank Circuit. Changes in the frequency, due to vehicle loading are detected by the discriminator. AC Amplification & DC Pulse conversion feed the output relay.

Detector Z. (Figure 11)

Contains a sealed oscillator unit with unknown number of components coupled to the sensing loop, plus 16 transistors, 14 diodes and a built-in power supply. The loop oscillator frequency is mixed with a local frequency reference oscillator, filtered and the difference frequency signal amplified, frequency discriminated, rectified and fed to a diode gate switching circuit.

A third source oscillator is also connected to the diode gate. Depending upon vehicle passage the gate is open or closed which in turn allows the third oscillator signal to be amplified through another diode gate towards the output and rectifier. The delay and the feedback circuit provide presence detection possibilities and improve stability.

The more than thirty semiconductor devices employed and the three oscillators did not result in a good detector. The output pulses are distorted and stability and sensitivity were poor. It is definitely overdesigned without any resulting improvement over the more simple types.

The experimental arrangements used in testing these detectors was the same as that shown on Figure 5, Page 15.

A series of photographs of pulses were taken in connection with each detector at various speeds using a standard automobile with a length of L = 201" (17 feet) and a wheel base of d = 118" (10 feet). Reference signals of 60 cps and 20 cps with the tube detector and loop detector are shown respectively. Some oscillograms were taken from the collectors of the output stage, some directly from the output relay contacts. The pictures P.2 to P.32, are in Appendix II.

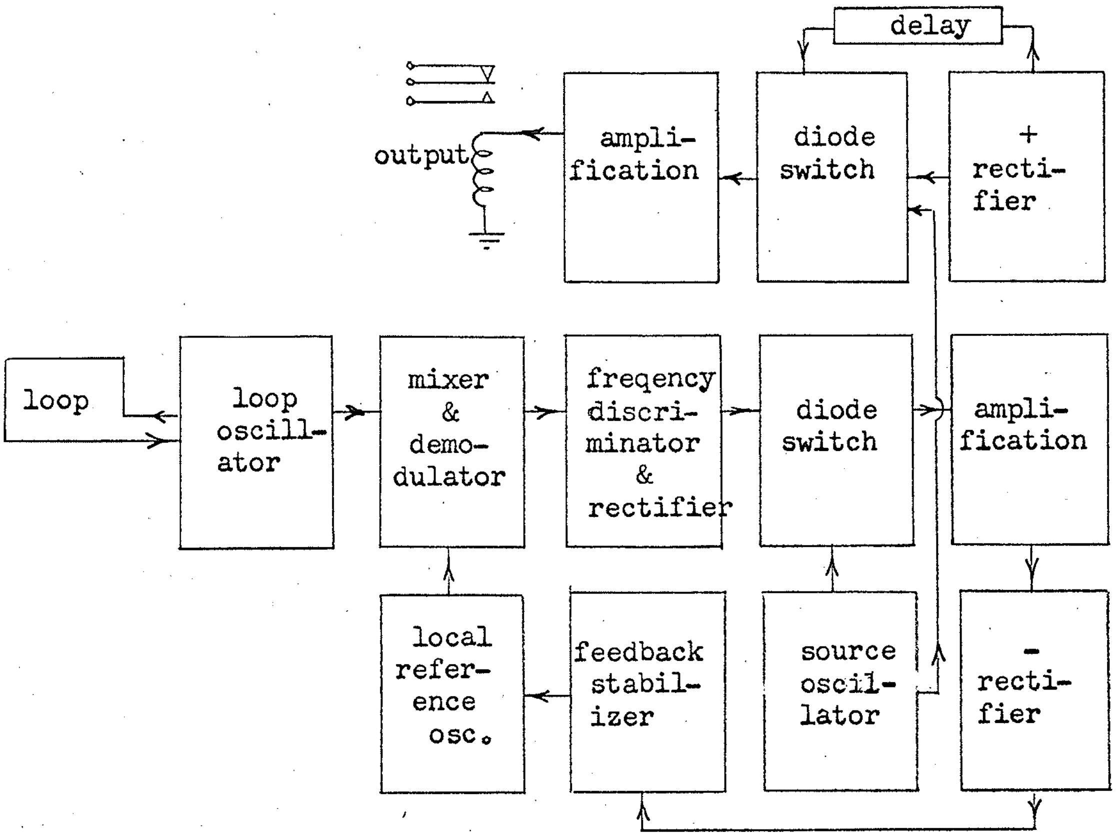


Figure 11

Block Diagram of Detector Z

A Superheterodyne type mixer combines the loop and reference oscillator frequencies. Switching logic stages and further amplification, form the output pulse.

From the gaps between triggering pulses and from the length of pulses speed (V) and vehicle length (L) were calculated. Figure 12 and 13 show the correspondence between the computed values of speed and those recorded by the speedometer of the testing vehicle. The spread is greater than normal. This is due to the inaccuracy of the speedometer and that Y and especially Z detectors did not give accurate pulses.

The summarized results of these measurements are:

a) The basic detector unit should be designed along those principles worked out in the earlier chapters, to give sharp square pulses.

b) Even this form of extremely simplified experimental presentation gives reasonable (10 to 20%) accuracy in the calculation of speed. Vehicle length as the theory shows, is the most critical measurement. The inherent sensitivity to pulse distortions is reflected in the spread of experimental results shown in Figure 13.

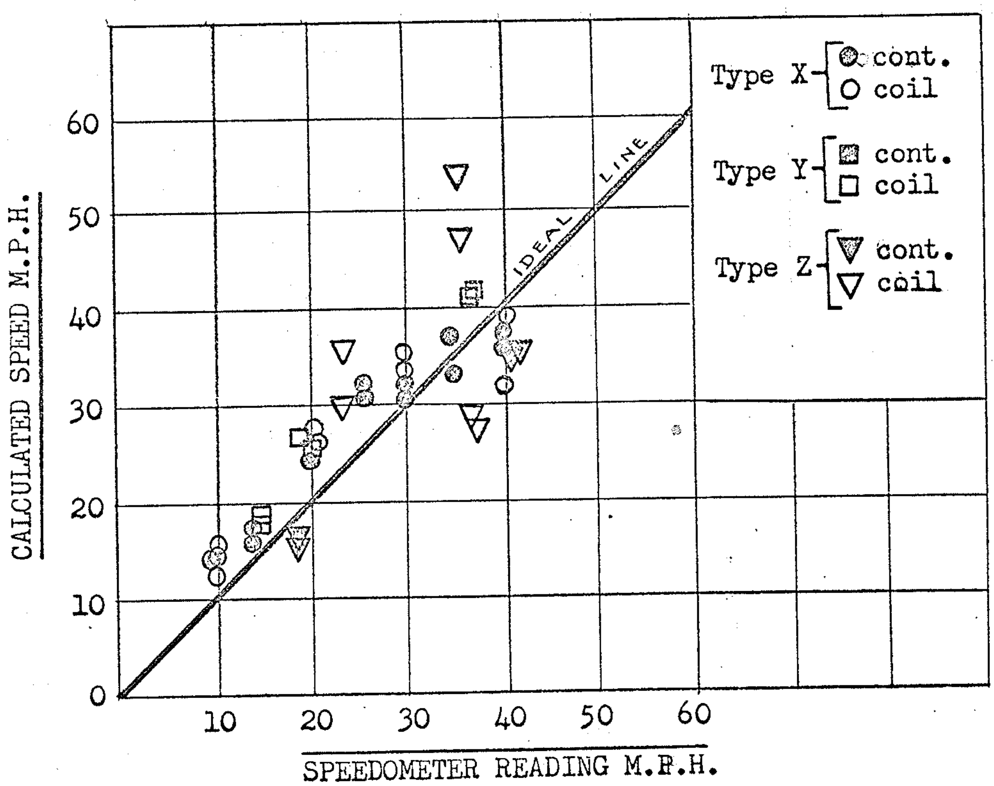


Figure 12

Graph of speed measurements on X, Y & Z Detectors

c) The actual measurements and calculations show that the equations developed are usable in a practical manner. In this particular application (an analogue technique) time lapses were converted to lines on oscillograms, measured with a time standard signal. Speed and lengths were calculated with these data. (see Table of Measurements P 77)

In the following chapters, other techniques will be introduced leading to several possible multi-parameter detecting systems. Each design will serve one or more specific purpose, offering speed, accuracy, convenience and other advantages.

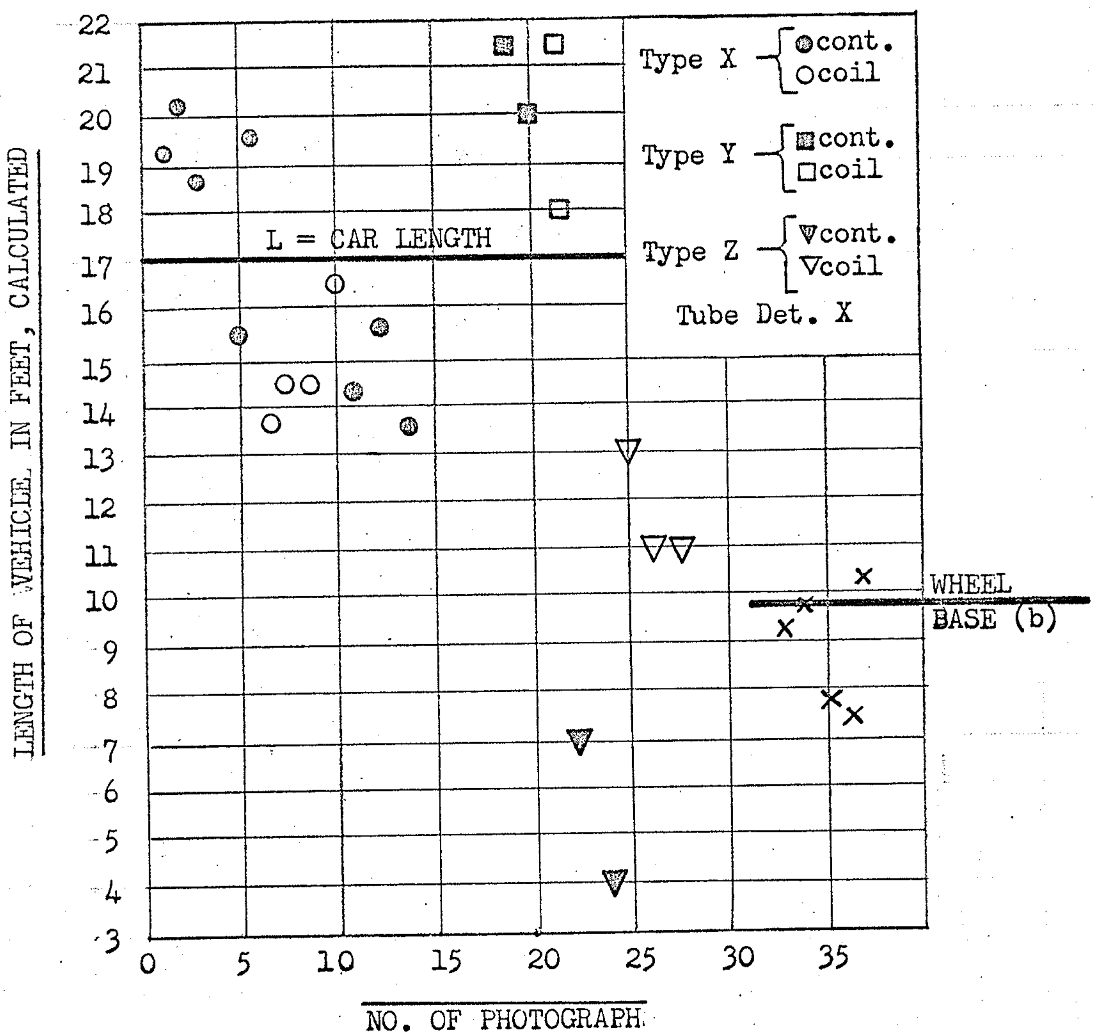


Figure 13

Graph of length measurements of vehicles in motion

CHAPTER II

MULTI-PARAMETER DETECTION

II (a) Calculation of Parameters

In this legend a list of symbols is given which is used throughout the study.

	Symbol	Designation	Unit
1)	Q	Vehicle Volume	Vehicles/second
2)	V	Vehicle Speed	Miles/Hour
3)	D	Vehicle Density	Vehicles/mile
4)	L	Vehicle length	Feet
5)	P	Vehicle position on the roadway	Placement in the Lane numbered.

The techniques of obtaining the parameters Q, V, D and L, will be subjected to an analysis. The measurement of vehicle position "P" on the roadway is so simple that it will not be discussed further. A good article on this subject was published by Hubert & Thompson (2).

Volume (Q) measurement is simple in digital form and it involves no errors as long as the sensitivity of the detector is sufficient to sense every vehicle. This however is a basic requirement for any detector. Volume may also be measured by analogue integrating techniques. This method will be discussed in the next chapter.

Speed (V) measurements will be based upon the elapsed time method which was discussed in connection with the errors of detection in Chapter I (b) (Page 6).

This measurement involves the known detector spacing Δs and the elapsed time Δt from detector #1 to #2 such that:

$$V = \frac{\Delta S}{\Delta t} \qquad \text{-----------------20)}$$

Again time measurement may be digital or analogue and the equipment must be capable of performing division. Different techniques of division will be discussed in the next chapter.

The measurement of vehicle flow rate or quantity Q is a simple process of integration. A count of the pulses accumulated over a period of time t will give

$$Q = \frac{\text{Vehicles}}{\text{Unit time}} \qquad \text{-----------------21)}$$

The measurement of density D involves a count of vehicles on a section of the road. The density is the number of vehicles occupying this section of the road between points A and B in a given instant. The physical measurement of the density in a continuous traffic stream poses some practical problems. It is necessary to synchronize counts at two remote detector locations and to make a subtraction of the volumes at point A and B. At present there are three methods to overcome this problem. One method is based upon the assumptions that there is no change in the traffic flow between the two closely spaced detecting stations, and that the flow is smooth and the speed is relatively constant. Therefore a simple volume comparison Q1 and Q2 between the two observational points in regular intervals will show a density-like relationship. Details of this method are given by Barker (5). It should be noted however that this is not a true expression of density, but is rather a figure of "traffic unbalance" expressed by;

$$U = \frac{Q1}{Q1 + Q2} \qquad \text{----------------22)}$$

A dimensionless number which is the ratio of traffic inflow over the sum of inflow and outflow of the section of roadway in question.

The spot density method is another technique of density (D) measurement and in practical applications it is the simplest. The spot density is given by the following equation:

$$D = \frac{Q}{V} \qquad \text{----------------23)}$$

Which by dimensional analysis is:

$$(D) = \left(\frac{\text{Vehicles/hour}}{\text{Miles /hour}} \right) = \left(\frac{\text{Vehicles}}{\text{Mile}} \right)$$

It should be understood that in this case the measurement of Volume and speed is confined within a few feet of roadway length and a short time interval.

The spot density gives a very good indication of the spatial distribution of vehicles over a longer section of the road. If the values of Q are measured in intervals of a few minutes, the spot density approaches the true spatial density. Theoretical (74) and practical studies (17) show that the minimum possible time spacing between vehicles on an ideal average speed roadway is approximately 1.2 to 1.4

seconds. This represents a maximum of 40 to 50 vehicles flow per minute. These vehicles occupy 1600 to 2000 feet of roadway. Therefore a spot density measurement over a one minute interval satisfactorily indicates the density condition over 1600 to 2000 feet of roadway.

A third method is described by Kendall (23) and is defined as "Lane Occupancy" and is expressed as:

Lane Occupancy = K x D or by dimensional expression

$$\left[\%\right] = \left[\frac{\text{MILES}}{\text{100 VEH.}}\right] \times \left[\frac{\text{VEHICLES}}{\text{MILE}}\right]$$

where K is a constant of calibration and leads to a dimensionless quantity. The constant is so chosen that the quantity approaches 100% as the density approaches the practical maximum.

The spatial density measurement requires synchronization between two remote stations. This requirement has many practical disadvantages. the lane occupancy figure is an approximation of density which does not suggest an exact theoretical basis. Therefore these techniques will not be treated further in the following discussion.

The required accuracy and ease of measurement are combined in the spot density and in the following all reference will be associated with the spot density.

The next parameter of interest is the length of vehicles (L), to be measured while they are in motion. The time lapse T over a line of detection spent by a vehicle having speed V is:

$$T = \frac{L}{V} \qquad \text{----------------24)}$$

which may be expressed by substituting $V = S/t$; $(S/t \equiv \Delta S/\Delta t)$ such as;

$$T = \frac{L}{S/t} = \frac{L\,t}{S} \qquad \text{------------------25)}$$

The ratio of pulse duration T and the elapsed time (t) to the second detector is equal to the ratio of vehicle length and detector distance expressed by;

$$\frac{T}{t} = \frac{L}{S} \qquad \text{------------------26)}$$

The vehicle length may therefore be expressed as;

$$\boxed{L = \frac{T\,S}{t}} \qquad \text{------------------27)}$$

and contains a ratio of two time measurements multiplied by S constant detector spacing.

In summary of this chapter, it was shown that four parameters (Q,V,D,L) flow, speed, density and vehicle length may be obtained by two simple elapsed time measurements. It is reasonable therefore to base the realization of a multi-parameter detector upon the elapsed time measuring principle.

II (b) The Measurement of Elapsed Time

An excellent account of the measurement of time is given by Puckle (31). Some of his ideas are reproduced in this introduction.

The measurement of time, and instruments for so doing, have existed from remote antiquity. One of the earliest was the sun dial. The best known of the early "day and night" indicating instrument was the water-clock or clepsydra used by the Greeks, Romans, Babylonians and Egyptians. If the jar of water is replaced by a condenser or electrical "jar" and electricity is allowed to drip in or out it becomes apparent that fundamentally, our most modern method of measuring time is very much like that used 2000 or 3000 years ago.

The use of such simple techniques is not uncommon even today. A typical example is the "Enescope" (10) still used sometimes for time measurements in speed surveys. The enescope basically is a mirror placed at a 45 degrees angle to the roadside, projecting the image of bypassing vehicles to the observer some distance (a few hundred feet) away. The observer actuates a stop watch when the image of a car flashes on the mirror and stops timing when the vehicle reaches his line of observation. The speed is then calculated from the distance and time duration.

The evolution of measuring apparatus, for the measurement of time, from ancient days is notable. The task today is to make the right choice from a large number of available equipment that combines simplicity, reliability, and the desired standards of precision.

Essentially any scheme developed to measure a time interval must contain a trigger circuit and a time base such as shown in Figure 11.

Any circuit which is to function as a triggered time base must have a steady state or stable condition in which it can operate or rest without producing any output signal, when no triggering pulses arrive.

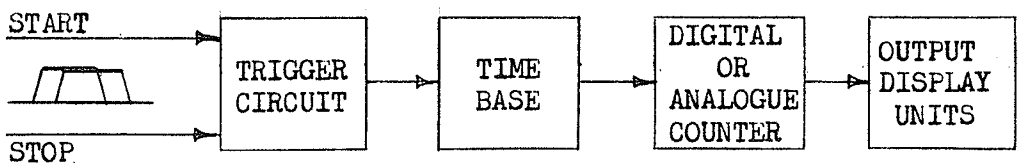


Figure 11

Triggered, Externally Operated Time Base

The function of the trigger circuit is to provide well determined signals to initiate and stop the timing process of the time base. The time base is a generator either of a linear D.C. signal or a constant frequency standard. Analogue, or digital counters responding to the respective time base operate the output display units.

As far as the time base itself is concerned the simplest is the capacitive charging circuit. (Figure 12)

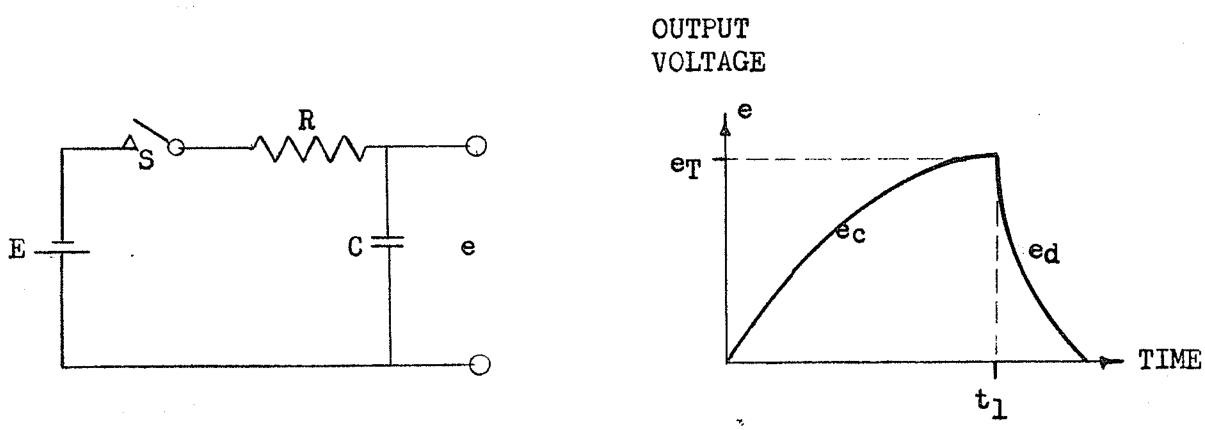


Figure 12

Capacitive Time Base

The literature contains many sources discussing capacitive time bases (29, 33, 34, 35, 43) and the student is referred to those.

Nonlinearity and error calculations are contained in the book by Millman (3) and Strauss (29) using three different methods. Another timing circuit may be constructed by interchanging R and C (high pass filter). There is no basic difference from the timing point of view between the high pass and low pass filters.

An entirely different method of time measurement may be achieved by a digital method called pulse counting. The basic principle of time measurement by a fixed frequency generator is based upon the counting of cycles. The block diagram of a typical time base is shown on Figure 13.

The oscillator is crystal controlled for stability and may be steadily running as shown on Figure 13 or may be triggered to start and stop oscillating as shown on Figure 14.

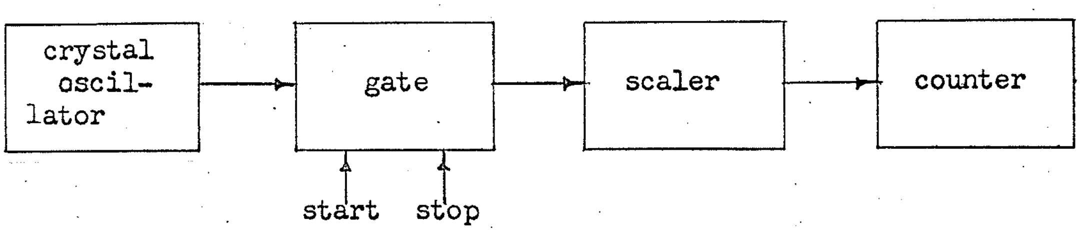


Figure 13

Digital Time Base or Counter, With Continuously Running Oscillator

Basically however the principle of measuring time is the same in both cases. The number of cycles (n) recorded, or counted between the start and stop pulses, is proportional to the time measured (t_m)

between the two pulses. If the frequency is f then the time duration of one cycle is $T=1/f$ and the time measured is;

$$t_m = nT \qquad \text{-----------------28)}$$

Since the frequency and thus the period $T=1/f$ is known a counter may be calibrated directly in time. In order to achieve a high accuracy of the time measurement the oscillator frequency should be relatively high.

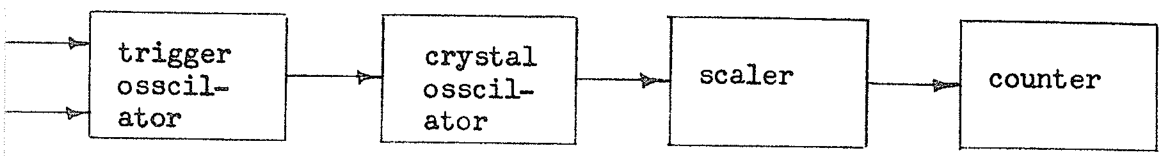


Figure 14

Digital Time Base, with Triggered Oscillator

The start and stop pulses do not necessarily coincide with a given phase of oscillation, and the interval between them may not be a whole number integer of the period. (see Figure 15) This explains the approximation of equation 28. The exact expression is;

$$t_a = nT + \delta T \qquad \text{-----------------29)}$$

$$n = 1,2,3\cdots \text{ and } 0 \leq \delta \leq 1 \qquad \text{-----------------30)}$$

where t_a is the actual time that elapsed between Start and Stop pulses, n is a whole number and δ is the rate of error, a number less than one.

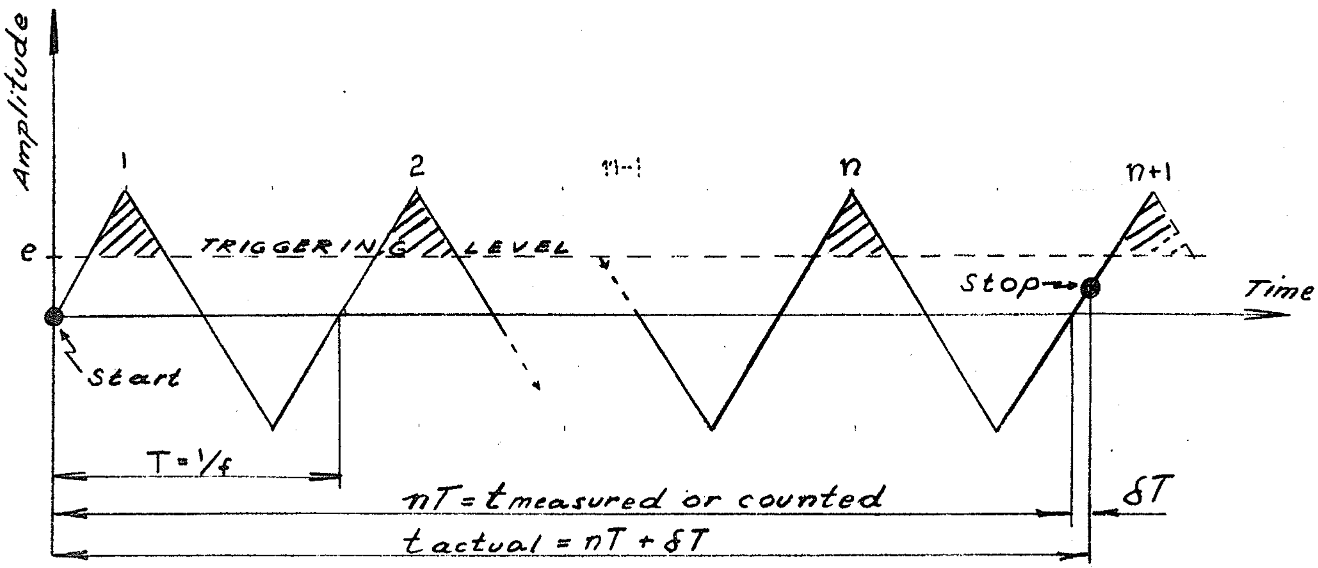


Figure 15

Demonstration of Error in Digital Time Measurement

The relative error e_r may be expressed such as:

$$e_r = \frac{\delta T}{t_a} = \frac{\delta T}{nT + \delta T} \quad \text{------------------31)}$$

$$e_r = \frac{1}{1 + n/\delta} \quad \text{------------------32)}$$

By substituting equation 28 the relative error is:

$$e_r = \frac{1}{1 + \frac{t_m f}{\delta}} \quad \text{------------------33)}$$

or

$$\boxed{e_r = \frac{t_m}{t_m + f/\delta}} \quad \text{------------------34)}$$

Equation 34 shows, as it was indicated earlier that a desired level of accuracy may be achieved by increasing the frequency of the oscillator. The error $e_r \longrightarrow 0$ if $f \rightarrow \infty$ and the measured time t_m approaches t_a, the actual time.

This explains the application of frequency division, or scaling. By carrying out the actual timing process at higher frequencies, a greater accuracy may be achieved. Frequency scaling becomes necessary to actuate the counter at the output, which may be a relatively slow acting device.

II (c) Analogue Techniques for the Computation of Traffic Parameters

The multi-parameter detector is basically an analogue device as far as the elapsed time measurement is concerned. This was mentioned in Chapter I , Section e, in connection with the experiments performed. In this section analogue arithmetic operations, for the calculation of traffic parameters, will be studied. For most practical applications however the photographic method is very slow and continuous readout is necessary showing volume, speed, vehicle length and density values. Obviously a form of analogue display or computation involving multiplication and division is necessary, especially to obtain D and Q.

A simple method using a sensitive D.C. meter measuring the discharge of a condenser and calibrated in vehicle speed is described by Ellis (66) in his patent.

A simplified diagram of this system is shown on Figure 16. Switches b and f are normally closed and produce the timing pulses. C3 capacitor is charged to the potential of the high voltage source. Timing begins at the opening of b which (start pulse) disconnects the supply voltage. A rapid discharge of the condenser takes place through the relay and R1 and its rate is indicated by the meter. Since R3 $\gg$ R_2

the quantity of discharge is determined by R1 and by the duration of time that elapses until the opening of f, (stop pulse) the second timing switch.

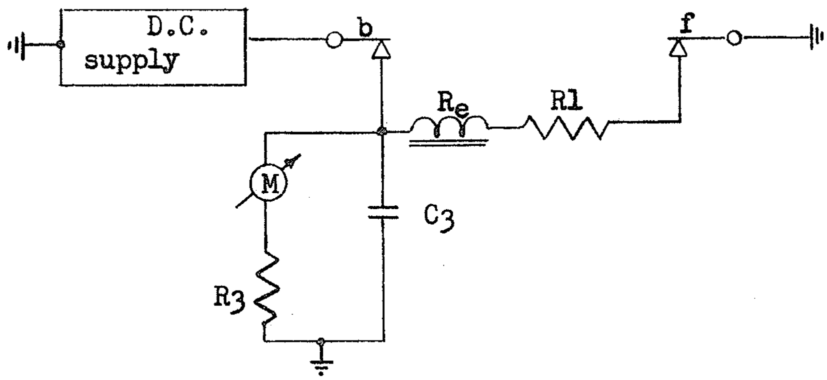


Figure 16

Condenser Discharge Measuring Analogue Speed Meter

At that point only the meter remains connected to the condenser through the large R3 and stays relatively still for a short period due to the large R3 C3 time constant. The meter is calibrated in miles per hour and a reading of speed (v) may be obtained.

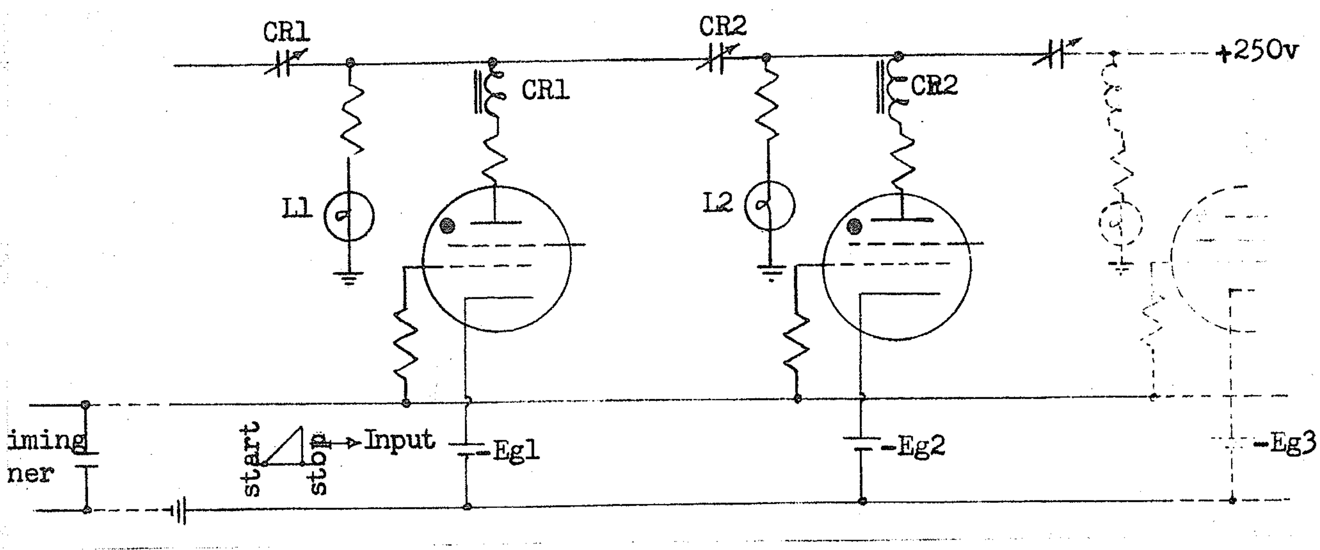


Figure 17

Measurement of Speed in Discrete Increments by Increasingly Biased Stages

A different field of application in which the sizes of objects are measured, and the readout in analogue form is discussed by Sanford (42). In the modification presented here a timing condenser voltage represents the input signal as shown in Figure 17.

The amplitude of the input voltage is proportional to the time lapse, and triggers each stage in succession due to their different bias levels. This method would give a step by step indication of speed levels, for example, 5, 10, 15, MPH. It has one advantage compared with the directly metered method of Ellis, in that it does not have a compressed nonlinear scale.

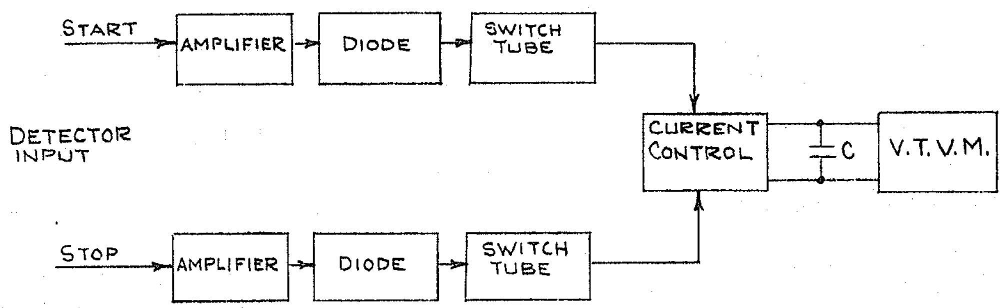


Figure 18

Block Diagram of Filter's Method of Measuring Time. The Meter is Calibrated in Speed.

Garfield (46) gives an oscilloscope type ultrasonic pulse velocity measuring method, and the associated circuitry. It was used for the examination of mechanical properties of road materials, particularly concrete.

Filter's (43) method is also applied to concrete beams. The velocity of shock waves is measured by a microsecond interval timer. Figure 19, shows the block diagram of the equipment modified for vehicle detection. The tube circuits used can be easily replaced with transistor circuitry.

This method is a straight forward application of the capacitive time base principle described in section II), (b). Calculated and measured values were in close agreement and an error calculation is contained in this article.

Other circuits for "time to amplitude conversion", used in nuclear physical experiments, are presented by Thomlison, Brown (47) and Fraser (48).

Another interesting application is published by Weltman, Sullivan and Bredon (63) in the measurement of arterial pulse velocity in the human blood vessels (see Figure 19).

The unique features of this system compared with the previous ones are the dividing circuit which performs the analogue speed calculations and the strip chart recording of the same.

The above examples indicate the many possible methods available for analogue vehicle speed measurements.

Vehicle volume per unit time (Q) may also be shown as an analog quantity. This however is a type of information best suited for digital recording, since each vehicle produces a pulse. Connection of a digital counter or a strip chart recorder to the start pulse, would result in Q being obtained. Cancellation of counts, after readout, should follow.

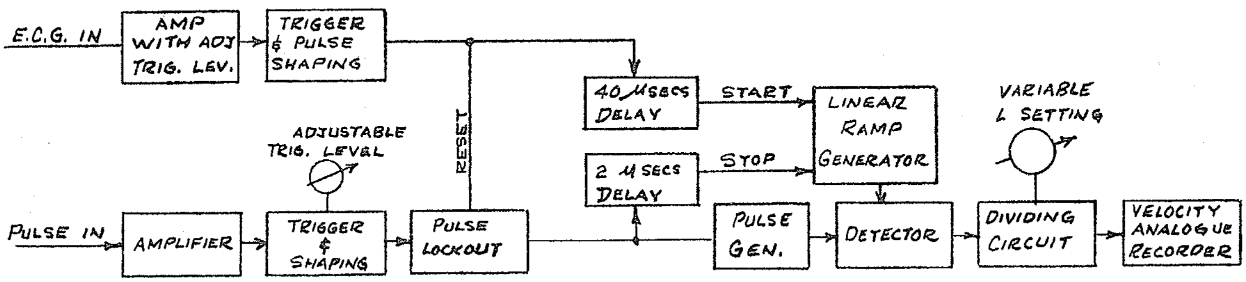


Figure 19

Block Diagram of Blood Vessel Pulse Wave Velocity Computer

Several analogue counting techniques are available and a short description is warranted. The Counting-rate meter is one of these.

It is an instrument for measuring the mean rate of arrival of pulses over a period of time (see Figure 20). One of its main applications is to count random emanations from radioactive sources.

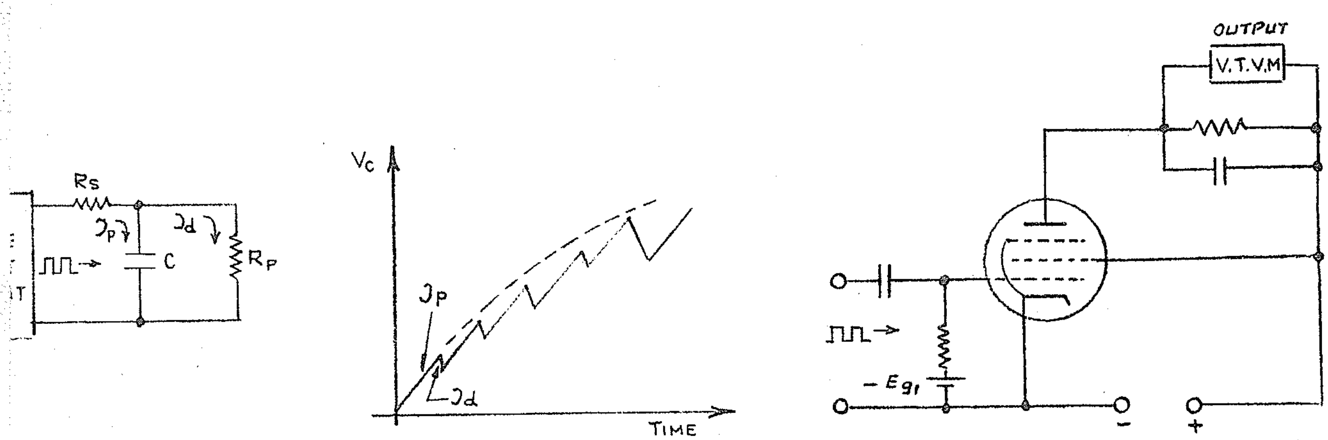


Figure 20

The Principle of Rate Measuring Integrating Circuits

Pulses (p) charge the C condenser via the source resistance R_s which is very large, close to infinite, when the pulses are switched off. The maximum voltage possible on the condenser is the source potential. During off periods C discharges (d) through the parallel resistor R_p. The mean value of V_c is a measure of the mean rate of pulse arrivals, which equals the rate of vehicle arrivals Q. As the time constant RC increases the ripple becomes smaller and the holding time or memory of the circuit is increased.

A thorough discussion of the different practical rate meters is given by Smith (73) including computations and a summary of the advantages of rate-meters compared with scalers. A study of linearization of the output is contained in Blitzer's book (30, P362-85).

The voltage representing Q may be read by a meter connected to the output in regular intervals by a sequence timer. In this case the reading (Q) is an analogue value of the average rate of vehicle flow.

The measurement of vehicle density D involves the computation of;

$$D = Q/V \qquad \text{------------------35)}$$

as was discussed in Chapter II , Section (a). Both quantities (V and Q) are available by the use of some of the methods described in this Chapter in an analogue form. A division of Q/V must now be performed.

Similarly the measurement of vehicle length (L) requires a multiplication by T/t such as;

$$L = \frac{T}{t} \quad S \qquad \text{------------------36)}$$

Again T, t and s are available. The discussion of analogue multiplication and division is reviewed in the following.

One of the most promising and the simplest method of multiplication is described by Wright (59). The element used is called by him the "Space-Charge-Limited Surface-Channel Triode". This is essentially a solid state triode or field effect transistor. The space-charge limited current between source and drain is given by;

$$C = PV_2 \quad (2V_1 - V_2) \qquad \text{-----35)}$$

The symbols used are:

V_1 = gate voltage

V_2 = drain voltage

P = Perveance = $E \mu w / 2 h d$

E = permittivity of the gate insulation

μ = mobility of the charge carriers in the conducting channel.

d = spacing between source and drain

h = thickness of gate insulation layer

w = length of electrodes

The application of Vo voltage to the source ($V_o \leq V_1$) results in:

$$i = P (V_2 - V_o) \quad 2 \quad (V_1 - V_o) - (V_2 - V_o) \qquad \text{-----------37)}$$

If $V_o = -V_2$ and $V_1 \neq o$ the current is

$$i = 4PV_1.V_2 \qquad \text{-----------38)}$$

and the resulting equation gives straight multiplication.

Wright (59) tested the theory by using a cadmium sulphide thin film transistor with $V_1 = A + a \sin w t$ for the gate and $V_2 =$ B-b Sin w t for the drain. The magnitudes were A and B = 1 volt and a and b = 0.1 volt at f = 1 Kc/s, resulting in the cancellation of (AB-bA) sin w t first harmonic. The remaining second harmonic is ab/2 cos 2 w t is proportional to ab.

The results showed practically no distortion. Ranges were indicated for a possible input of 0.1 to 10 volts and up to several megacycles. Apply equation 38, and substitute $V_1 = Q$ and $V_2 = t/s = 1/v$ the reciprocal value of vehicle speed where Q and t are the variables, then

$$i_d = 4\ PQ\ (t/s) = 4\ P\ (Q/V) = 4\ PD \qquad \text{------------39)}$$

or

$$\boxed{i_d = k_1 D} \qquad \text{------------40)}$$

a current proportional to the vehicle density is obtained. In summary, the surface channel semiconductor element, with proper inputs, gives a current proportional to the vehicle density D.

Any multiplying device may be used for division provided the reciprocal value of the multiplicand is fed to the input. The same technique therefore is suitable for the measurement of vehicle length. Substitute $V_1 = T$ and $V_2 = S/t$ into equation 38, where t and T are the variables such as;

$$i_1 = 4PT(s/t) = 4PL \qquad \text{------------41)}$$

or

$$\boxed{i_1 = K_2 L} \qquad \text{------------42)}$$

is a current proportional with the vehicle length (L) is resulted. K_1 and K_2 are constants.

Another multiplier was developed by Barber (53). The principles of its operation are explained in Figure 25.

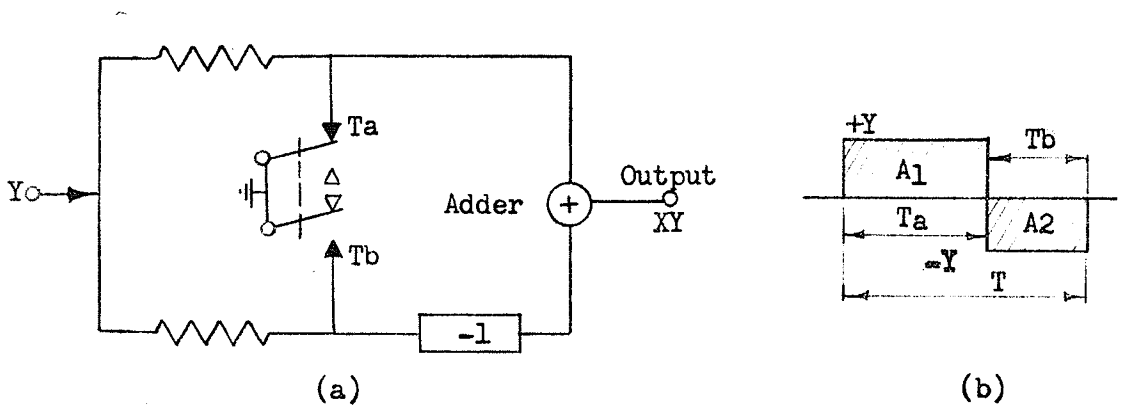


Figure 21

Symbolic Representation of Barber's Analogue Multiplier

The transistor switches symbolized on a) are operated continuously but allowed to dwell in the two available positions for T_a and T_b durations. During T_a the output is $+Y$ while in the interval T_b it changes to $-Y$ resulting in the diagram of b)

The average value of the waveform is:

$$\frac{A_1+A_2}{T} = \frac{YT_a - YT_b}{T_a + T_b} \qquad \text{---------------43)}$$

if

$$X = \frac{T_a - T_b}{T_a + T_b} \qquad \text{---------------44)}$$

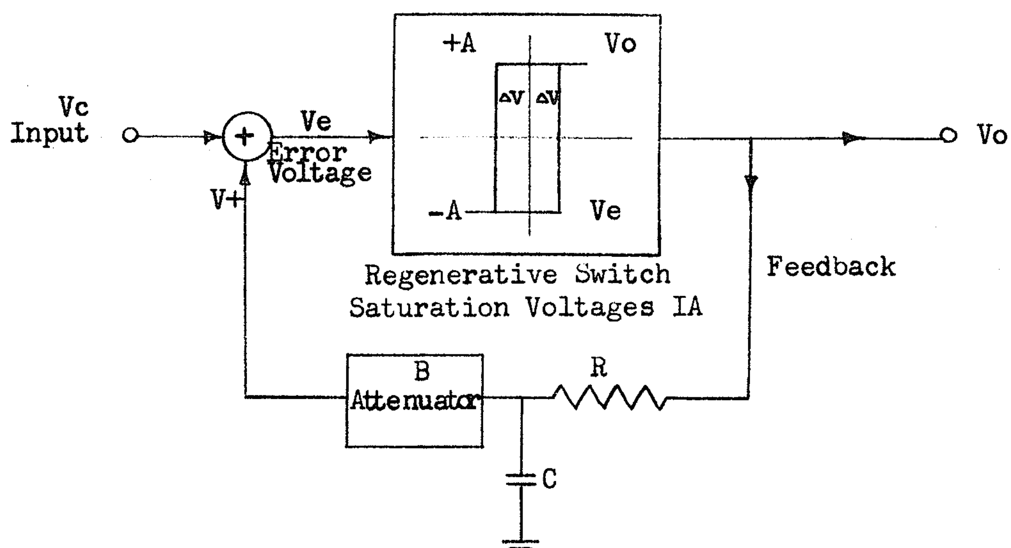
the area becomes the product XY. This method is called the Variable Mark to Space-area technique. By substituting the traffic parameters, the vehicle length and the density of traffic flow will be proportional to the output voltage.

Another pulse modulating technique is given by Rosenthal (57) (Figure 22). His system can be used as an amplifier, a multiplier or a divider. It is a sampling technique in which a "pulse-ratio" modulation is produced resulting in a pulse train, whose frequency and pulse duration both vary with the input signal. Compared with PWM this system responds instantly and with maximum effort to a change in the input signal not merely producing a pulsewidth code.

The mathematical form of its output is

$$V_o = \frac{EV}{AB} \qquad \text{------------------45)}$$

The forward loop switches between $\pm$ E and the feedback loop between $\pm$ A voltages. If E is time varying, the modulator functions as a multiplier and when A is the time variable it is a divider. There is a possibility of simultaneously operating as a multiplier and divider.



<u>Figure 22</u>

<u>Pulse-Ratio Modulating Principle for Amplification, Multiplication or Division</u>

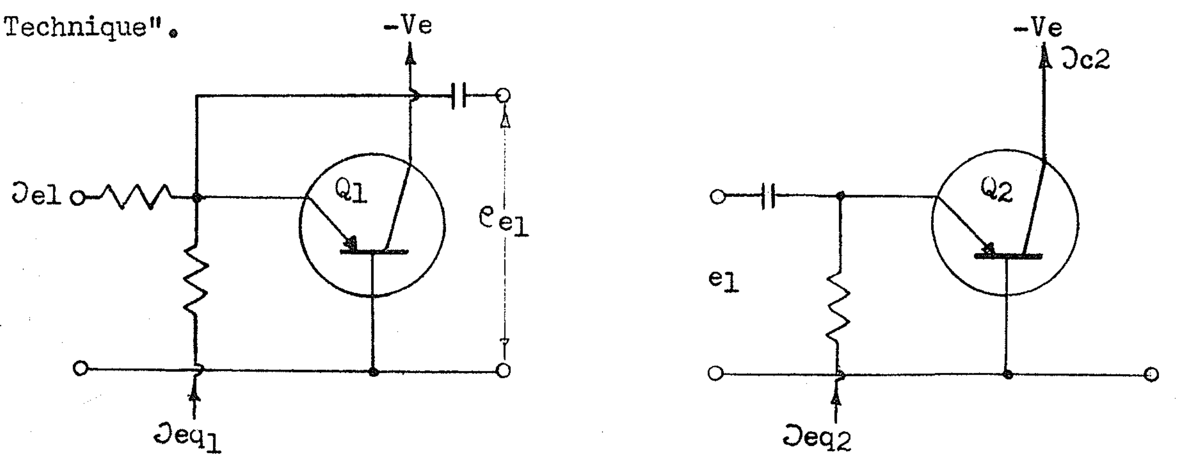
Kundu and Banerji (62) discuss the use of the inverse pair of logarithmic and exponential functions obtained from the current-voltage characteristics of junction transistors. The combination of these two in the same device results in a direct method of analogue multiplication and division "which has an inherent tendency of self compensation" for temperature change and nonlinear distortion. Using Ebers and Moll's (65) equations a current of

$$i_{c2} = \frac{\alpha_n I_{eQ2}}{I_{eQ1}} i_{e1} \qquad \text{------------------46)}$$

is obtained from the cascaded stages in Figure 23.

The circuit diagram of a divider and multiplier using three transistors was given, with performance curves showing an accuracy of 2%.

A review of electronic analog computers is given by Schmid (64) pointing out some advantages of the "Repetitive Pulse Time Computing Technique".



a) Logarithmic Circuit b) Exponential Circuit

Figure 23

Circuits Resulting an Inverse Pair of Logarithmic and Exponential Currents

While Schmid does not give any final wiring diagram, circuit details are discussed and 31 references are mentioned in the article.

His PWM form is more complicated than the previously mentioned analogue techniques. In application however where more than one variable quantity is measured simultaneously and continuously the PWM form may result in an overall system simplification through the sampling of all the variables. This is why "other inputs" are indicated on Figure 24, but only one common analogue computing unit is required.

Other references such as a book by Korn & Korn (35) written almost 15 years ago is listed in the bibliography. A more up-to-date classification of analog multipliers is given by Celinsky and Rimary (40) with tables containing details of accuracy, input and output ranges, bandwidth or time constant and drift. A comment on their main features is included. This work has 65 references.

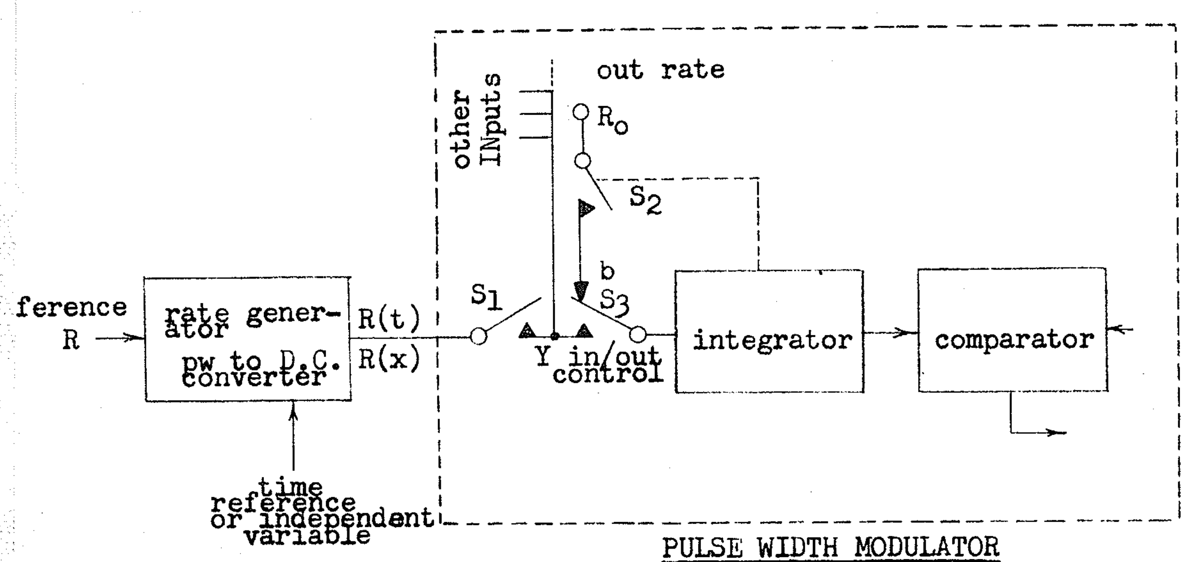


Figure 24

A Repetitive Pulse Time Computing Technique Using Pulse Width Modulation (PWM)

The analogue techniques introduced in this section for multiplication and division were necessary for the measurement of vehicle flow density and length, which functions may be performed by one single surface channel triode or with more complex circuits.

The designer of a multi-parameter detector would have to consider these circuits in detail. Preference would depend upon the expected performance or specification of the device. The discussion of this problem however is left for the last chapter.

II (d) Analogue to Digital Conversion and Computations

The basic information about the flow of traffic and vehicles exists in an analogue form represented by time lapses, with the exception of the pulses per vehicle (Q) which is digital. In some applications especially computer input and traffic surveillance it is desirable to present traffic flow parameters in digital form. (References 3 to 23) The first topic to discuss therefore is the conversion of analog data in the form of time lapses into digital form.

In section II (b), of this chapter a time base was described by a fixed frequency generator. The positive or negative half of each period was the triggering pulse for a digital counter. This is the simplest type of analog to digital conversion.

Minor (41) describes a method of analogue voltage conversion to digital code. A resistor-divider network produces internal voltages for reference. A successive approximation of the input voltage is performed by switching the reference voltages. The switching logic gives a binary digital code representing the analogue input voltage. Block diagrams and a complete discription of the switches are given.

Digital voltmeters serve another good example for converting analogue voltages into digital form. Blitzer (30) gives the block diagram of a digital voltmeter (page 318). The principle of its operation is similar to Miner's using a constant current source, a chain of resistors switched by the control circuitry via a set of gates, bi-stable multivibrator switches and the hold circuit. (Figure 29).

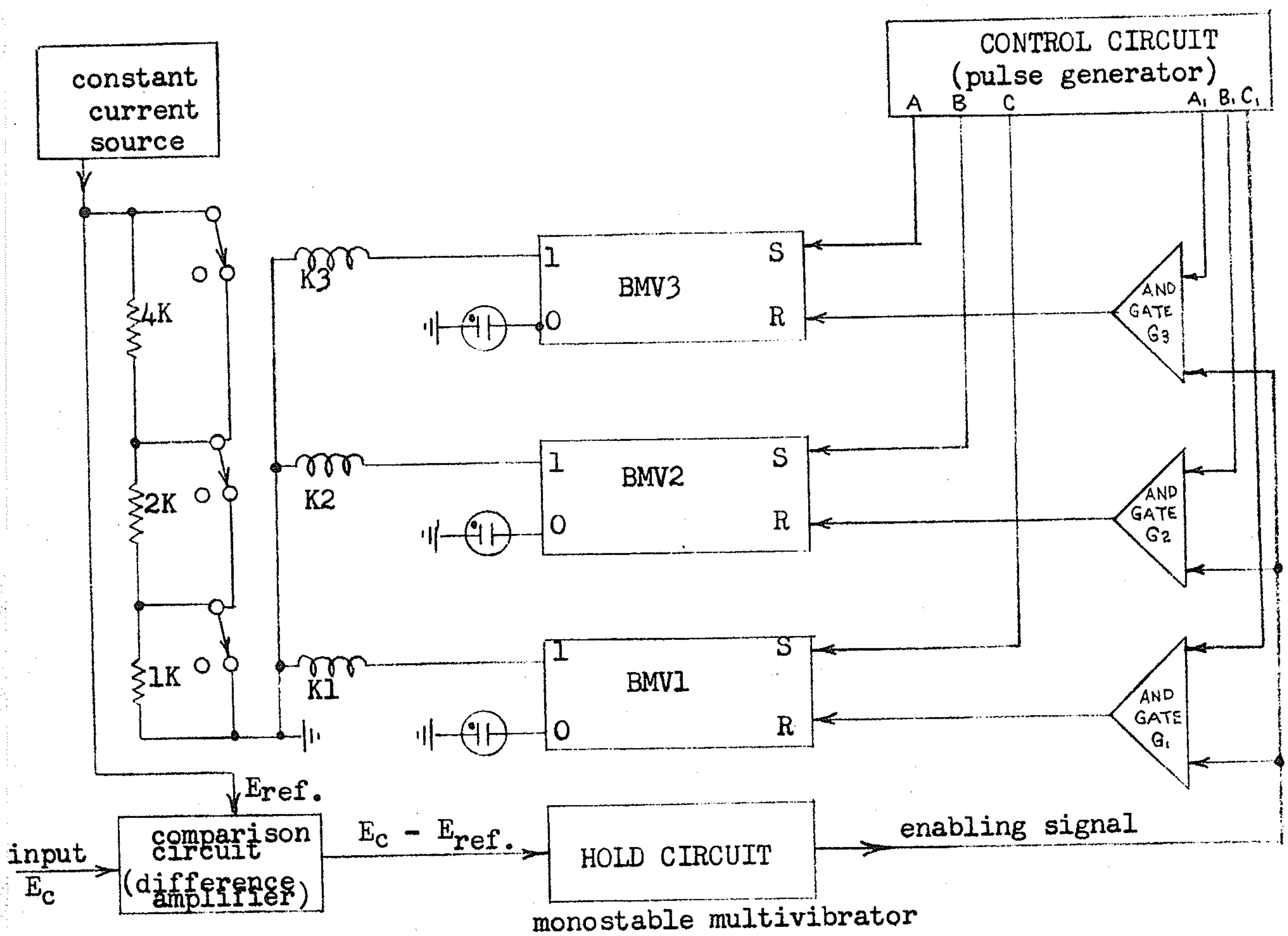


Figure 25

Block Diagram of a Digital Voltmeter - Analogue to Digital Conversion

A good practical review of measurements using counting techniques is written by Chaffin & Ahlstrom (42). Through 21 block diagrams and short descriptions, the basic principle of operation is explained. Almost all of the systems described can be used in some form for multi-parameter traffic detection in digital form.

One particularly fast time interval measuring system described by Engelmann (58) is shown on Figure 26. This scheme contains two quinary scalers instead of one, operating parallel against the 500 MC/s time base. Digital traffic detectors however can be much simpler since there is no need for such a high frequency.

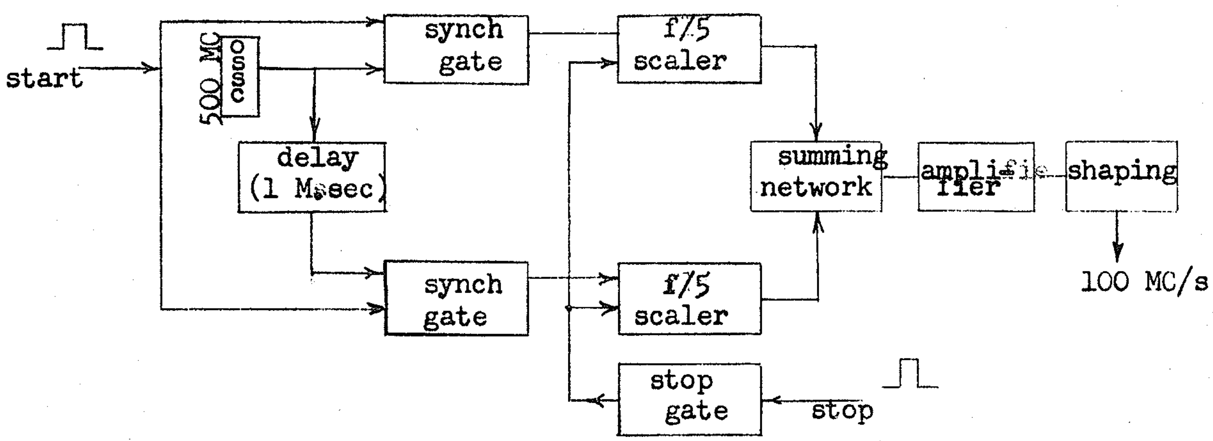


Figure 26

Fast Digital Time Interval System Using Start and Stop Pulses

An "Electronic Digital Ratio Equipment" is published by Russell (54) which measures the accuracy of gear wheels. A part of this system may be used for digital multi-parameter traffic detection with some modification as shown on Figure 27.

A time delay $t_d = RS/M$ is to be measured, which has basically the same multiplying and dividing demand as shown by equation 40 and 42: $i_d = 4PQ/V$ and $i_e = 4PST/t = 4\ PX$.

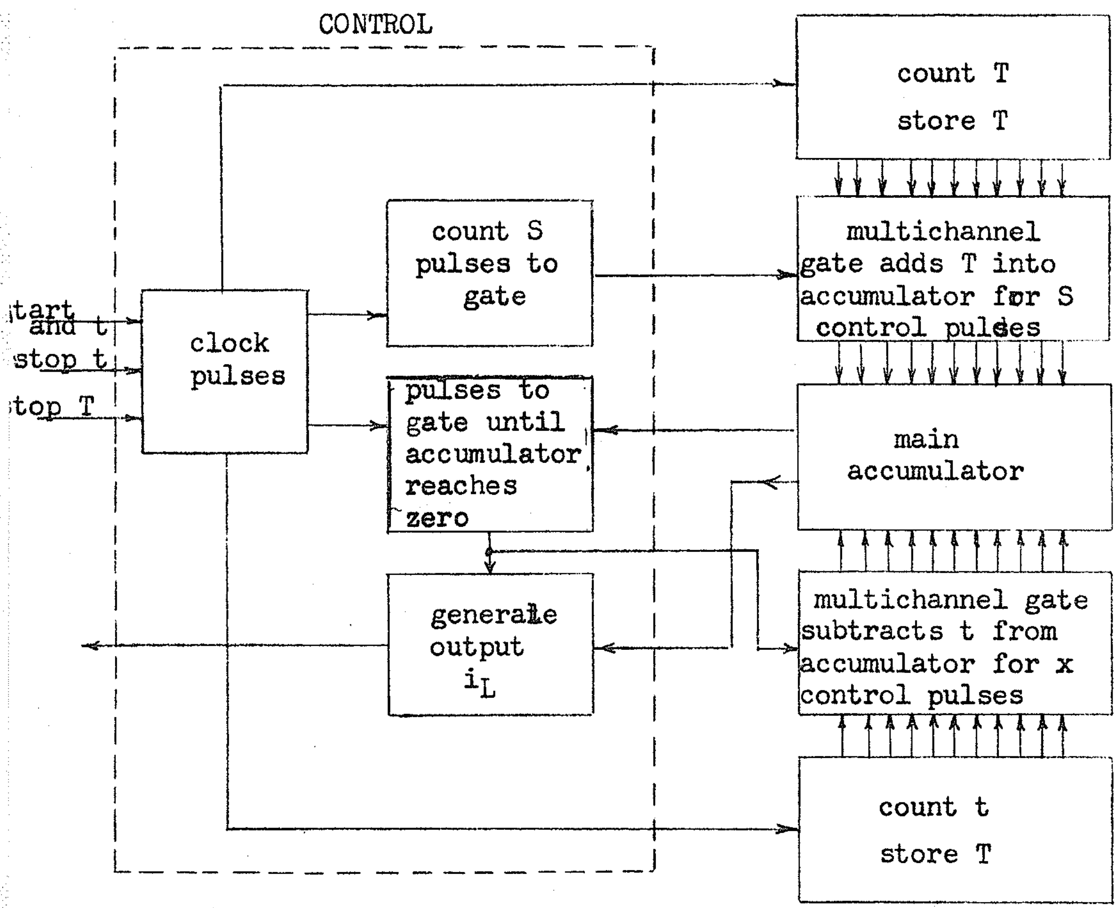


Figure 27

Block Diagram of the Digital Ratio Equipment, Used for Multiplication and Division.

One starting pulse, representing the beginning of both t and T intervals, initiates clock pulses to be stored in the binary counters respectively, until the two independent Stop pulses (t & T) arrive.

Then the control unit starts feeding S and X pulses to the respective gates and the main accumulator registers the end result by performing multiplication by addition and division by subtraction. The accumulator is emptied to zero by gating clock pulses into it. These pulses at the same time generate the output.

In other applications a general purpose computer may be available. Then the computation of traffic parameters is done by the computer. In such case data recording and storing of input data in digital form is required from the detecting system. One example of such a technique was mentioned. Another system using Decatron scalers and punch tape storage is described by Oxley (49) for computer input.

A practical system is given by Smith (52) using mechanical or stroboscopic digitizers, pulse generator, direction logic, counter drive and counter units, also the power supply details.

A low cost arithmetic unit is suggested by Thomasson (55) using either Decatrons (see also Acton's article 25), 10 states stored by voltage levels, or 10 state bi-stable multivibrators.

Some details are given for the design of a fast multiplier by Wallace (56) which generates the product of two numbers using combinational logic. These examples show the different digital techniques available for multi-parameter vehicle detection. Other references may be found in the books written by Millman and Taub (33), Babb (37). Booth & Booth (38), Strauss (29), Neeteson (28) and Blitzer (30) on the subject of pulse generating, shaping, digital circuits and computing techniques.

In closing this chapter two digital multiplication schemes will be discussed, along the lines laid by Neeteson (28) and Blitzer (30), which will give an opportunity to go into some details of the binary logic. Figure 28, shows a chain of four bistable multivibrators (BMV). This counter operates according to Table 4.

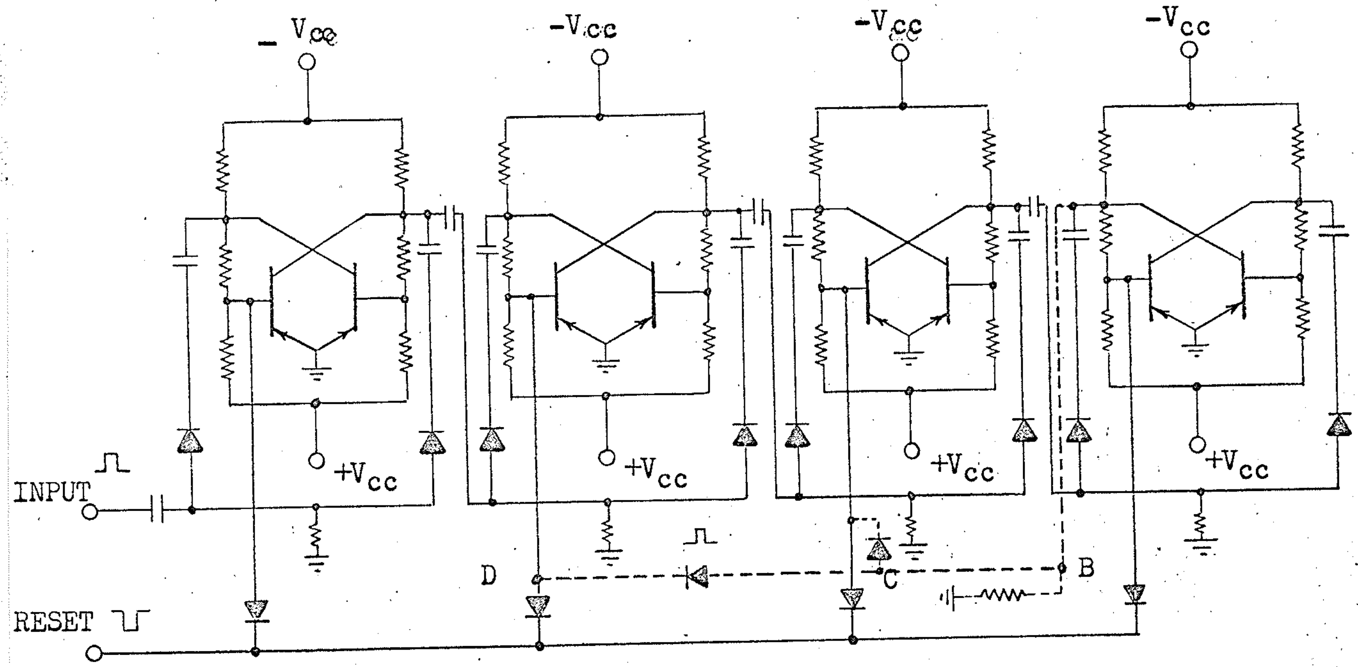


Figure 28

Transistor Type Decade Counter

Suppose each BMV is reset into the zero state initially with its N side (N' side is at 1). The first input pulse flips BMV1 into the 1 state all other stages remain unchanged. The second input pulse flops BMV1 into its zero state, which actuates the second BMV2 flipping it into its 1 state. Thus every second pulse goes to the next stage.

When the feedback is connected (dotted lines) the operation remains the same until decimal 8 is reached. At this point the 4th multivibrator switches to the one state with its N_4 side, first time during the sequence. This generates a positive pulse at point A, C and D points via B dropping resistor, thus switching these stages from decimal 14.

Table 4

Binary and Decimal Counting

BMV 4		BMV 3		BMV2		BMV 1			
N_4	N_5	N_3	N_3	N_2	N_2	N_1	N_1	SIDES OF BVM	
	2^3		2^2		2^1		2^0	BINARY POWERS	
1	0	1	0	1	0	1	0	1	D
1	0	1	0	1	0	0	1	2	E
1	0	1	0	0	1	1	0	3	C
1	0	1	0	0	1	0	1	4	I
1	0	0	1	1	0	1	0	5	M
1	0	0	1	1	0	0	1	6	A
1	0	0	1	0	1	1	0	7	L
1	0	0	1	0	1	0	1	8	
0	1	1	0	1	0	1	0	9	N
0	1	1	0	1	0	0	1	10	U
0	1	1	0	0	1	1	0	11	M
0	1	1	0	0	1	0	1	12	B
0	1	0	1	1	0	1	0	13	E
0	1	0	1	1	0	0	1	14	R
0	1	0	1	0	1	1	0	15	S
0	1	0	1	0	1	0	1		

Table 4a

0	1	0	1	0	1	1	0	(14) 8	chan-
0	1	0	1	0	1	0	1	(15) 9	ged
1	0	1	0	1	0	1	0	(16)10	deci-
									mals

Table 4 (a)

Change To One Decade Due To Feedback

BMV4	BMV3	BMV2	BMV1		
0 1	0 1	0 1	1 0	(14) 8	Changed Decimals
0 1	0 1	0 1	0 1	(15) 9	
1 0	1 0	1 0	1 0	(16) 10	

The system performance altered by the feedback is shown in Table 4 (a), the former binary positions are in brackets. The ninth pulse switches BMV1 only, the feedback is not effective in this case. The tenth pulse goes through the stages as the former 16th bringing the counter back to its zero original state. The feedback again is not working due to the negative pulse polarity and to the diodes blocking this process.

Thus the feedback results in ten combinations representing the ten input pulses. These ten combinations may be wired to a digital display system either through a resistance network (reference 33, P. 644 or 30, P.244) or through a series of gates. With the cascading of several counters of four BMV's any decimal number may be expressed.

In a speed measuring digital system for example, two counters each having $4x2=8$ transistors a total of 16 transistors would be used to display a range up to 100 miles per hour. If the output was in a binary form ($N=2^7=128$) seven stages of BMV's consisting of 14 transistors would allow a speed measurement up to 128 MPH. It is seen therefore that the binary system results a saving in comparison with the decimal. For the computation of Q and L the basic principles of digital multiplication will be discussed next.

The block diagram of a digital multiplier using "And" gates, "Nor" gates and BMV-s for the accumulator is shown on Figure 29, with the operation chart of its accumulator below.

The operation is explained by carrying out 7x5=35 multiplication. From Table 4, the binary equivalent of this expression is 111x101=100011.

1) From a storage register $X_1 = 1$; $X_2 = 1$; $X_3 = 1$; (111=7) is PLACED TO THE X inputs. Following this:

Input to A

1) (representing the first binary digit of 5) is fed into A

2) X_1A coincides, AND gate opens - OR gate opens - BMV1 flips to 1.

3) Since no input to B & C yet all combinations of the AND gates with B & C remain closed.

4) X_2A & X_3A AND gates also open - OR gates open, BMV2 & BMV3 also flip to state 1. Following this in time sequence the second character of decimal five B=0 is fed to input B.

Input to B

5) All combinations of B results no coincidence since B=0 and the system remains in the same state.

Input to C Next in the sequence C=1 the last character of decimal five is placed to input C.

6) X_1C coincidence flops BMV3 back to state 0 (BMV1 & 2 remaining in 1) which in turn

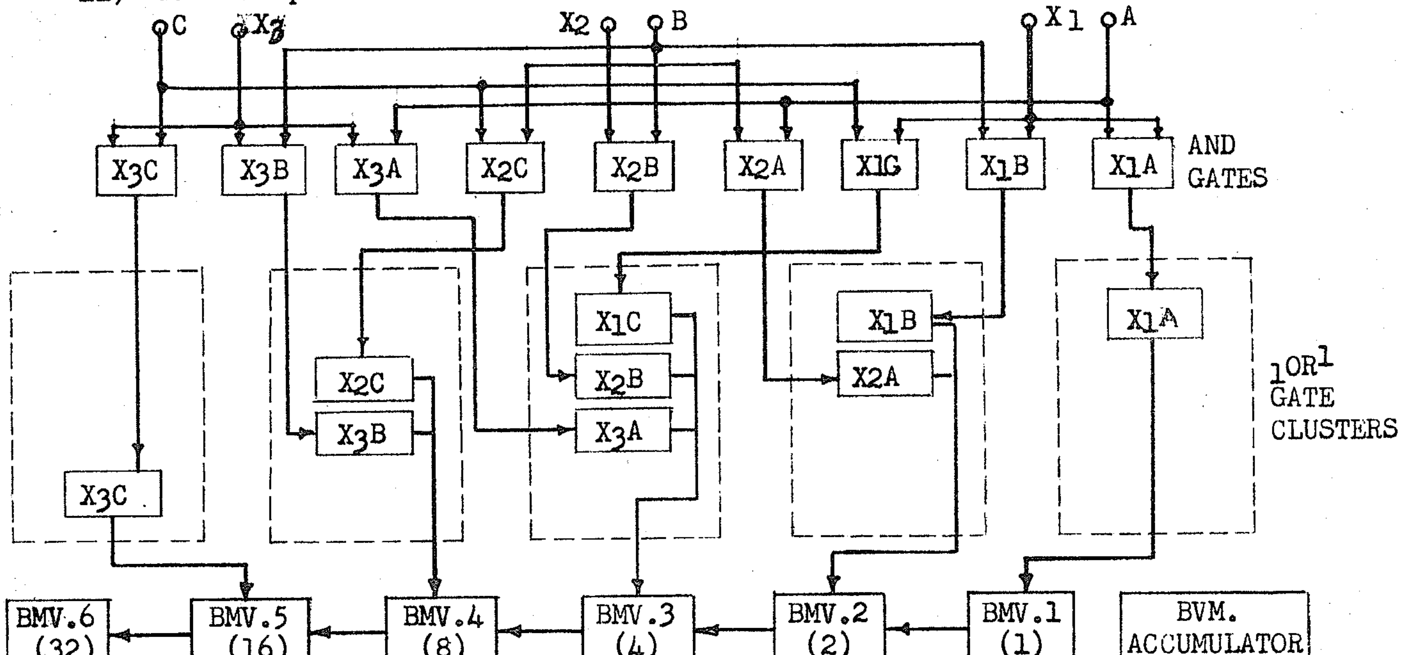
7) rolls BMV4 which flips to 1, but X_2C coincidence

8) flops BMV4 back to state 0, which in turn rolls BVM5

9) BMV5 flips into state 1, but X3C coincidence

10) flops BMV5 back into state 0, which in turn rolls BMV6

11) BMV6 flips into state 1.



STATE V6	STATE V5	STATE V4	STATE V3	STATE V2	STATE V1	INPUT TO A,B,C TERMINALS
0	0	0	0	0	0	start
0	0	0	1	1	1	A(1)
0	0	0	1	1	1	B(10)
flips to 1	Flips to 1 then back to 0 rolls V6	flips to 1 then back to 0 rolls V5	0 rolls V4	1	1	C(1)

Figure 29

Digital Multiplier Using AND & OR Gates and Bi-stable Multivibrators

The final status of the accumulator results in 100011 which is the binary product of the multiplication.

The method described by Neeteson (28) is a simple register read-out type circuit that can multiply. This system is explained through

Figure 30.

For example, suppose two numbers x and y to be multiplied and stored in D_1 and D_3 decimal registers respectively. The D decimal registers and A accumulators are decade counters similar to the BMV types previously described. Assigning X=3 and y=6, xy=18 multiplication is to be performed.

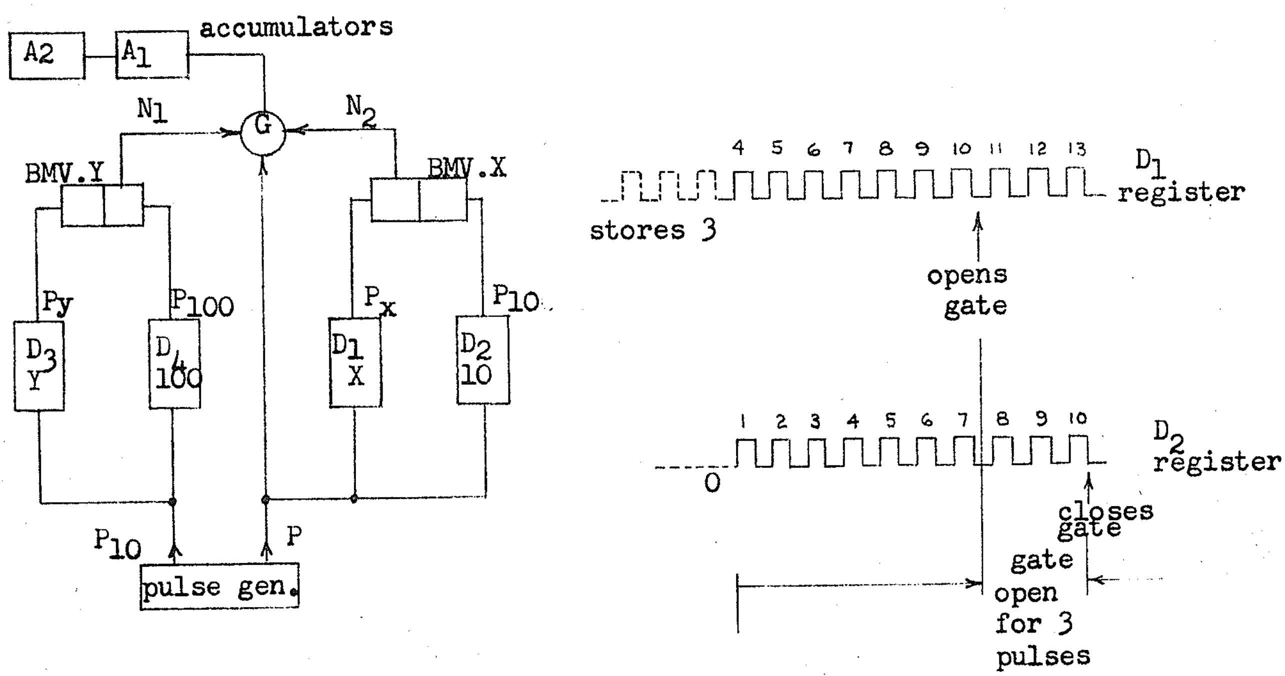


Figure 30

Digital Multiplier with Decade Counters and Bi-stable Multivibrators

Concentrate only on the right side of the figure, storage register D_1 stores y=3 as shown on the pulse diagram. It will receive 7 pulses from the Generator to reach its tenth position. At this point it flips BMV_X which in turn favorably biases G AND gate. The D_2 register starting at the same time at D_1 is only at its 7th position yet. It allows therefore BMV_x to remain in its #1 state for three more pulses. When D_2 reaches its 10th position it flops BMV_x back to its original 0 state, which in turn closes the gate. At the end of the 10th pulse D_1 is back at position 3 and D_2 at zero just as they were at the beginning.

Follow the left side of the figure now, storage register D_3 stores y=6. The most important feature is that the speed of the read-out device on the left is lowered by a factor of 10. After every tenth pulse on line P only one pulse appears on line P_{10} from the generator. It takes therefore 100 P pulses to complete one cycle of D_3 and D_4 registers. This equals ten D_1 and D_2 cycles.

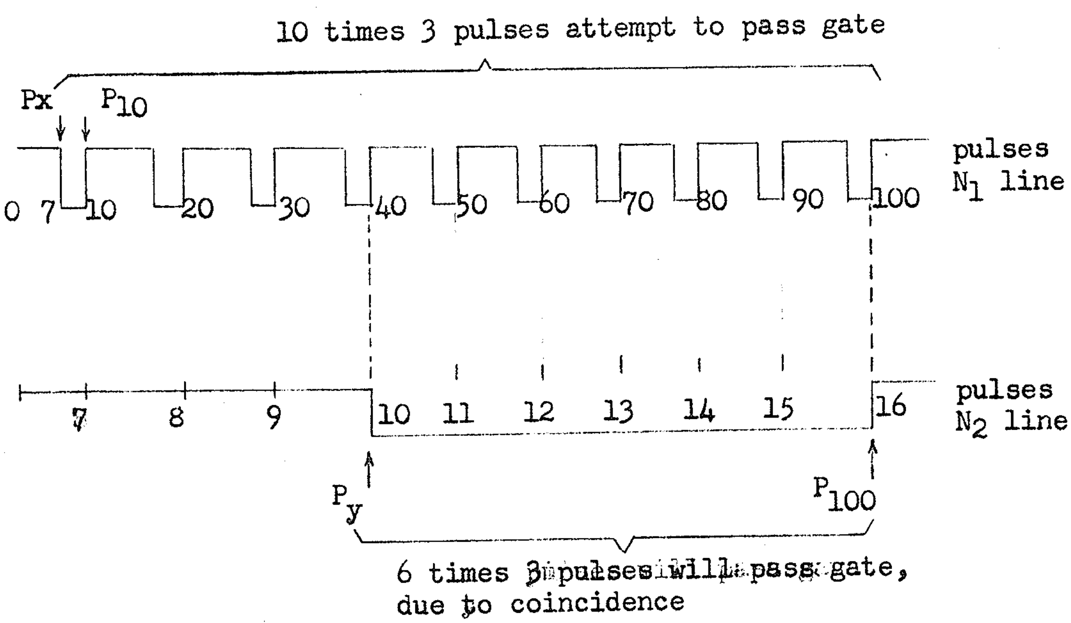


Figure 31

Time-Pulse Relations of Multiplication at the "AND" Gate

Due to the same facts as explained in connection with the right side BMV_y will only bias the gate favorably six times out of ten. As a result $6 \times 3 = 18$ pulses become stored in the accumulator which of course is the correct answer. The time-pulse relations of this example of multiplication are shown on Figure 31.

The digital techniques introduced here provide sufficient information for the computation of traffic parameters Q, V, D, and L either in binary or decimal form.

CHAPTER III

MULTI-PARAMETER DETECTING SYSTEMS

III (a) Manual - Operated by Human Observers

The many possible multi-parameter detectors may be classified into three major groups. Table 5, shows such a classification.

Table 5

Type of Multi-Parameter Detector	Purpose
Manual: Readings taken by the attending personnel which need further mathematical treatment to obtain final results (Q,V,D,L)	Occasional use for short periods only. Experiments, laboratory usage.
Semi Automatic: The detector performs the calculations and displays the final results. Readings and tabulations are performed by personnel.	May be used for laboratory experiments and short duration surveys in low density traffic situations.
Fully Automatic: a) For Engineering Uses Performs all functions automatically produces printed records or charts for human readers.	Used in time consuming traffic engineering surveys, studies and data collection under any traffic condition.
b) For Machine Applications The detector output is special and not suited for direct human reading. May be an input device for traffic signal controllers, computers or data recording systems.	Continuous use of real time computation and control of complex systems.

The block diagram of a manually operated system is drawn in Figure 32. The function of components and the features of the system is described in the followings.

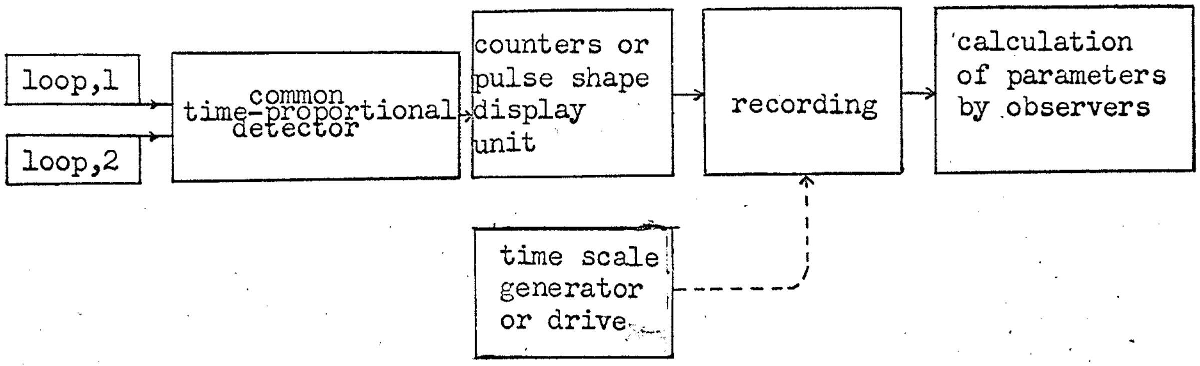


Figure 32

Manual, Multi-parameter Detecting System

The loops are connected to a common detector. The only requirement for the detector output pulse is a linear relationship with time and space events. The pulse shape display following may be a triggered base scope, strip charte recorder for analogue systems and counters for digital systems. The time scale generator or drive is needed for the former two only. Recording may be done by a camera in the case of the oscilloscope display or for reading the counters. It is possible however that some of these units are combined. For instance in the case of counters a human observer can make the recording and calculations, or in the case of a strip-charte recorder the drive, display and recording is one common unit. This system is slow, but it performs laboratory experiments, demonstrations and tests.

The word "manual" tries to express that a human observer is necessary to calculate the parameters. The output consists of time lapses in digital or analogue form and the observer has to perform the computations of traffic parameters from this data.

III (b) Semi-Automatic Detecting System

The semi-automatic scheme is shown in Figure 33. The pulse shaping circuit here is more elaborate. Triggering pulses must be provided for the beginning and end of both (t and T) time periods. Separate units execute the analogue or digital calculation of volume Q, speed v, density D, and vehicle length L contained in the arithmetic unit. Each parameter is displayed on a separate meter or counter and read by the human observer.

The operation of a semi-automatic detecting system such as outlined in the block diagram of Figure 33 will be described.

Loops #1 and #2 feed one common detector. The detector generates two identical square output pulses of T duration and t time lapse between them. With the known detector distance this is sufficient information for the calculation of all traffic parameters in question.

The triggering unit shapes and distributes these pulses into three separate output channels for the arithmetic unit. The top section of the arithmetic unit is the volume (Q) integrator. The Q unit uses only one pulse per vehicle and integrates the volume of vehicles in regular time intervals, provided by the "Clock". Two channels connect to the speed measuring unit (V). The first delivers a start pulse which is the beginning of the first detector pulse and the second carries the stop pulse which is the beginning of the second pulse (see P.12 Figure 3). The computation of speed follows, and the result channelized two ways, towards the output speed meter and into the density unit (D).

Vehicle density is the ratio of the volume over speed. Division of these quantities is performed and displayed by the density meter.

The last part of the arithmetic unit executes the vehicle length calculation (L). Start and stop pulses give (t) and a third pulse gives T duration are necessary for this calculation. (see P.33 equation 27) The resulting length (L) is metered or displayed.

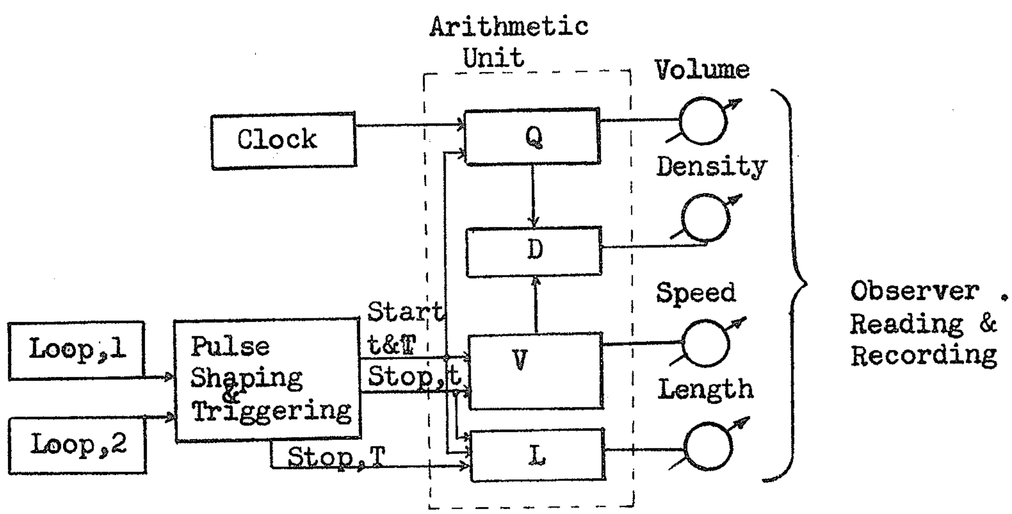


Figure 33

Semi-Automatic Multi-parameter Detector

III (c) Fully Automatic Multi-parameter Detecting System

Finally the block diagram of a fully automatic system is shown on Figure 34. This unit, in almost every use visualized, will have to have a digital output. On the other hand the semi-automatic type may be a much simpler analogue unit. The initial building blocks of this system are similar to the semi-automatic type.

The Control Unit includes storage registers and sequencing devices to secure a series or sequential output for machine use. These machines may be traffic signal controllers, computers for traffic surveillance or control and other similar devices. There is only one output required for these. In traffic engineering surveys, the machines receiving these parameters may be recorders, punch tapes or cards and each parameter may have to be recorded separately. In such a case the Control Unit should have a multi-channel output, one for each parameter as indicated by the dotted lines.

The operation of a fully automatic system, such as shown in Figure 34, is the same as of the semi-automatic up to the arithmetic unit. The "clock" occupies a more central position and provides the digits as well as the synchronizing functions for and between the arithmetic and Control Units. The arithmetic unit may be analogue and the outputs digitized by the control unit. Or the two units may be combined into one single special purpose digital computer. This computer must work in real time and must perform parallel calculations of four different programs. The output for control purposes should be single, with series digital information and multiple with parallel information for individual recording of the parameters.

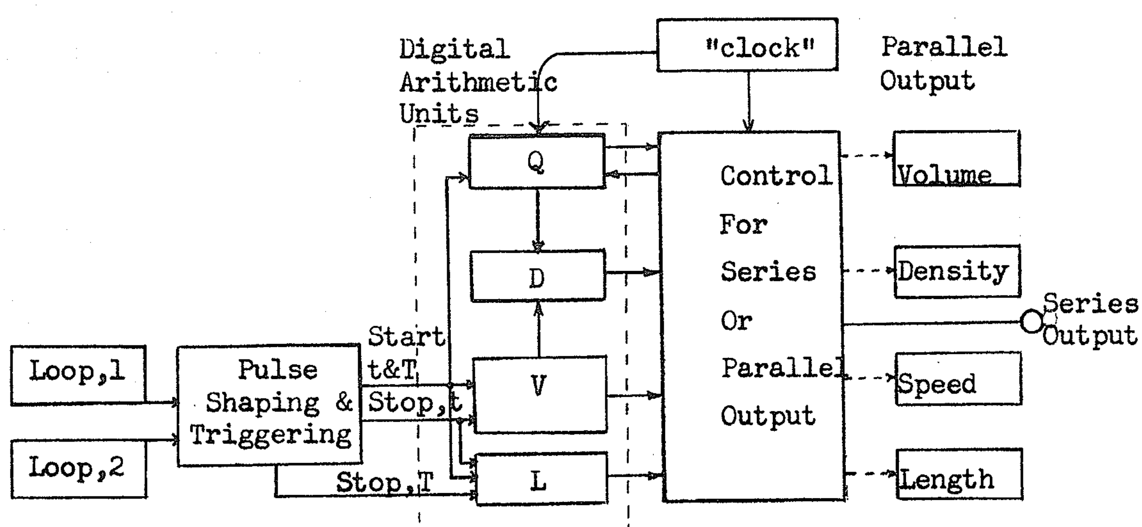


Figure 34

Block Diagram of a Fully Automatic Multi-parameter Detector System

CHAPTER IV

CONCLUSIONS

IV (a) Review

The purpose of this study was to examine the possibilities of multi-parameter traffic flow detection. A **survey** of the available single parameter counting detectors was undertaken, and test results of three typical units were presented. The experiments revealed, that when the output of a single parameter detector is a fast rising square pulse and when the length of the pulse is proportional with the speed and vehicle length, such a system may be used as an input for multi-parameter detection.

Error analysis regarding the speed and vehicle length measurements resulted in two error functions. These functions show that the ideal detector has a line instead of an area of detection and that accuracy of measurements increases with decreasing distance between loops or other sensors. An examination of the effect of varying pulse shapes, distortion and drifting of the triggering and amplification levels showed parameter dependence on these factors. The least sensitive to changes of such factors is the vehicle volume (Q) measurement and the most critical is the vehicle length (L).

These findings become important in the process of equipment and system design.

A calculation of vehicle flow parameters in Chapter II) was based upon the elapsed time measuring technique. Two sensing devices are necessary to measure vehicle speed, volume, density and individual length of vehicles. Many different methods of measuring time electronically was discussed and both analogue and digital techniques of vehicle parameter computations surveyed.

In the last chapter three multi-parameter detecting systems the manual, semi-automatic, and fully automatic were discussed, which lead to the final conclusion of this study that multi-parameter detection has real possibilities.

IV (b) Discussion of Other Areas of Investigation

Another purpose of this study was to investigate the underlying principles of automatic traffic flow detection. This topic involves so many different subjects that some of them have to be studied separately. This study may serve as a guide-line to undertake such detailed investigation. The purpose of such works may be the actual design of a multi-parameter detector, and may be summarized in the following:

1) Investigations and design of a vehicle detector with two input sensors built in the roadway. The sensors should have a narrow longitudinal area of detection, approaching a line of detection perpendicular to the traffic flow. The detector should provide two identical square pulses, with fast rise and fall times and a duration which is proportional with the presence of vehicles above the sensor.

2) Design of a pulse shaping and triggering unit. The function of this unit is to provide standard pulses for the different stages of the arithmetic unit.

3) Design of a "Clock" oscillator.

4) Development of two, an analogue and a digital arithmetic unit. Each may be divided into four separate designs of:

I An integrator for the measurement of vehicle flow volume Q. This unit would utilize standard width and height pulses from the trigger.

II A speed calculating unit V, which would be fed with a fast start and stop pulse both generated when the front of vehicles touch the line of the two sensors.

III A vehicle flow density meter D, driven by the volume and speed units.

IV A vehicle length calculator driven by the triggering unit and utilizing the start and stop pulses and also the durations of pulses indicating vehicle presence over one of the sensors.

5) A study of output devices alone is an extensive task, which involves metering, charting, card or tape punching or recording devices.

6) A study to specify detector output characteristics and devices especially suited for computer input.

7) And finally further elaboration on the different system design possibilities is necessary. This work should actually be undertaken at the beginning of a program to develop a multi-parameter vehicle detector. All the other points 1 to 6 describing the system components should be designed subsequently and fitted into the system design. The details of such program may be worked out by graduate students or by a research group. A single individual would probably spend several years of design work to develop only one type of multi-parameter detector.

END

APPENDIX 1

Appendix 1 was prepared for a review of the basic types of detectors available today. A choice of a detector type would depend upon the particular field of application. For the purpose of short range experiments such as vehicle counting an inexpensive and simple surface mounted detector may serve well. Permanent systems, for example a centralized traffic control, or freeway surveillance and control equipment require long lasting reliable detectors with well defined pulse shape and pulse duration. Aesthetic considerations may have an influence on the choice between overhead or underground detector types. Table 1 (Page 3) and Table 2, give some guidance in a limited space. Properties which are common however, are not necessarily repeated over and over again. The effect of wind and motion for example may create false pulses with any type of overhead detector. This fact is mentioned in the description of the infrared detector and not repeated with the ultrasonic, and radar or any other overhead mounted detector after, regarding the type and operating principles, for a given application.

Table 2

VEHICLE DETECTOR TYPES AND OPERATING PRINCIPLES

YPE	OPERATING PRINCIPLE	ADVANTAGES	DISADVANTAGES
ubber Tube	Mechanical pressure operates diaphragm switch.	Simple.	Short life time.
ressure Pad tural or ed, flexible some types nstalled by ations, or groove.	Mechanical. Contains either pneumatic switches or contact strips. Gives axel count.	The surface mounted types are portable, may be cemented to the surface. Gives individual lane detection when cut to size. Gives well defined pulses.	Has longer life span than tube, otherwise similar.
Contact Strip plastic strip aining electri- contacts.	Mechanical. The contacts are continuous or segmented, pressed together by the weight of the vehicles.	Inexpensive to purchase and install. The segmented type gives occupancy information. (See #1)	See #1
Impact synthetic er strip into a in the ment or a ow tube in oove.	Mechano - Acoustic. Vibrations set by the impact of vehicles actuates a microphone, the signal is amplified.	Has no advantages over 1, 2 & 3.	The amplifier introduces unwarranted extra.
Strain Gage etal bar or wire into the pave- .	Mechanical stress and strain may be measured electrically or by direct method.	Long life. Makes automatic weighing possible.	Expensive installation cost normally. No presence detection, each lane must have one unit. Pulse shapes may depend on temperature, icing & other factors.

Table 2 (cont'd)

arth's tic Field			
ge coil,(app. inches) in ferrous housing, ed in or the pave-	Electro-magnetic induction is provided by the change in earth's flux density due to the motion of vehicles.	Medium price. No climatic dependence. Simple.	Expensive installation and maintenance. Subject to corrosion, moisture and electrical interference unless compensated, zone of influence is not sharply defined, needs motion to provide detection. Not sensitive below 5 MPH. Needs amplification; pulse shapes are not well defined.
etal Locator			
ll high fre- y coil in a drical cap- installed in tical hole in avement.	High frequency is provided by the auxiliary equipment. A change in the electromagnetic field due to vehicle presence is detected.	Simple, medium priced, including installation. Not sensitive to stray fields when shielded cable is used. Spot zone of influence (may be a disadvantage).	Subject to moisture. Sensing Unit is destroyed when pavement replaced. Each lane requires one. Non-directional needs amplification and pulse shaping for well defined output.
agnetic Bridge			
ll permanent t with pick- ils installed weatherproof drical plastic , including the .	Balanced magnetic conditions exist in the field of the bridge. The iron body of the vehicle upsets this balance, which generates a pulse.	Very similar to the metal locator (#8) above, the sensing head is slightly more complicated.	See #8
noto electric	Electro-optical		
cells or semi- ctor photo- ric devices are d with optical atus.	A light beam is broken or reflected by the vehicle present. The change in light intensity creates a small electric pulse, which is amplified.	Gives excellent pulse shape. The pulse duration is proportional to the speed and vehicle length combined. Spot zone of influence (may be advantageous in position detection).	Subject to smog, dust, fumes and fog, needs cleaning and burnt out bulb maintenance. High price and installation cost; needs amplification but in some special cases (18) it may prove to be very effective for multi-parameter detection. Unmodulated types may be affected by stray beams of light.

Table 2 (cont'd)

Infrared	Electro-Optical		
npact package ted on a pole, lar to a et light.	A modulated beam of infrared light is reflected by the moving vehicle which causes a change in the electric output of the photo-electric receiving device.	Has a relative advantage only; May detect pedestrians and animals	Expensive to install and maintain. Unreliable due to the variation of reflecting surfaces. Wind may cause a swing of any overhead detector and result in false detecting. Not recommended.
Ultrasonic	Electro-acoustic		
age similar to infrared.	Contains an ultrasonic sound generator. The sound beam transmitted changes intensity and phase when reflected from a moving object. The resulting pulse is amplified.	Medium priced. Detects pedestrians and practically any object that enters its sphere of influence. May be used for single lane or multiple lane detection.	Subjected to false actuations by noises and sounds that contain ultrasonic harmonics. Older types need considerable maintenance. Does not give well defined pulse shapes. Has no advantage in multi-parameter detection.
Radar			
the same over- package as infrared or asonic unit.	Micro waves are generated and transmitted in a beam towards the pavement. When a vehicle passes through the beam some of the energy is reflected back to the receiving antenna located in the unit. The resulting pulse is amplified.	Portable and easy to install on existing poles. Covers single or multiple lanes.	The most expensive type, including maintenance. Needs electronic technician for repair. Motion caused by wind or raindrops may result in false actuations. The domain of detection and pulse shapes are not well defined.

Table 2 (cont'd)

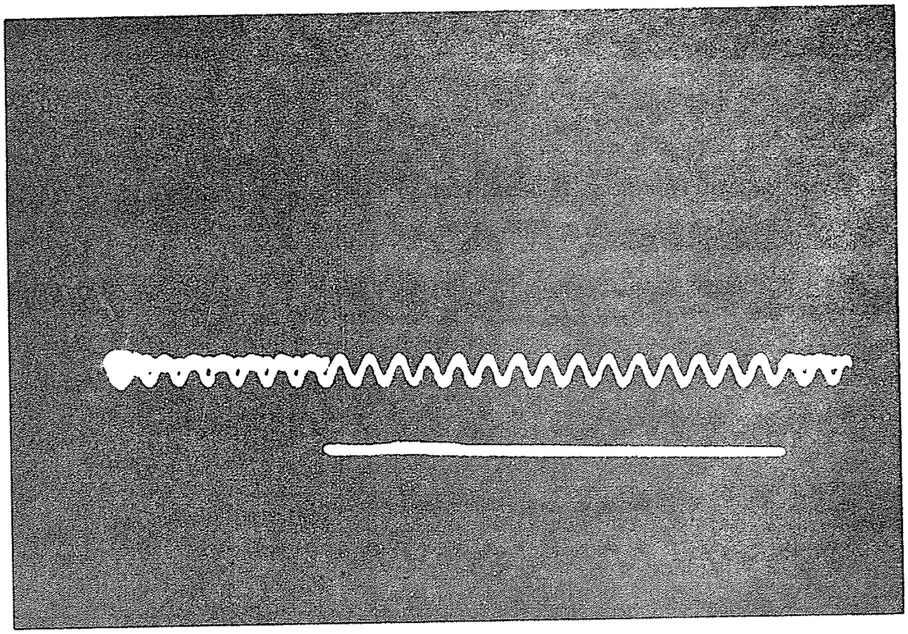
Radio-active			
tested in Rail- car identifi- on. A Geiger ter is the re- ing head, mount- eside the tracks.	Input pulses are provided by painted radio-active patterns on the side of railway cars, passing by the detecting Geiger Counter. Each sequence represents the painted code. Contains an amplifying unit.	Positive identification. Code directly applicable to computer input. Well defined pulses. Good for multi-parameter detection.	Not applicable to street traffic directly and especially in its present form.
Loop	Electro-magnetic		
ılated wire nstalled into oove cut into pavement. (it be attached to surface).	A long wave radio frequency current is generated and fed to the loop or the loop may be part of the oscillator circuit. See Detector Tests for details. (Chapter I)	The cost of the sensing loop is negligible. Installation cost is moderate, and causes only minor traffic interruption only with no damage to the pavement. Not subjected to climatic conditions. Transistorized reliable circuits are available, gives one pulse per vehicle. Both motion and presence detector. The zone of detection is fairly well defined, may cover single or multiple lanes.	Some types need tuning which is time consuming. The length of leads from the loop to the equipment is limited. In some cases power and equipment housing should be available at all four legs of an intersection. Cutting of the pavement is difficult below freezing temperature.

oll #3 Plymouth, L=201"; Wheel base 9.5', S=9' const. W=4', f=3' (front to wheel)

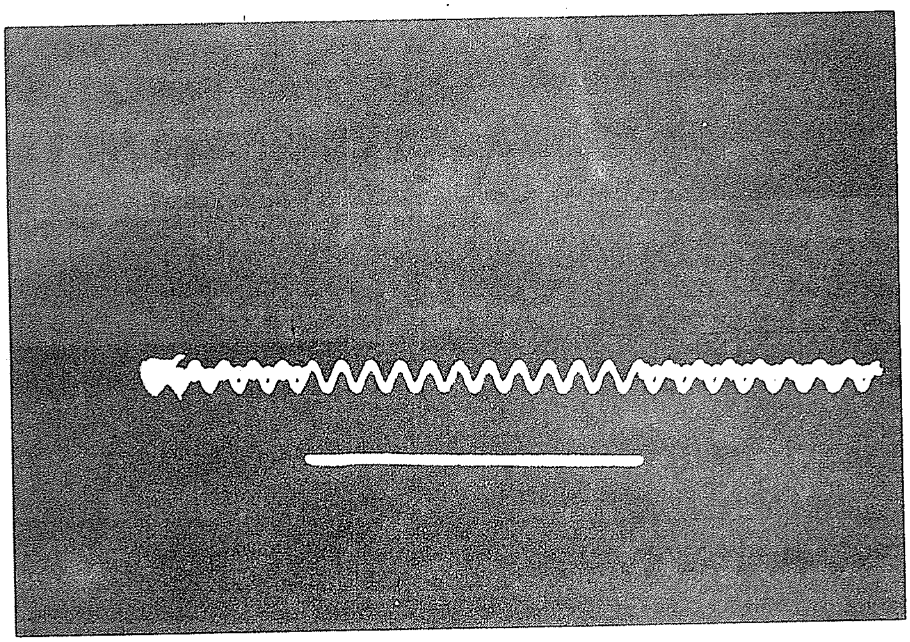
PHOTO No.	DETECTOR	TERMINAL	Remarks	t (Seconds)	T (Seconds)	$\frac{T}{t}$ S= L feet	Speed in M.P.H. Speedometer reading	Calculated Valves * 1st reading v=s/t	* 2nd reading v=s/t	2nd reading $v=\frac{s-f}{t}$
1		CONTACTS	T runs off pict.	0.456	>0.7	14.8	10.	13.5	13.1	8.5
2				0.35	0.75	19.28	15	17	18.7	12.7
3				0.245	0.55	20.2	20	24	25.7	17.2
4	TYPE			0.2	0.42	18.9	25	31	32.3	21.5
5				0.185	0.317	15.42	35	33	36.2	23.8
6				0.16	0.309	19.4	45?	35	41.0	27.4
7				0.16	0.22	13.8	40?	32	38.4	25.5
8				0.184	0.3	14.67	30	33	34.1	22.8
9		COIL		0.184	0.3	14.67	30	33	36.2	24
0				0.24	0.45	16.88	21	25	27	17.7
1	X		T runs off pict.	0.535	>0.75	13	10	11	13	8.5
2				0.165	0.26	14.18	40?	37	38.4	25.5
3				0.2	0.35	15.75	30	31	32.5	21.1
4		CONTACTS	T runs off pict.	0.5	>0.75	13.5	10	12	12.3	8.0
5			2 trucks	---	---	---	≈15	---	---	---
6			Bus & Car	---	---	---	≈12	---	---	---
7			½ T truck	0.235	0.335	12.83	≈20	26	26.2	17.3
8			Group of Veh.	---	---	---	---	---	---	---
9		CONT.		0.14	0.315	19.5	40?	43	42.4	28.4
0				0.36	0.72	18	15	17	17.7	12
1				0.15	0.315	19.5	37	41	41	27.3
2	Y	COIL		0.265	0.47	16.0	20	23	23.6	15.7
3		CONT.		0.165	0.125	7.0	40?	37	37.5	24.8
4				0.33	0.15	4.0	19	18.5	18.8	12.4
5				0.12	0.175	13.0	36	51.5	47.0	34.0
6	Z			0.215	0.265	11.0	36	28	28.6	19.0
7		COIL		0.2	0.225	11.0	22	30	34.2	22
8	TUBE	CONTACTS	One reading (b)	0.21	**b	9.25	30	$\frac{b}{t}$ 35.5	30.6	→ $v=\frac{b}{t}$
9			taken from front	0.325		9.6	20	25	20	
0			wheel to rear	?0.35		7.8	15	21.7	18.6	
1				0.57		7.5	11	14.8	11.4	
2				0.92		10.2	7	8.5	7.1	
3	DET.		one actuation only			---	5	---	---	
4			Photo not clear	?1.07		3.2?	≈2	7.04	6.2	
5			5 actuations	---		----	--	---	---	
6			Group	---		----	--	---	---	

*NOTE: Accurate reading of photos is impossible. The 1st and 2nd reading refers to calculations based upon two different readings. (2nd not incl. in Table)

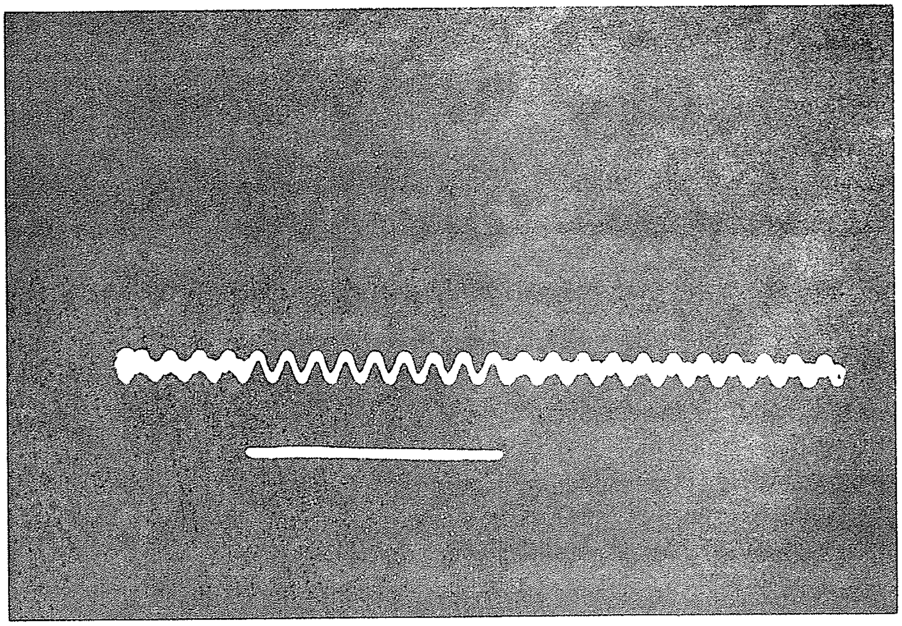
** Wheel base (b) is calculated with Tube Detectors. b=Vt; (?) mark indicates uncertain speedometer readings.



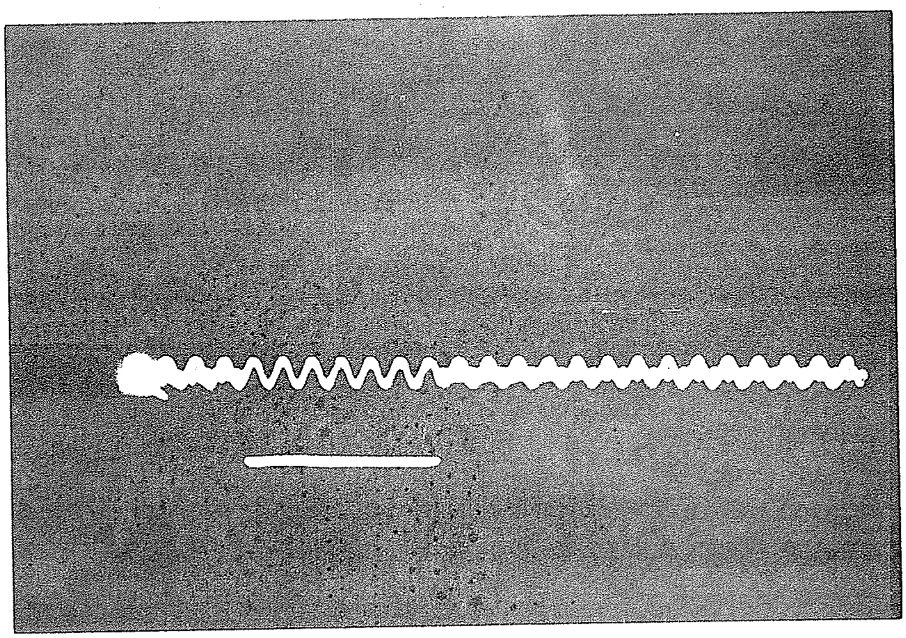
Picture 1
Detector X, Relay Contacts
Speed 15 M.P.H.



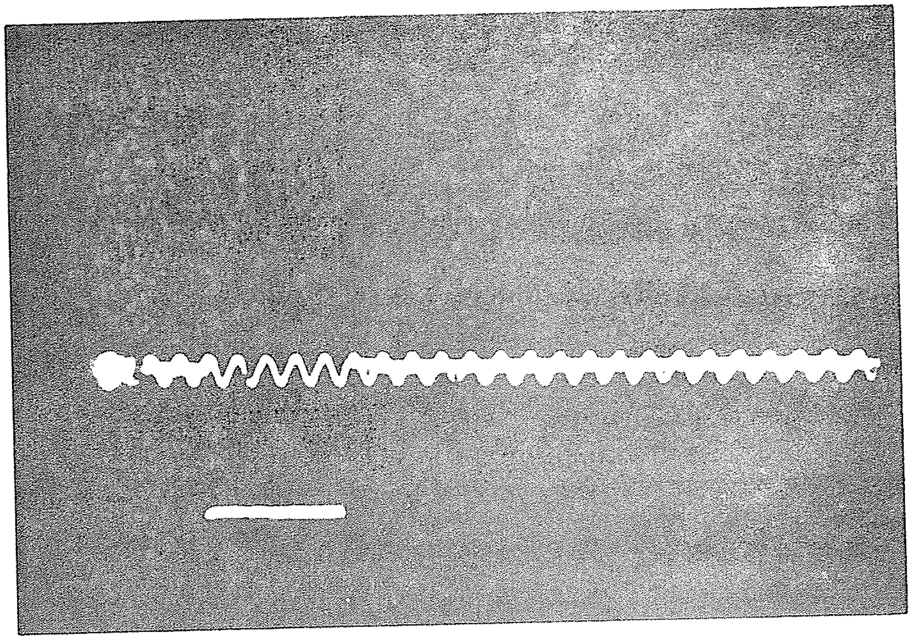
Picture 2
Detector X, Relay Contacts
Speed 20 M.P.H.



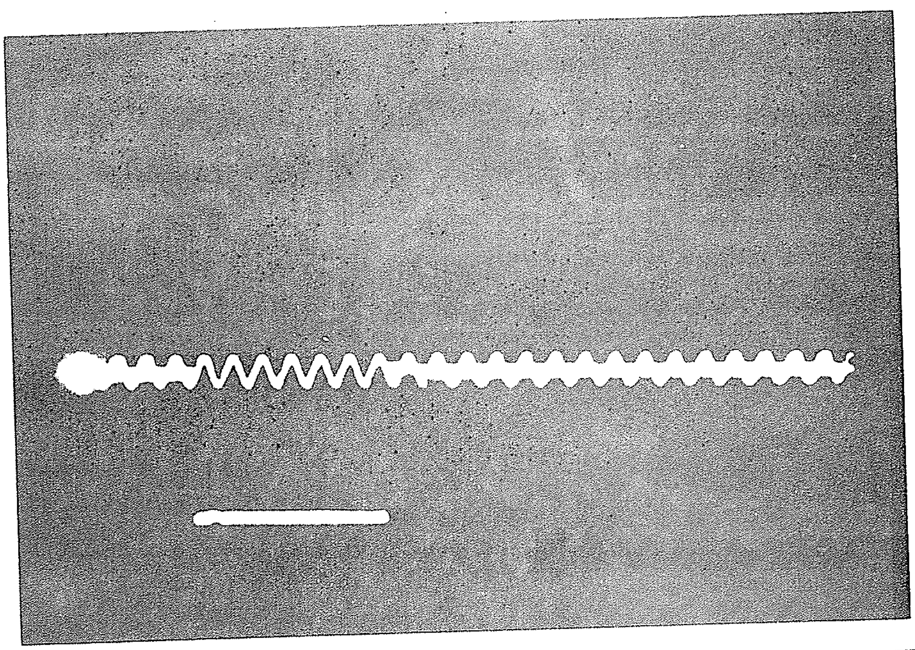
Picture 3
Detector X, Relay Contacts
Speed 25 M.P.H.



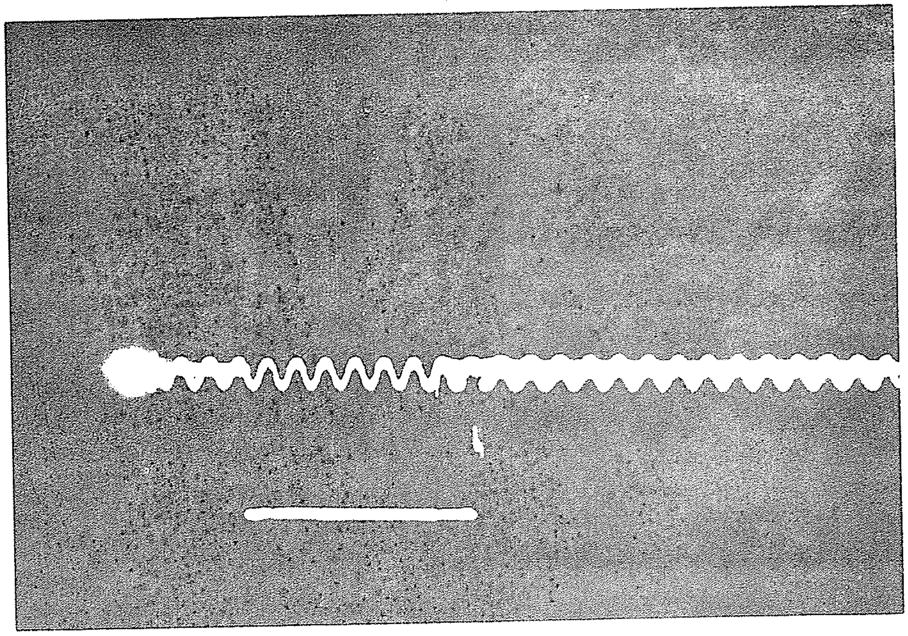
Picture 4
Detector X, Relay Contacts
Speed 35 M.P.H.



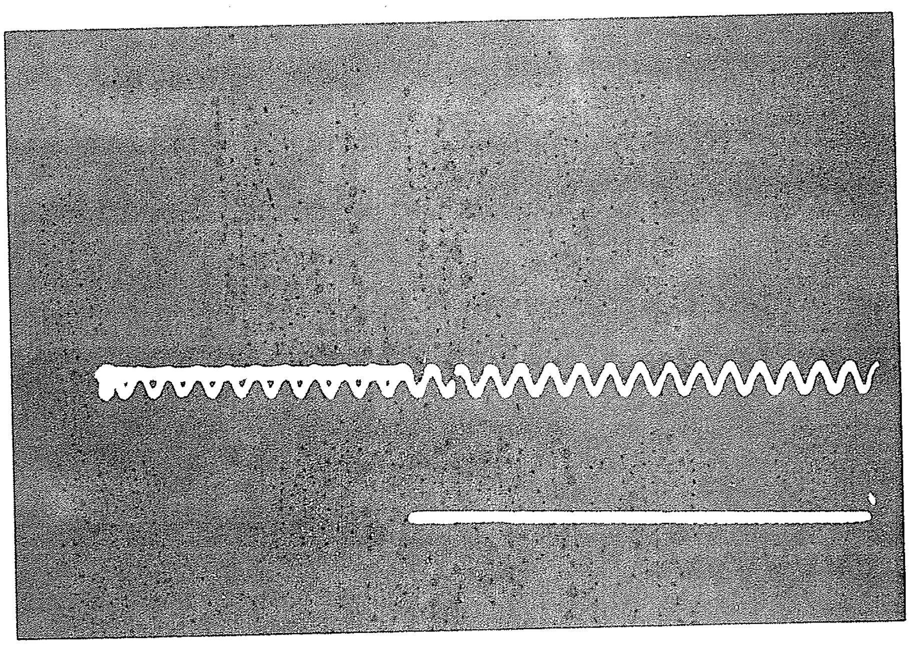
Picture 5
Detector X, Output Current
Speed 40 M.P.H.



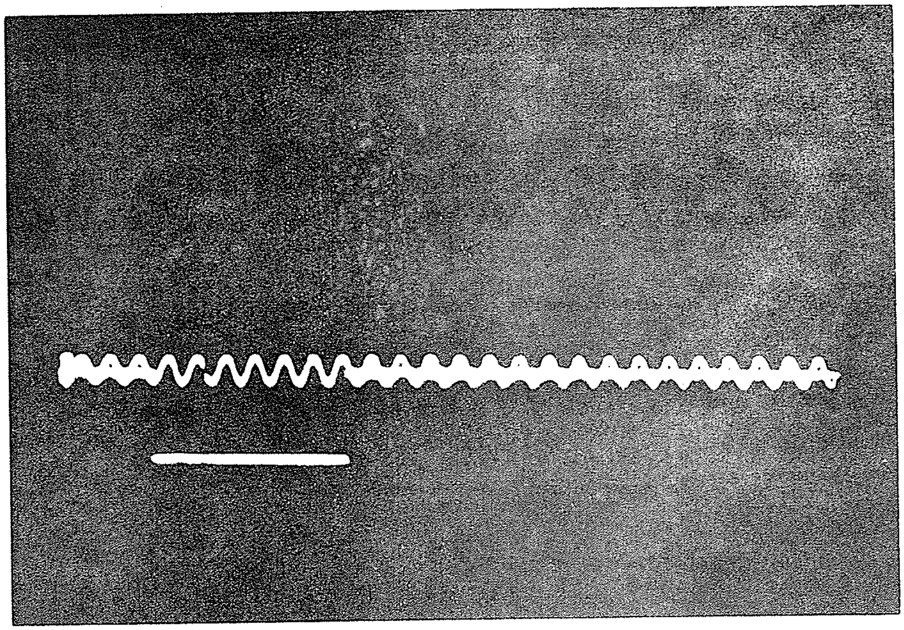
Picture 6
Detector X, Output Current
Speed 30 M.P.H.



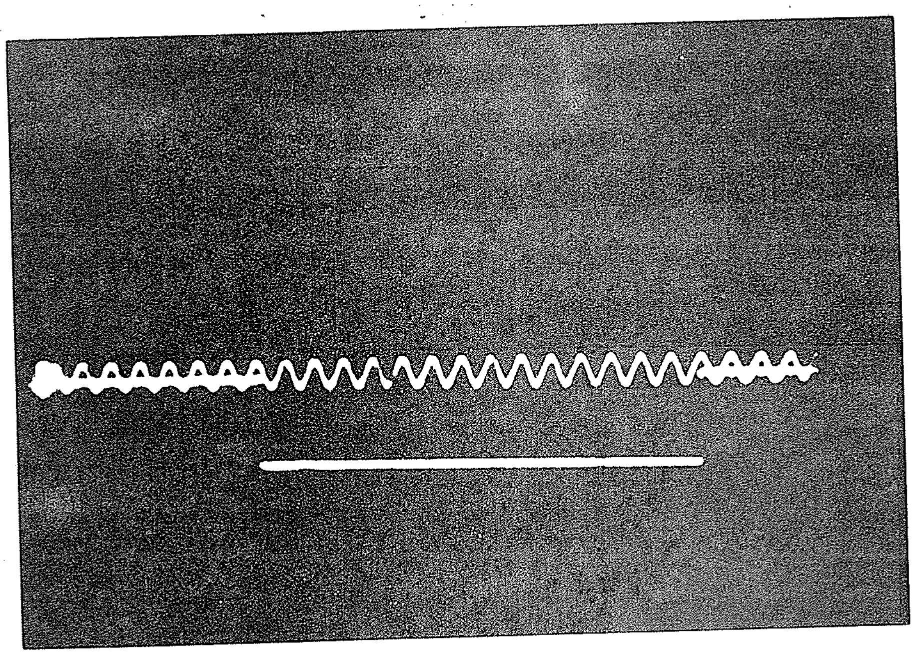
Picture 7
Detector X, Output Current
Speed 21 M.P.H.



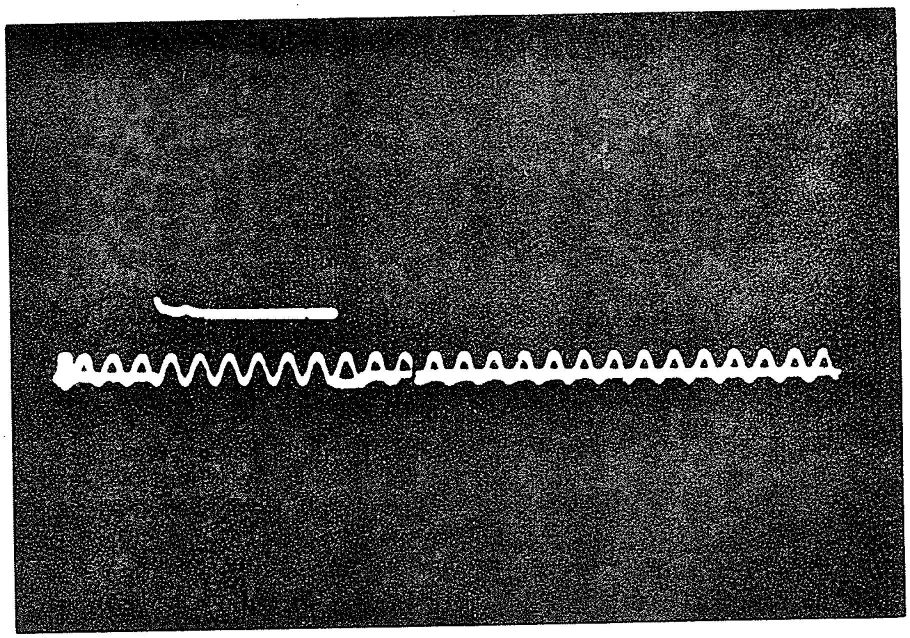
Picture 8
Detector X, Output Current
Speed 10 M.P.H.



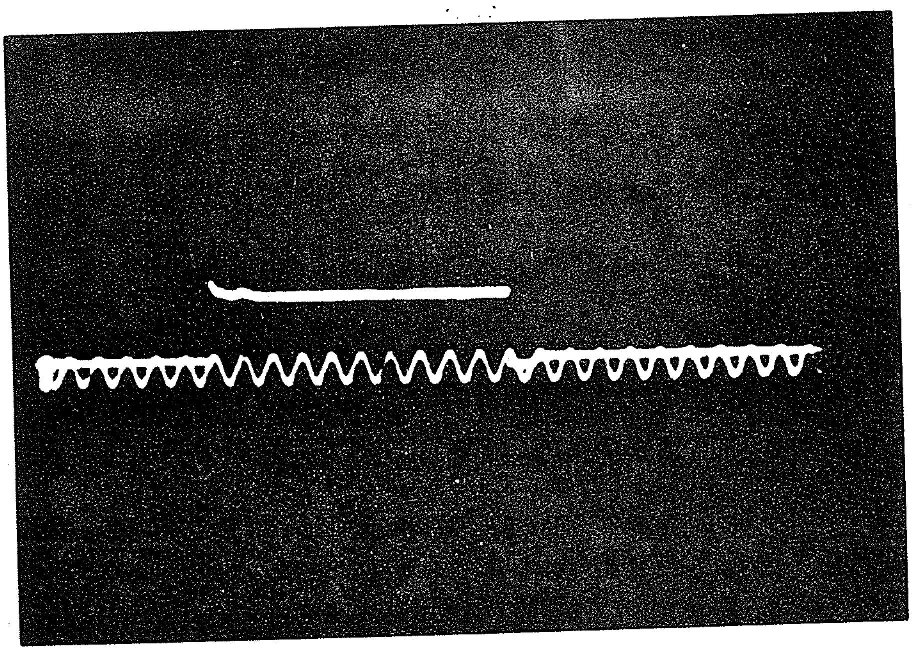
Picture 9
Detector Y, Relay Contacts
Speed 40 M.P.H.



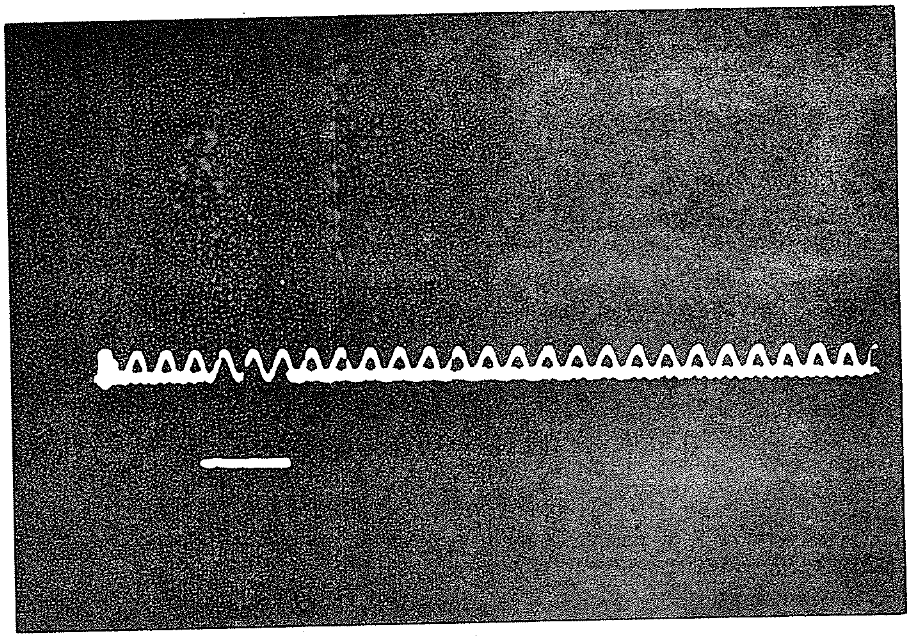
Picture 10
Detector Y, Relay Contacts
Speed 15 M.P.H.



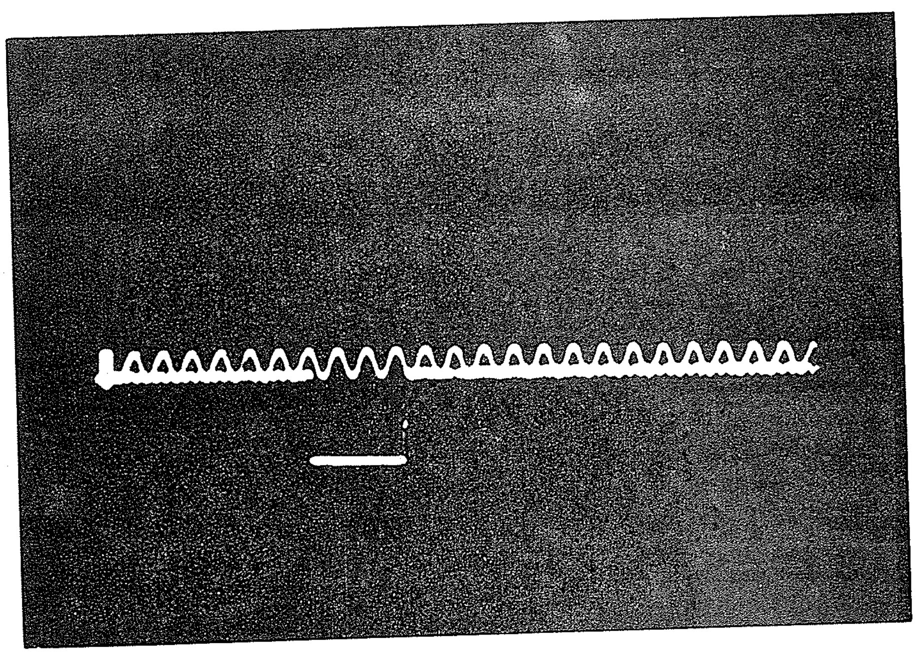
Picture 11
Detector Y, Output Current
Speed 37 M.P.H.



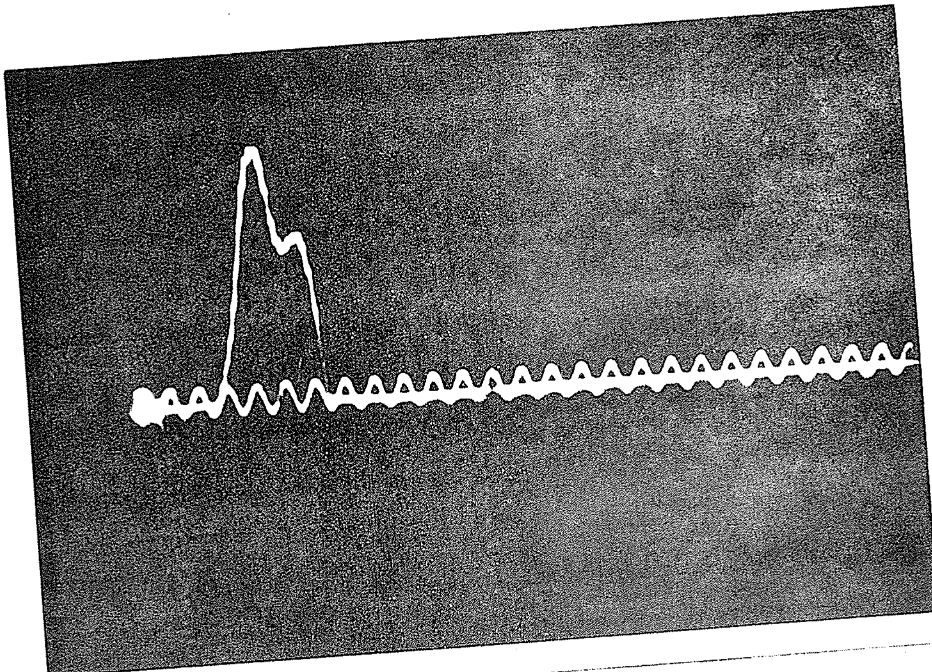
Picture 12
Detector Y, Output Current
Speed 20 M.P.H.



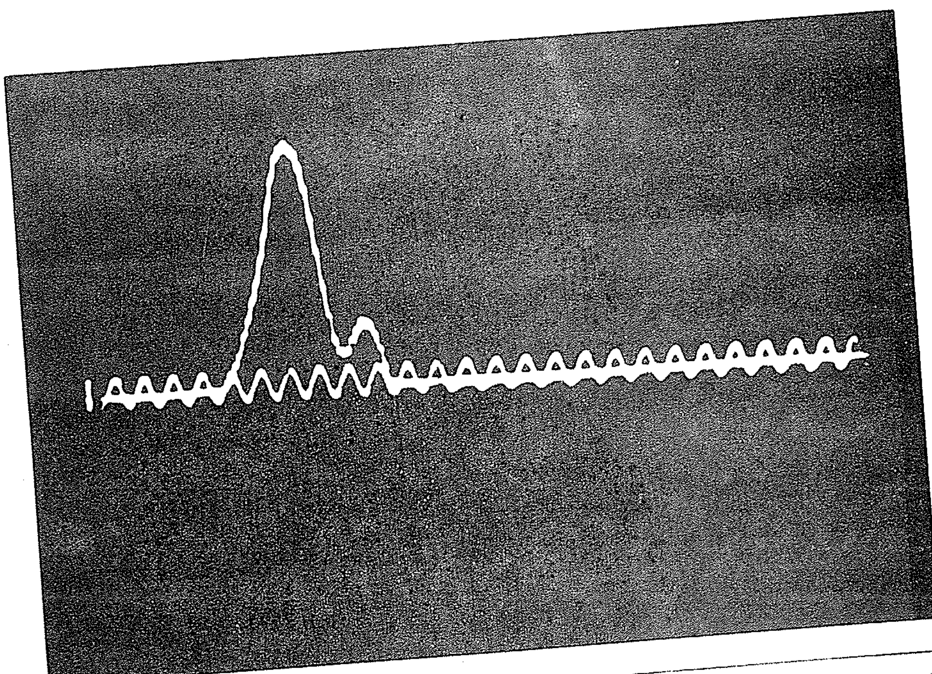
Picture 13
Detector Z, Relay Contacts
Speed 40 M.P.H.



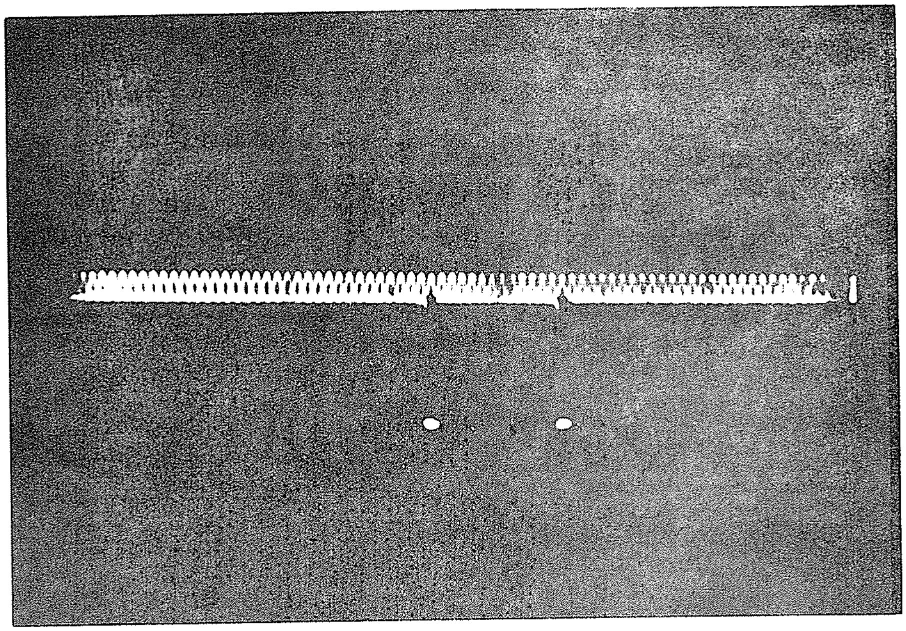
Picture 14
Detector Z, Relay Contacts
Speed 19 M.P.H.



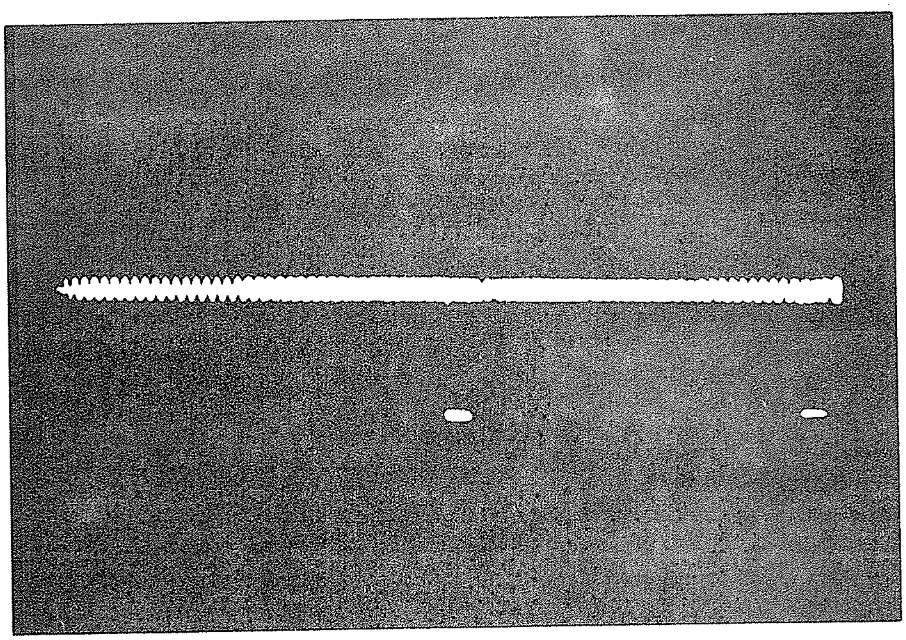
Picture 15
Detector Z, Output Current
Speed 36 M.P.H.



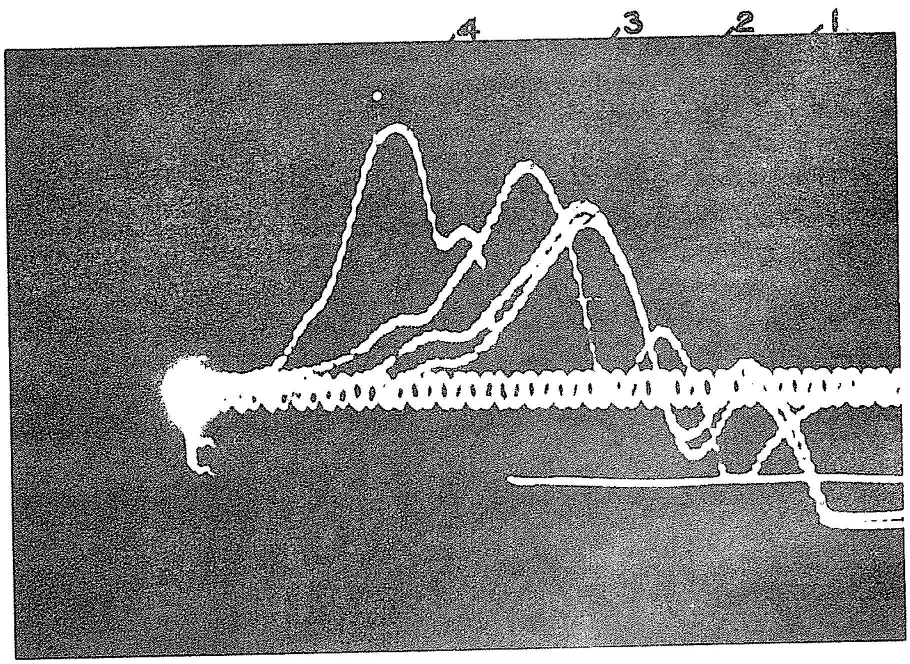
Picture 16
Detector Z, Output Current
Speed 21 M.P.H.



Picture 17
Pneumatic Tube Detector
Speed 30 M.P.H.



Picture 18
Pneumatic Tube Detector
Speed 11 M.P.H.



Detector Z

Four Vechicle Pulses Superimposed.

1 - Failed to energize the output relay - Speed 5 M.P.H.
2 - Failed to energize the output relay - Speed 10 M.P.H.
3 - Failed to energize the output relay - Speed 15 M.P.H.
4 - Energized the output relay - Speed 20 M.P.H.

BIBLIOGRAPHY

1. H. K. Ewans, TRAFFIC ENGINEERING HANDBOOK - 1950, P52-P70

The following articles were published in the "Traffic Engineering"

2. P. H. Thompson and M. J. Huber, MEASURING LATERAL PLACEMENT & VELOCITY Vol. 31, Oct. 1960, No.1, P. 26-28.

3. R. C. Hopkins, VEHICLE DETECTION FOR ANALYSIS AND CONTROL Vol. 31, July 1961. No. 10, P. 14-16.

4. S. M. Breuning and F. A. Wagner, ANALYSIS OF 24-HOUR TRAFFIC COUNTS by DIGITAL COMPUTER. Vol. 31, April 1961, No.7, P. 15-18.

5. J. L. Barker, DETERMINATION OF DISCONTINUITIES IN TRAFFIC FLOW AS A FACTOR IN FREEWAY OPERATIONAL CONTROL. Vol. 32, Nov. 1961, No. 2 P. 11-17 & 50.

6. G. F. Hagenauer, THE CHICAGO EXPRESSWAY SURVEILLANCE RESEARCH PROJECT. Vol. 32, July 1962, No. 10, P.11.

7. H. A. Barnes, USE OF ELECTRONICS IN TRAFFIC CONTROL Vol. 32, Jan. 1962, No.4, P. 25-30.

8. G. R. Claiborne, INDUCTION VEHICLE DETECTORS Vol. 33, Dec. 1962, No. 3, P. 21-25.

---

9. Sam Cass and L. Casciato, CENTRALIZED TRAFFIC SIGNAL CONTROL BY A GENERAL PURPOSE COMPUTER, Proceedings Institute Traffic Engineering, Vol. 30 1960, P. 203.

10. T. M. Matson, W. S. Smith, F. W. Hurd, McGraw-Hill, TRAFFIC ENGINEERING, 1955.

11. J. T. Hewton, THE METROPOLITAN TORONTO AUTOMATIC TRAFFIC CONTROL SYSTEM, Proceedings Institute of Traffic Engineering, 1963 - P.129.

12. J. T. Hewton, VEHICLE DETECTORS, Proceedings Institute of Traffic Engineering, 1963, 33rd Ann. Meet. P. 184.

14. Brainard, Trabold, Becker, A DIGITAL DATA RECORDING SYSTEM FOR TRAFFIC FLOW ANALYSIS. Nat. Electronics Conference (Chicago) Vol. XVII Oct. 1961, P. 435-44.

Articles from the book of Proc. Highway Conference, (Washington D. C.) Sept. /64 U. S. Department of Commerce Bureau of Public Roads, Traffic Simulation Surveillance and Control.

13. J. T. Hewton, A. Christensen, DEVELOPMENTS IN CONVENTIONAL GROUND BASED DETECTION. P. 13.

15. A. Torain, SIMULATION NEEDS IN INTEGRATED TRAFFIC CONTROL, P. 175.

16. E. F. Gervais, NATIONAL PROVING GROUND FOR FREEWAY SURVEILLANCE CONTROL AND ELECTRONIC TRAFFIC AIDS. P. 193.

17. A. D. May, CHICAGO AREA EXPRESSWAY SURVEILLANCE PROJECT, P. 204.

18. R. S. Foote, VEHICLE SURVEILLANCE TO IMPROVE THE LEVEL OF TRAFFIC SERVICE, P. 258.

19. Sh. H. Hiller, THE NEW TAMPA SIGNAL SYSTEM, P. 297.

20. S. Cass, L. Casciato, PROGRESS AND EXPERIENCE IN TORONTO TRAFFIC SIGNAL SYSTEM, P. 324.

21. H. H. Fite, PROSPECT FOR SMALLER CITIES IN THE USE OF COMPUTERS FOR TRAFFIC CONTROL, P. 347.

22. J. L. Barker, PROSPECT FOR SMALLER CITIES IN THE USE OF COMPUTERS FOR TRAFFIC CONTROL, P. 356.

23. H. C. Kendall, PROSPECT FOR SMALLER CITIES IN THE USE OF COMPUTERS FOR TRAFFIC CONTROL, P. 364.

24. F. C. William, N. F. Moody, LINEAR TIME BASE GENERATORS, J. Instr. E. E. PT III, A. P. 1188-98, 1946.

25. J. R. Acton, THE DECATRON, E. E. 1952, P. 48.

26. L. A. Yardeni, VEHICULAR TRAFFIC CONTROL: A TIME-SPACE DESIGN MODEL: PROC. INST. TRAFFIC ENGS. 34th Annual Meet. 1964.

27. E. F. Gervais, THE JOHN LODGE FREEWAY SURVEILLANCE SYSTEM, Proc. Inst. Traffic Engs. Vol. 32, July 1962, No. 10, P. 15-19.

Books on Switching Circuits, Computers, and Mathematics:

28. P. A. Neeteson, JUNCTION TRANSISTORS IN PULSE CIRCUITS, Philips Techn. Libr. 1961.

29. L. Strauss, WAVE GENERATION AND SHAPING, McGraw-Hill, 1960.

30. R. Blitzer, BASIC PULSE CIRCUITS, McGraw-Hill, 1964.

31. O. S. Puckle, TIME BASES, Second Ed. Chapman & Hall 1952.

32. Traffic Institute, Northwestern University, Training Outline, Speed Studies. C. 33.04 1959-8 P 3041.

33. Millman J. & Taub H. PULSE AND DIGITAL CIRCUITS, McGraw-Hill 1956.

34. R. V. Churchill, COMPLEX VARIABLES AND APPLICATIONS. McGraw-Hill 1960 P. 129.

35. Korn & Korn, MATHEMATICAL HANDBOOK, McGraw-Hill 1961 P. 130.

36. Lewis & Wells, MILLIMICROSECOND PULSE TECHNIQUES PERGAMON PRESS, 1959.

37. D. S. Babb, PULSE CIRCUITS, SWITCHING AND SHAPING, Prentice-Hall, 1964.

38. Booth and Booth; AUTOMATIC DIGITAL CALCULATORS, Butterworth Scientific Publ. 1956.

39. Korn and Korn; ELECTRONIC ANALOG COMPUTERS McGraw-Hill 1952.

---

40. O. Celinsky and I. H. Rimary, CLASSIFICATION OF ANALOG MULTIPLIERS, Instruments and Control Systems, June /64 P. 149-56.

41. J. G. Miner, INTEGRATED ELECTRONIC ANALOG-to-DIGITAL CONVERTER. Pcoc. IEEE Vol. 52, 1964, P. 1710-12.

From: Electronic's Engineering Manual Vol. 7:

42. A. C. Sanford, PRECISE PARTS SORTING ON PRODUCTION LINES, P. 62.

43. J. H. J. Filter, MICROSECOND TIMER CHECKS CONCRETE BEAMS, P. 70.

44. W. W. Schroeder, PULSE GENERATOR HAS WIDE CONTROL RANGE, P. 90.

45. B. C. Forter, A SIMPLE VALVE COMPARATOR, E. E. 1952, Vol. 24, Jan. - Dec.

46. Garfield, DETERMINING THE VELOCITY OF AN ULTRASONIC PULSE, E. E. 1952, Vol. 24, Jan. - Dec. P. 390.

47. R. Tomlinson & R. Brown, A FAST-SLOW COINCIDENCE SYSTEM EMPLOYING A MULTICHANNEL TIME DISPLAY. IEEE, Trans. N.S.-11 Apr/62, P. 28.

48. J. Fraser & R. Tomlinson, TRANSISTOR CIRCUITS WITH NANOSECOND RESOLUTION (Time to Amplitude Converter) Meeting Can.Assoc. of Physicists, June 6-9, 1962.

49. A. J. Oxley, ON FEEDING COMPUTERS FROM SCALERS, Electronic Engineering (G.B.) Vol. 35, 801-5, Dec./63.

50. R. J. Barber, TWENTY ONE WAYS TO PICK UP DATA OFF MOVING OBJECTS Control Eng. (USA) Vol. 10, No. 10, P. 82-6, Oct./63.

51. Second Part - Vol. 11, No.1, P.64-4, Jan./64.

52. S. G. Smith & C. Roberts, A DIGITAL SHAFT POSITION INDICATOR, Electronic Engineering (G.B.) Vol. 36, P.72-9, Feb./64.

53. D. L. A. Barber, A HIGH SPEED ANALOGUE MULTIPLIER, Electronic Engineering (G.B.) Vol. 35, P.242, Apr./63.

54. A. Russell, ELECTRONIC DIGITAL RATIO EQUIPMENT, Radio Electronic Engineering (G.B.) Vol. 27, No.3, P. 197-207, March/64.

55. D. W. Thomasson, LOW COST ELECTRONIC ARITHMETIC, Rad. Electronic Engr. (G.B.) Vol. 27, No.3, P.219, March/64.

56. C. S. Wallace, A SUGGESTION FOR FAST MULTIPLIER, IEEE Trans. Electronic Comput. (USA), Vol. EC-13, No.1, P.14-17.

57. J. A. Rosenthal, A PULSE MODULATOR THAT CAN BE USED AS AN AMPLIFIER A MULTIPLIER, OR A DIVIDER. IEEE Trans. Inst. Meas. (USA), Vol. IM-12, No.3, P.125-33, Dec./63.

58. R. Egelmann, MEASURE TIME INTERVALS DIGITALLY, Electronics, (USA), Vol. 37, No.5, P.34-6, Jan./64.

59. G. T. Wright, ANALOGUE MULTIPLICATION WITH THE SPACE-CHARGE-LIMITED SURFACE-CHANNEL TRIODE, Rad. Electronic Eng. (G.B.), Vol. 28, No.1, P.13-15, July/64.

60. D. G. W. Mace, ELECTRICITY IN THE SERVICE OF ROAD-TRAFFIC CONTROL, Electronics & Power (G.B.) Vol. 10, P.120-3, Apr./64.

61. R. L. Chafin & F. Ahlstrom, MEASUREMENTS USING COUNTING TECHNIQUES, Instrum, Control Syst. (USA), Vol.37, No.6, P.109-14, June/64.

62. P. Kundu, S. Banerji, TRANSISTORIZED MULTIPLIER AND DIVIDER AND ITS APPLICATIONS, IEEE Trans. (USA) Vol. EC-13, No.3, P.288-95, June/64.

63 G. Waltman, G. Sullivan, D. Bredon, THE CONTINUOUS MEASUREMENT OF ARTERIAL PULSE WAVE VELOCITY. Med. Electronics Biol. Eng. (G.B.), Vol. 2, No.2, P.145-54, Ap.64

64 H. Schmid, A REPETITIVE PULSE TIME COMPUTING TECHNIQUE, IEEE Trans. Aerospace (USA), Vol. AS-2, No.2, P.211-26, Ap.64.

65. J. J. Ebers, J. L. Moll, LARGE SIGNAL BEHAVIOR OF JUNCTION TRANSISTORS, Proc. IRE, Vol.42, P.1761-72, Dec./54.

66. J. S. Ellis, Patent No.604,544. Sept.6, 1960. AUTOMATIC PHOTOGRAPHIC RECORDER OF TRAFFIC VEHICLES SPEEDS AND NUMBER PLATES. Pamphlets:

67. Flory, Gray, Morey, Pike and Caulton, RCA LABORATORIES ELECTRONIC TECHNIQUES IN A SYSTEM OF HIGHWAY VEHICLE CONTROL. RCA Review, Sep. 1962, Vol. XXIII, No.3 Reprint avail. from the David Sarnoff Res. Centre, Princeton, New Jersey.

68. Philips ELECTRONIC ROAD SPEED METER TYPE GM 4150/PHOTOGRAPHIC EQUIPMENT, TYPE PM 6120. Pamphlets; Ind, Eq. Div. Electronic Meas. App. EM 4-V1 & V3.

69. Speedophot. & Hasta
Traffipax. - Vertriebe
Dusseldorf Germany Aachener Strasse 21

70. Traffic Detector TP-1 INSTALLATION MANUAL
R. H. Nichols Co. Ltd. Downsview, Ontario

71. Vehicle Detector Type EW50
INSTRUCTION MANUAL Eagle Signal Co. Georgetown, Ont.

72. Presence Detector Link/Model HLS-1
INSTRUCTION MANUAL Municipal Signal, Div. CAE
2676 Marcel St., Montreal 9

73. G. D. Smith, COUNTING-RATE METERS
Electronic Engineering, Man. 1952, P14-18.

74. G. Sagi, THEORETICAL TRAFFIC VOLUME AND TIMING STUDIES,
TRAFFIC ENGINEERING, May, 1960, P.11.