MAGNETIC LOOP DETECTORS IN
TRAFFIC ENGINEERING STUDIES

A Thesis
Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

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1978

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ACKNOWLEDGMENTS

This thesis could not have been completed without the assistance of many people. I would like to thank my advisor, Dr. Joseph Treiterer, for his valuable consultation. I would also like to thank another Professor of Transportation, Dr. Zoltan A. Nemeth, whose comments were very beneficial to me in selecting my graduate courses.

A very special thanks goes to two technicians, Don Murfield and Tony Bernardo, whose cooperation and expert workmanship made construction of the experiment a success.

Thanks are also extended to Mr. Thomas E. Young, City Traffic Engineer for the City of Cincinnati, who granted me a leave of absence so that I may obtain my Master of Science Degree.

I would also like to thank two graduate students, Ben Williams and Nagui Rouphail, for assisting me in the installation of the equipment during the testing phase of the experiment. Many thanks also go to Cheryl Helm, whose long laborious hours of typing made completion of this thesis possible.

Most of all, I want to thank my family, whose encouragement and moral support throughout my academic pursuits gave me the determination to complete my education.
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CHAPTER I
INTRODUCTION

1.1 Background

Magnetic loop detectors have become the most common type of traffic sensor today. Loop detectors are used in traffic control at intersections by controlling signal timing. Loop detectors are also used in gap acceptance on "entrance" ramps, and in traffic engineering studies. These traffic studies deal with parameters such as vehicle lateral placement, speed, spacing, headway, volume, density, and vehicle length.

1.2 Objectives of the Thesis

The objectives of this thesis are:

(a) To study the theory, design, installation, and operation of magnetic loop detectors used in traffic engineering studies.

(b) To construct and test a portable loop-tapeswitch system which can be used to determine traffic flow parameters.
1.3 **Definitions**

**Capacitance** is the ratio of charge to potential on an electrically charged isolated conductor,

**Capacitive reactance** is the opposition to the flow of alternating current in a circuit, due to the presence of capacitance.

**Dead spots** are areas having no magnetic field.

**Density** is the number of vehicles occupying a unit length of a moving lane or moving lanes of a roadway at a given instant of time.

**Dielectric loss** is the loss of capacitance due to the resistance of a non-conducting material separating the coils of a magnetic field.

**Eddy current** is a current induced in a mass of conducting material by a varying magnetic field.

**Headway** is the time between the arrival of the front of one vehicle and the arrival of the front of the next vehicle at a point on the roadway.

**Impedance** is the total opposition to the flow of alternating current in a circuit, due to the presence of resistance, inductance, and/or capacitance.

**Inductance** is the change in the magnetic field surrounding a conductor, due to a variation of current inducing a counter electromotive force into the conductor.
Inductive reactance is the opposition to the flow of alternating current in a circuit, due to the presence of inductance.

Magnetic flux is the magnetic field or lines of force surrounding a current-carrying conductor or a natural magnetic substance.

Operational amplifier circuit is a circuit that increases the magnitude of a varying quantity (current or voltage) without altering any other quantity.

Picofarad is one trillionth ($10^{-12}$) of a farad.

Rectifier is a device that converts alternating current to direct current.

Reference oscillator is an oscillator with a signal of a pre-set frequency which is used as a reference in detecting the alternation of a tuned circuit.

Resistance is a property of a conductor which depends on its dimensions, material, and temperature. The resistance determines the amount of current through the conductor at a given difference of potential.

Resonant frequency is the frequency at which the inductive reactance and the capacitive reactance of a circuit are equal.

Saturation is a state of ferromagnetic substance in which an increase in applied magnetic field strength does
not produce an increase in magnetic intensity.

Spacing is the distance between the front of one vehicle and the front of the next vehicle.

Speed is the distance traveled by a vehicle in a unit of time.

Trigger circuit is a circuit which initiates or activates the detection mechanism.

Tuning is the adjustment of a circuit for maximum response to a given signal or frequency.

Volume (or flow rate) is the number of vehicles passing a given point during a specified period of time, or the number of vehicles that pass over a given section of a lane or a roadway during a specified period of time.
2.1 Inductance Theory

Loop detector operation is dependent on a property inherent in all electrical conductors, namely inductance. In order to understand the operation of the loop detector, it is necessary to understand inductance theory. An electrical current through a conductor, such as a wire, is the unidirectional movement of tiny charged particles known as electrons. Due to the motion of these electrons, a magnetic field is created around the conductor. This magnetic field is dependent on the current flow and varies when the current changes.

Another physical property of all electrical conductors is that when in the presence of a changing magnetic field, a voltage is induced into them. This induced voltage always opposes the original voltage which initially produced the flow of current. The magnitude of the induced voltage is determined by the amount of inductance in the conductor.

The basic formula for the voltage induced into a conductor is:
\[ V_L = L \times \Delta I \]

where

- \( V_L \) is the induced voltage in volts;
- \( L \) is the inductance of the conductor in henries; and
- \( \Delta I \) is the change of current through the conductor in amperes.

The basic unit of inductance is the henry. However, one henry of inductance is an inconveniently large amount of inductance when discussing loop detectors. Therefore, the microhenry, or one millionth of a henry, is the unit which will be mentioned.

The amount of inductance in a conductor depends on many factors. Two of the more important factors are the length of the conductor and the presence of other magnetic materials, such as steel, in the area near the conductor. Thus, a long conductor has a larger magnetic field and greater inductance than a short conductor. The presence of other magnetic materials in the vicinity of the conductor tend to reduce the variations of the magnetic field surrounding the conductor. This reduction in the magnetic field variations is due to the voltage being induced into the nearby magnetic materials by the current through the conductor. Thus, there is a reduction of energy in the original conductor\(^2\).

### 2.2 Loop Detector Circuit Theory

All loop detectors use a coil with one or more turns
of wire to detect the presence of a vehicle. A typical loop has a rectangular shape and a width of approximately six feet. The length of the loop varies, depending on the particular application for which the loop is designed. The loop is laid about two inches below the surface of the road and forms the inductive part of a parallel tuned circuit. When a vehicle enters the magnetic field of a loop, the change in inductance is detected.

The operating frequency of the loop is usually between 10 kilohertz and 150 kilohertz. The upper frequency is limited because it must remain outside the longwave broadcasting band. The lower frequency can be below 10 kilohertz. However, the sensitivity of the loop may become inconveniently small if the frequency is too low. This reduction in sensitivity is due to the eddy current loss in the vehicle body. The eddy current loss is proportional to the square of the frequency in the low frequency range.

The frequency of a detector unit may be fixed, usually by means of a crystal-controlled oscillator. The frequency may also fall between certain specified limits. Within these limits, the tuned loop circuit depends on the manufacturing tolerances, the number of turns of wire, and the size of the loop.
Diagram 1. Tuned Loop Detector Circuit With Losses

The tuned loop detector circuit is shown in Diagram 1. $L$ is the inductance of the loop. $R$ is the sum of the series resistance of the loop and the eddy current power loss caused by the presence of a vehicle within the loop. $RD$ represents the dielectric loss of the material caused by air, water, insulation, and pitch between the loop wires. $RF$ is the combination of the series resistance and the shunt conductance of the feeder cable. $C$ is the capacitance located in the electronic unit, and is used to tune the loop circuit. $CL$ is the capacitance of the loop; and $CF$ is the capacitance of the feeder cable. Both $CL$ and $CF$ affect the tuning of the loop circuit.

The resonant frequency of the tuned loop circuit is given by the following equation:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{LC_T} - \frac{R_T^2}{L^2}}$$

where

$f_0$ is the resonant frequency in cycles per second (hertz);
L is the loop inductance in microhenries;

$C_T$ is the total capacitance of the parallel combination of $C$, $CL$, and $CF$;

$R_T$ is the total resistance of the circuit due to $R$, $RD$, and $RF$ acting as an equivalent resistance in series with $L$.

The presence of a vehicle in the loop alters only the value of $L$ and the eddy current loss component of $R$. All of the other resistive components are inherent in the circuit and only serve to reduce the sensitivity.

The capacitive and the resistive components of the loop and feeder cable affect both the tuning and the sensitivity. Therefore, the values of these components must remain relatively stable during any environmental changes.

When a vehicle enters the loop, the following changes occur:

(a) Eddy currents are induced in the metallic mass of the vehicle. The eddy currents produce a magnetic field which opposes the magnetic field of the loop, reducing the inductance. The eddy currents also increase the series resistance which produces a power loss in the circuit.

(b) The presence of iron in the vehicle body increases the density of the magnetic field. The larger magnetic field density increases the inductance and tries to
offset the demagnetizing effect of 
the eddy currents. However, the eddy 
current effect is larger and predomi-
nates the interaction.

(c) Capacitance, which is due to the 
proximity of the loop wires and the 
vehicle, tends to get larger. How-
ever, the increase in capacitance 
is negligible\textsuperscript{3}.
CHAPTER III
METHODS AND TYPES OF LOOP DETECTION

3.1 Methods of Loop Detection

3.1.1 Phase Shift Detection

The basic phase shift circuit is shown in Figure 1. Phase shift detection requires that part of the circuit that contains the field loop be tuned to exactly the same frequency as that of a reference oscillator. The tuning is accomplished by adding various sizes of capacitors across the loop until the oscillator frequency and loop frequency are equal. Thus the loop and the capacitor form an inductive-capacitive (LC) network.

When there is no vehicle passing over the loop, the voltage across the loop and the oscillator coincide in phase. Thus, the voltages start and end each cycle at the same point. When a vehicle does pass over the loop, the inductance of the loop decreases while the capacitance remains unchanged. The reduction in inductance causes a 5 to 10 percent shift in phase between the loop voltage and the oscillator voltage. Any change in amplitude (voltage level) is not important in this type of circuit.

The phase shift is sensed in the detector circuit and
Figure 1. Phase Shift Detection
is amplified to actuate an output device. If the phase shift detector is used as a presence detector, the phase shift caused by a vehicle entering the loop is used to latch a call. The phase shift in the opposite direction for a vehicle leaving the loop dismisses the call.

The phase shift circuit is reliable as long as the frequency of the power supply is well-regulated. Thus, any outside power variations will not produce a simulated phase shift or a false call. Another requirement for reliability is a high ratio of circuit reactance to line resistance. Therefore, the resistance of the feeder line and the loop is a factor. Large gauge wire has less resistance and has the best sensitivity. If two detectors are to be placed near each other, different reference oscillator frequencies must be used to prevent cross-talking. Cross-talking is an electrical interaction between two adjacent circuits. The problem is solved by furnishing different crystal oscillator sources for the two detectors.

In the Sarasota phase shift detector, the loop has its own separate oscillator. The frequency of the loop oscillator is locked to the frequency of the reference oscillator. Then, the two signals undergo a phase shift with respect to one another when a vehicle passes over the loop. During the presence of the vehicle in the loop, there is a D.C. level change at the output of the phase sensitive detector. This D.C. change is coupled by means of a capacitor into a trigger.
circuit which will release the normally-operated output device. The coupling circuit conducts only the rapid voltage level changes which are produced by the moving vehicles. The coupling circuit rejects the lower voltage level changes that are due to the variations in the environmental conditions. The circuit can also reject the signals from slow-moving vehicles.

The trigger circuit is voltage sensitive and will give an output as long as the input voltage exceeds a certain level. The trigger voltage is stored on a capacitor which gradually discharges the voltage to provide the restoration time. Restoration time is the time taken by a detector to reset in the presence of a stopped vehicle. The trigger circuit is reset by the vehicle leaving the loop and immediately discharging the restoration time capacitor. The trigger circuit can also be reset by the eventual discharge of the capacitor during the restoration time. The restoration time that is required is dependent upon the magnitude of the voltage change at the phase sensitive detector output. The voltage magnitude is determined by the size of the vehicle in the loop and the distance of the vehicle body to the loop.

A vehicle can remain parked within the loop while the trigger circuit is providing the restoration time. During this period, the detector output will remain at a higher level than is normal. The non-moving vehicle will produce a continuing out-of-phase condition, yielding the higher
voltage. Most circuits, however, have sufficient range to produce a distinguishable output if another vehicle enters the loop.

Due to environmental conditions, the output from the phase sensing detector will drift. The output range must be designed so as to accommodate the drift without saturation occurring. The output device is usually a relay, although a solid state output circuit may be used in place of a relay\(^5\).

3.1.2 Voltage Level Change Detection

The voltage level change circuit, as shown in Figure 2, is designed to measure the amplitude change instead of phase shift. When there is no vehicle passing over the detector, the voltage level of the loop and the oscillator are equal. When a vehicle enters the loop, the voltage level of the loop becomes lower than the voltage level of the oscillator\(^6\).

The Philips passage detector for voltage level change drives the tuned loop circuit from an oscillator with a constant current output. An impedance change, caused by a vehicle entering the loop, results in a change in the voltage level. The voltage level change is rectified and fed to the output trigger circuit. The operational amplifier circuit includes the circuits for rejection of environmental changes and for the restoration time. The change in the voltage level is represented by a decrease in the voltage amplitude.
Figure 2. Voltage Level Change Detection
The reduction is usually about 5 percent of the original voltage.

The advantage of the voltage change circuit over the phase shift circuit is its simplification. However, the voltage level change circuit is more difficult to design for reliable operation. In addition, inductive coupling between other wiring and the feeder cable can occur if the proper installation precautions are not taken.

3.1.3 Frequency Change (Heterodyne) Detection

In the frequency change circuit, as shown in Figure 3, the loop oscillator is initially tuned to the same frequency as the reference oscillator. When no vehicle passes over the loop, the frequency of the loop and the reference oscillator are equal. However, when a vehicle enters the loop, the decrease in loop inductance causes the loop oscillator to change its frequency. The loop oscillator frequency is mixed with the reference oscillator frequency in the frequency changer (mixer). Then, the difference between the two frequencies are detected in the discriminator, amplified, and triggered into an output device.

The frequency change circuit is relatively simple. However, the temperature compensation must be excellent. During steady state conditions, both oscillators must track frequencies throughout the temperature range. In addition, the circuit requires minimum wire resistance both in the
Figure 3. Frequency Change (Heterodyne) Detection
loop and the feeder for the best sensitivity$^9$.

3.1.4 Impedance Comparison Detection

The impedance comparison type loop detector circuit is shown in Figure 4. The voltage across the impedance of the loop is compared with the voltage which is developed across an internal reference impedance.

If the voltages across the two impedances are equal, there is no output. When a vehicle passes over the loop, there is a difference between the two impedance voltages. The voltage difference is detected, amplified, and triggered into an output device. In presence detection, the reference impedance is slowly adjusted by the circuit to match the loop impedance after a fixed amount of time.

The impedance comparison eliminates the need for a stable frequency oscillator, a tuned loop, and a voltage reference. The circuit does require a built-in variable impedance which is initially set to match the loop impedance. A feature of the circuit that makes the system the best for battery operation is the very low unregulated power consumption$^{10}$.

3.2 Types of Loop Detectors

3.2.1 Passage Detectors

Passage detectors comprise most of the detectors in use today. The output of the detector increases when a
Figure 4. Impedance Comparison Detection
vehicle enters the loop and decreases when the vehicle leaves the loop. If a vehicle should stop on the loop, its presence is acknowledged only for a limited time. The time limit can be as short as a few seconds and as long as a few hours; however, the limit is usually from 5 to 25 minutes. When the time limit has expired, the output resets. If the loop is large enough to accommodate another vehicle, the detector is able to sense the passage of other vehicles.

3.2.2 Continuous Presence Detectors

A perfect continuous presence detector will indicate the presence of a stopped vehicle for an indefinite period. This type of detector behaves as a passage detector with an infinite restoration time. The difficulty with this detector is that it has no means of resetting itself if a false call should activate it. A false call can be caused by electrical noise in the loop coil or by a vehicle whose entry into the loop is detected, but whose exit from the loop is not detected.

3.2.3 Extended Presence Detectors

A version of the presence detector is the extended presence detector, which is used in applications requiring long period detection. Many manufacturers are now building the extended presence detector to meet the changing demands for vehicle sensing.
3.2.4 Analog Detectors

The analog detector has a loop that is large enough to accommodate several vehicles. The detector gives an analog output that is proportional to the number of vehicles in the loop. Analog detectors can be utilized to indicate the number of cars waiting in a queue\textsuperscript{11}. 
CHAPTER IV
LOOP PARAMETERS

4.1 Loop Sensitivity

4.1.1 Sensitivity Definition

Loop sensitivity is defined as the smallest percentage change of the inductance at the detector terminals which will cause the detector to actuate.

4.1.2 Derivation of Sensitivity Equation

The basic relationships of radian frequency (\(\omega\)), frequency (\(f\)), inductance (\(L\)), and capacitance (\(C\)) of a resonant circuit are:

\[
\omega = 2\pi f, \quad f = \frac{1}{2\pi \sqrt{LC}}, \quad \omega^2 = \frac{1}{LC}
\]

The following conditions will be given:

- \(L_0\) is the inductance with no vehicle present;
- \(L_V\) is the inductance with a vehicle present;
- \(f_0\) is the resonant frequency related to \(L_0\);
- \(f_V\) is the resonant frequency related to \(L_V\).

Therefore, \(\omega_0 = 2\pi f_0\) and \(\omega_V = 2\pi f_V\)
\[ W_0^2 = \frac{1}{L_0 C} \text{ and } W_V^2 = \frac{1}{L_V C} \]

Then,
\[ L_0 = \frac{1}{C W_0^2} \text{ and } L_V = \frac{1}{C W_V^2} \]

Let \( \Delta L = L_0 - L_V \)
\[ \begin{align*}
\Delta L &= \left( \frac{1}{C W_0^2} - \frac{1}{C W_V^2} \right) \\
&= \frac{1}{C} \left( \frac{1}{W_0^2} - \frac{1}{W_V^2} \right) \\
&= \frac{1}{C} \left( \frac{W_V^2 - W_0^2}{W_0^2 W_V^2} \right)
\end{align*} \]

Defining sensitivity (S) as \( \Delta L/L_0 \) gives:
\[ S = \frac{\Delta L}{L_0} = \frac{1}{L_0 C} \left( \frac{W_V^2 - W_0^2}{W_0^2 W_V^2} \right) \]

Since \( 1/L_0 C = W_0^2 \)
\[ S = W_0^2 \frac{W_V^2 - W_0^2}{W_0^2 W_V^2} = \frac{W_V^2 - W_0^2}{W_V^2} \]

Substituting \( 2\pi f_0 \) for \( W_0 \) and \( 2\pi f_V \) for \( W_V \) gives:
\[ S = \frac{(2\pi f_V)^2 - (2\pi f_0)^2}{(2\pi f_V)^2} = \frac{f_V^2 - f_0^2}{f_V^2} \]
Knowing that \( f_0 = f_V - \Delta f \) and substituting gives:

\[
S = \frac{f_V^2 - (f_V - \Delta f)^2}{f_V^2} = \frac{f_V^2 - (f_V^2 - 2\Delta f f_V + \Delta f^2)}{f_V^2} = \frac{(2\Delta f)(f_V) - \Delta f^2}{f_V^2} = \frac{2\Delta f}{f_V} - \frac{\Delta f^2}{f_V^2}
\]

The percentage of inductance is:

\[
\text{Percent } S = \left( \frac{2\Delta f}{f_V} - \frac{\Delta f^2}{f_V^2} \right) \times 100
\]

However, \( \Delta f^2/f_V^2 \) is negligible for small frequency changes. Thus,

\[
\text{Percent } S = \frac{2\Delta f}{f_V} \times 100
\]

This equation for inductive shift sensitivity is accurate within one percent for inductive shifts of four percent or less.

4.1.3 Maximum Loop Sensitivity

The maximum sensitivity of a resonant-tuned, inductive
loop vehicle detector can be found from the procedure described below:

(a) Measure the operating frequency of the free-running oscillator as applied to the loop circuit, using a high resolution digital frequency counter.

(b) Apply the smallest inductance change recognizable by the detector to the loop field. Allow the detector to tune to the new inductance and stabilize at the new frequency.

(c) Measure the frequency of the loop oscillator in the detect condition to find $f_V$. Remove the detect source from the loop field.

(d) Re-check the operating frequency after the oscillator has stabilized in a non-detect condition to find $f_0$.

(e) Refer to the equations $\Delta f = f_V - f_0$ and $S = 2\Delta f/f_V \times 100$ to arrive at the lowest percent of inductive shift the detector will recognize. The result is the maximum sensitivity of the detector to a percentage change in inductance.
Example\textsuperscript{13}: \(f_0 = 50,000 \text{ Hz}, \ f_V = 50,010 \text{ Hz}\)

\[\Delta f = f_V - f_0 = 50,010 - 50,000 = 10 \text{ Hz}\]

\[S = \frac{2\Delta f}{f_V} \times 100\]

\[S = \frac{2(10)}{50,010} \times 100\]

\[S = 0.040\%\]

4.1.4 Another Sensitivity Equation

The sensitivity of the loop detector system can also be defined as the total inductance change. The loop sensitivity can be found from the equation:

\[S = \frac{\Delta L}{L_T} \times 100\]

where

- \(S\) is the loop sensitivity in percent;
- \(\Delta L\) is the change in the loop inductance in microhenries; and
- \(L_T\) is the total loop inductance in microhenries.

4.1.5 Effect of Lead-In Inductance on Loop Detector Performance

A short example will illustrate the effect of the inductance of the lead-in on the performance of the loop system:
Case 1: Suppose that the lead-in inductance of a loop is 80 microhenries, and the loop inductance is 140 microhenries. The total inductance is 220 microhenries. A vehicle enters the loop and causes a 10 percent change in the inductance of the loop. The sensitivity is:

\[
S = \left( \frac{\Delta L}{L_T} \right) \times 100
\]

\[
S = \left( \frac{0.10 \times 140}{220} \right) \times 100
\]

\[
S = 6.36\%
\]

Case 2: Suppose that in another loop, the lead-in inductance is 140 microhenries, and the loop inductance is 80 microhenries (reverse of Case 1). The total inductance is again 220 microhenries. A vehicle entering the loop causes a 10 percent change in the inductance of the loop. The sensitivity is:

\[
S = \left( \frac{\Delta L}{L_T} \right) \times 100
\]

\[
S = \left( \frac{0.10 \times 80}{220} \right) \times 100
\]

\[
S = 3.64\%
\]
The sensitivity of the loop detector unit in Case 2 is almost one-half the sensitivity of Case 1. Therefore, the loop in Case 2 is only one-half as sensitive to vehicles passing over it as the loop in Case 1. This example shows that the higher lead-in inductance only serves to reduce the sensitivity of the system.

4.2 Loop Quality Factor (Q)

4.2.1 Bandwidth

Bandwidth is defined as the difference between the two frequencies on either side of the resonance curve. The voltage across the parallel tuned circuit is reduced to 70.7 percent of the voltage at resonance. Thus,

\[ \text{B.W.} = f_2 - f_1 \]

where

- B.W. is the bandwidth of the resonant circuit in cycles per second;
- \( f_2 \) is the frequency in cycles per second on the left side of the resonance curve at 70.7 percent of the applied voltage; and,
- \( f_1 \) is the frequency in cycles per second on the right side of the resonance curve at 70.7 percent of the applied voltage.

4.2.2 Q in Terms of Bandwidth

The frequency of the applied voltage will deviate from the resonant frequency of the circuit by a value that is \( \frac{1}{2Q} \) of the resonant frequency. At this point, the current
through the circuit is reduced to 70.7 percent of the resonant current and is 45 degrees out of phase with the applied voltage.

If we let \( \Delta f \) equal to the shift in frequency necessary to reduce the voltage of the circuit to 70.7 percent, then the bandwidth is equal to \( 2\Delta f \).

By definition, \( \Delta f = \frac{1}{2Q} \times f_0 \).

Then,
\[
2\Delta f = 2\left(\frac{1}{2Q}\right) \times f_0
\]
\[
2\Delta f = \frac{f_0}{Q}
\]
\[
Q = \frac{f_0}{2\Delta f}
\]
\[
Q = \frac{f_0}{B.W.}
\]

where

\( Q \) is the quality factor and is dimensionless.

4.2.3 \( Q \) in Terms of Loop Energy and Power Loss

The \( Q \), or the quality factor, of a resonant circuit is an indication of the lost or dissipated energy taken from the oscillating circuit. The \( Q \) is also defined as a measure of the frequency selectivity of a resonant network, such as a roadway loop. The \( Q \) of a loop can be expressed by the following equation:
where

\[ Q = 2\pi f_0 \left( \frac{W_S}{P_L} \right) \]

where

- \( W_S \) is the peak value of the energy stored in the field of the loop, measured in watts; and
- \( P_L \) is the average power loss in the loop, measured in watts.

Since the \( Q \) of a circuit is directly proportional to frequency, a test frequency should be specified when the loop \( Q \) is specified.

### 4.2.4 Resonant Frequency

The operating (resonant) frequency of the amplifier can be computed approximately from the following equation:

\[ f_0 = \frac{1}{2\pi \sqrt{LC}} \]

where

- \( C \) is the capacitance of the loop and the detector amplifier drive circuit in microfarads.

The value of capacitance depends on three factors. These factors are:

(a) The type of capacitors used in the manufacturer's design;

(b) The tolerance of the capacitors; and

(c) The amount of distributed capacitance in the loop.
Most of the distributive capacitance of the loop is in the feeder line, and is usually of the order of 25 pico-farads per foot. However, the value of capacitance in most amplifiers is approximately 0.05 microfarads. Different detector amplifiers operate at different frequencies on a given loop inductance. The amplifier frequency depends on the feeder line and amplifier capacitance. The variation in the operating frequency causes a corresponding variation in the Q of the circuit. Thus, when the test frequency is unspecified, the effective specification of the circuit Q is not very probable.

4.2.5 Q of a Series Circuit

The power lost in the inductive loop is the stored energy ($W_L$) that is dissipated in the resistance of the loop wire. Therefore, the Q of the loop can be restated in terms of its resistance, inductance, and test frequency. The equation for Q in a series circuit becomes:

$$Q_S = \frac{W L}{R_S} = \frac{2\pi f_0 L}{R_S}$$

where

$W$ is the radian frequency and equals $2\pi f_0$; and

$R_S$ is the equivalent series resistance in ohms.

4.2.6 Q of a Parallel Circuit

For a parallel circuit with a resistor ($R_p$) shunted
across the loop terminals, the equation for the Q of the circuit becomes:

\[ Q_p = \frac{R_p}{WL} = \frac{R_p}{2\pi f_0 L} \]

where

- \( R_p \) is the shunt or leakage resistance in ohms.

### 4.2.7 Q of a Series-Parallel Circuit

In practice, loop detector systems have both series and parallel resistances in the same circuit. Such a circuit is shown in Diagram 2 below.

![Diagram 2. Series-Parallel Inductive Resistive Circuit](image)

The total Q (or \( Q_t \)) of the circuit is found from the equation\(^{16} \):

\[ Q_t = \frac{Q_S Q_p}{Q_S + Q_p} \]

### 4.2.8 Q in Terms of Measurable Parameters

The Q equations in Section 4.2.7 are used to determine the Q of circuits with a relatively high Q or low losses.
The equations are also used where the frequency, resistance, and inductance can be measured readily with available test equipment. The inductance of loops cannot be easily measured because the inductance is distributed through the loop and the lead-in. The inductance is also masked by the associated lead-in capacitance. The resistance of the loop and the lead-in is larger than the value of the series resistance measured with an ohmmeter. The series resistance becomes a different equivalent resistance ($R^e$). The larger $R^e$ is due to the extra losses associated with a particular circuit configuration and varies with the location.

Basically, the sensitivity and the reliability of the system as a vehicle detector is directly affected by the quality of the loop circuit. Such quality can be measured in terms of response, voltage level across the circuit, and interaction with the detector unit. Therefore, the $Q$ or quality factor is simply a means of attaching a numerical value to the circuit conditions. The $Q$ provides a criterion for either an acceptance or rejection of any loop installation.

4.2.9 Effect of Feeder Line Length on Circuit $Q$

Table 1 shows the effects of adding 250 feet, 500 feet, and 750 feet of feeder line to the loop length. The additional length of the feeder line in every case increased essential parameters. Such parameters are:
<table>
<thead>
<tr>
<th>LOOP SIZE (ft) x (ft) x (turns)</th>
<th>FEEDER WIRE LENGTH (ft)</th>
<th>TOTAL WIRE LENGTH (ft)</th>
<th>INDUCTANCE (L) (µh)</th>
<th>REACTANCE AT 10K Hz (ohms)</th>
<th>RESISTANCE Rg for #12</th>
<th>#14</th>
<th>#12</th>
<th>#14</th>
<th>Q at 10K</th>
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<tr>
<td>4x4-3</td>
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<td>48</td>
<td>48</td>
<td>3.02</td>
<td>.078</td>
<td>.124</td>
<td>38.7</td>
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<td>250</td>
<td>548</td>
<td>103</td>
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<td>.888</td>
<td>1.41</td>
<td>7.31</td>
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<td>.165</td>
<td>48.4</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
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<td>250</td>
<td>564</td>
<td>135</td>
<td>8.48</td>
<td>.914</td>
<td>1.46</td>
<td>9.3</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
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<td>72</td>
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<td>250</td>
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<td>.927</td>
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<td>11.44</td>
<td>1.74</td>
<td>2.77</td>
<td>6.6</td>
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<tr>
<td></td>
<td>750</td>
<td>1572</td>
<td>237</td>
<td>14.89</td>
<td>2.55</td>
<td>4.06</td>
<td>5.8</td>
<td>3.7</td>
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<tr>
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<td>120</td>
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<td>.156</td>
<td>.247</td>
<td>48.3</td>
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<td>10.99</td>
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<tr>
<td></td>
<td>500</td>
<td>1096</td>
<td>230</td>
<td>14.45</td>
<td>1.78</td>
<td>2.83</td>
<td>8.1</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>1596</td>
<td>285</td>
<td>17.91</td>
<td>2.59</td>
<td>4.12</td>
<td>6.9</td>
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<td></td>
</tr>
<tr>
<td>4 ea. 6x6-3 S</td>
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<td>288</td>
<td>18.09</td>
<td>.467</td>
<td>.743</td>
<td>38.7</td>
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<tr>
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<td>788</td>
<td>343</td>
<td>21.55</td>
<td>1.28</td>
<td>2.03</td>
<td>16.8</td>
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</tr>
<tr>
<td>4 ea. 6x6-3 S</td>
<td>500</td>
<td>1288</td>
<td>398</td>
<td>25.00</td>
<td>2.09</td>
<td>3.32</td>
<td>12.0</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>4 ea. 6x6-3 S</td>
<td>750</td>
<td>1788</td>
<td>453</td>
<td>28.46</td>
<td>2.90</td>
<td>4.61</td>
<td>9.8</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>4 ea. 6x6-4 S/P</td>
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<td>384</td>
<td>120</td>
<td>7.54</td>
<td>.622</td>
<td>.991</td>
<td>12.1</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>4 ea. 6x6-4 S/P</td>
<td>250</td>
<td>884</td>
<td>175</td>
<td>10.99</td>
<td>1.43</td>
<td>2.28</td>
<td>7.7</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>4 ea. 6x6-4 S/P</td>
<td>500</td>
<td>1384</td>
<td>230</td>
<td>14.45</td>
<td>2.24</td>
<td>3.57</td>
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<td>4.0</td>
<td></td>
</tr>
<tr>
<td>4 ea. 6x6-4 S/P</td>
<td>700</td>
<td>1884</td>
<td>285</td>
<td>17.91</td>
<td>3.05</td>
<td>4.86</td>
<td>5.9</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
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<td>.363</td>
<td>.578</td>
<td>29.1</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>6x50-2</td>
<td>500</td>
<td>1224</td>
<td>278</td>
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<td>106</td>
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<td>.343</td>
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<td>1.96</td>
<td>3.13</td>
<td>6.9</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>

NOTE:
S is SERIES  S/P is SERIES PARALLEL
(a) Total wire length;
(b) Inductance;
(c) Inductive reactance at 10 kilohertz frequency; and
(d) Series resistance for both Number 12 and Number 14 wire.

The most significant column in Table 1 consists of values of Q at a 10 kilohertz frequency for both Number 12 and Number 14 wire. The Q decreased significantly for increased lengths of feeder line. The logic behind the large reduction in Q is understandable. The feeder line consists of two wires, entry wire and exit wire. An increase in the feeder line by 250 feet is equivalent to adding an additional 500 feet of wire, or twice the length of the additional feeder line. This additional wire length is added to the length of all turns of wire in the loop to get a new total wire length. Since wire resistance is directly proportional to wire length, the series resistance will greatly increase when the wire length becomes much longer. The Q of a circuit is inversely proportional to its series resistance; therefore, the Q will be vastly reduced. If Number 12 wire, which has a larger diameter and less resistance than Number 14 wire, is used, a higher circuit Q and greater sensitivity is achieved.

4.2.10 Loop Shunt or Leakage Resistance

The loop shunt or leakage resistance ($R_p$) should have
a resistance which exceeds one megaohm on a good loop. As the loop is aging, its leakage resistance should not appreciably change until a point in time near the end of the loop's useful life. At that point, the leakage resistance will begin to decrease rapidly with time. There is no precise leakage resistance value which is specified as a set point in time for loop replacement. However, some manufacturers recommend that when the leakage resistance decreases to 10,000 ohms, the loop should be replaced. At this resistance, variations in the contamination and moisture levels around the loop wires result in defective operation.

4.2.11 Summarization of Circuit Q Parameters

Summarizing, there are three basic variables which determine the value of Q. These variables are:

(a) \( R_s \) - the series resistance of the roadway loop and the feeder line;

(b) \( L \) - the inductance of the loop and the feeder line; and

(c) \( f \) - the frequency at which the loop is operated or tested.

Both \( R_s \) and \( L \) are determined by the type and size of wire used in the loop and feeder line. The amplifier principally determines the frequency \( (f) \). Due to the large numbers of manufacturers dealing with loop detector equipment, there are many different amplifier operating frequencies used throughout the industry. Thus, there exists the need to
standardize one operating frequency. Then, all of the different amplifier designs can be tested to a standard and well-defined Q.

4.2.12 Recommendation for Amplifier Design

A good recommendation is to standardize a test frequency of 10 kilohertz and a Q of 5 for all loop detector amplifiers in all future specifications. The Q values found in Table 1 present a good basis for this recommendation.
5.1 **Loop Size**

The roadway loop may be any width or length. However, the total inductance of the loop and the lead-in must be within the loop detector's range. For the best overall performance and to prevent dead spots within the loop, the loop width should be between 4 feet and 8 feet. The loop length may be any size between 4 feet and 100 feet.\(^{19}\)

The shorter loop dimension determines the height of the magnetic field. Therefore, this dimension must be at least 4 feet to detect the high-bed vehicles, such as trucks.

Although the longer loops are used for larger areas of detection, the sensitivity is reduced compared to one 6 foot by 6 foot loop. More turns of wire can be added to the shorter loop to make the total inductance of each loop similar. However, the actual sensitivity of each loop is dependent on the surface area under the vehicle in relation to the loop area. For example, a conventional sedan will yield greater sensitivity in one 6 foot by 15 foot loop than in two 6 foot loops with typical spacing. Nevertheless, the 6 foot by 15 foot loop will have a smaller effective detection area for vehicles
only partially over the loop area $^{20}$.

5.2 Loop Configurations

There has been considerable creativity shown in the layout of detector loops. From the traditional 6 foot by 6 foot square loop with angled corners, other configurations were developed. Such configurations are the octagon, diamond, skewed shape, figure "8", and various other loop shapes. The various configurations were designed to enhance loop sensitivity to a wide range of vehicles, particularly motorcycles.

The octagonal-shaped loop, as shown in Figure 5, has been adopted by the City of Los Angeles for several reasons. The slot length to be sawed is reduced from 24 feet for a 6 foot by 6 foot square loop to 20 feet for an octagon loop which is 6 feet across the flats. The required wire length is reduced from 72 feet to 60 feet for a 3 turn loop. The smaller sized octagon loop has less inductance. Therefore, the magnetic field distribution is more uniform across the loop area as compared with the square loop where the magnetic field is reduced at the corners.

The diamond loop, as shown in Figure 6, is basically two loops connected in series. The diamond loop has greater sensitivity at its corners than does the conventional square loop configuration.

If the orientation of the square or rectangular loop is shifted diagonally, vehicle detection is improved. When
Figure 5. Octagon-Shaped Loop
Notes: 1. These diamond loops are experimental loops being tried by the City of Waterloo, Iowa, for the purpose of detecting smaller vehicles such as motorcycles.

2. Each loop has an approximate inductance of 90 µH with three turns on loop.

3. The two loops are connected in series at the handhole.

4. The corners of the loop tend to be more sensitive than square corner.

Figure 6. Example of a Diamond Loop
the loop corners are positioned along the lane centerline, a 30 to 45 degree alignment produces a sharply defined inductance change. In computer-controlled systems, a sharp presence definition determines the accuracy of the speed computations. When these diagonally oriented loops are placed in adjacent lanes, a Chevron pattern configuration is produced, as shown in Figure 7.

Loop occupancy control concepts have been implemented by using long loops operating in the presence mode. The simple rectangular loop generally proved inadequate in producing a sufficient inductance shift to detect small motorcycles. One satisfactory solution to this problem is the addition of a small loop "powerhead" at one end of the long loop, as shown in Figure 8.

Another loop configuration uses a second powerhead at the upstream end of a long loop to improve performance. Other configurations, as shown in Figure 9, use the skewed concept with a powerhead 21.

The X-loop, or figure "8" loop, is shown in Figure 10. This loop configuration is especially designed to increase the sensitivity of the loop to smaller vehicles, motorcycles, motorbikes, and bicycles. The figure "8" loop is most effective when the vehicle is centered in the lane. The sawcut in the area near the crossing point should be twice as deep as the sawcut in the other parts of the loop 22.

Multiple interconnected small loops can be used instead
Figure 7. Diagonally Oriented Loops in Adjacent Lane

Figure 8. Long Loop with Powerhead
9a. Angled Powerhead

9b. Skewed Loop, City of Arlington, Tx.

Figure 9. Skewed Long Loops with Powerhead
Figure 10. The Figure "8" Loop Configuration
of long loops to obtain vehicle presence detection over a length of the roadway. Figure 11 demonstrates a typical multiple loop layout. This configuration has produced detection with greater reliability, more flexibility in sensitivity control, and improved detection of small vehicles.\(^{23}\)

5.3 **Wire Selection**

The wire insulation used in inductive loop construction must be able to withstand severe environmental conditions. The insulation must provide for the quality of inductance required for resonant circuits. The wire insulation must maintain a very high resistance after being subjected to abrasion and wear. Some of the roadway environmental stresses are:

(a) Shifting of the road surface;

(b) Moisture, petroleum solvents, and oils seeping through the road surface; and

(c) Sharp rocks and pebbles.

Insulation made of latex rubber with a thin jacket of neoprene has frequently been used for loop wires in the past. Many times, the erosion of the roadway surface and the loss of slot filling material allows the rubber-covered loop wires to be exposed. Then, the neoprene jacket which has been worn thin from use can be penetrated by solvents through various pinholes in the insulation. The rubber eventually deteriorates, exposing the loop turns and shorting the wires.
Note:
Splices permitted in handhole and cabinet only

Handhole

3" minimum slot depth

2' F.C.

Handhole

WIRING DIAGRAM

Handhole Connections

1. 1 to L-1
2. 1A to 4
3. 2 to L-1
4. 2A to 3
5. 3A to L-2
6. 4A to L-2
7. L-1 to 1 & 2
8. L-2 to 3A & 4A

Figure 11. Typical Layout of Multiple Loops for Presence Detection
If the wires are subjected to moisture, a low resistance path to the conduit ground will form. This path will effectively place a parallel or shunt resistance across the loop circuit. The shunt resistance will lower the $Q$ of the parallel resonant circuit formed by the loop, lead-in, and the capacitance at the detector input terminals. The operating voltage across the loop circuit is diminished. As a result, the amount of voltage level change at the detector terminals is insufficient to actuate the detector. If the detector is actuated, it may not stay actuated for the minimum presence time. Drainage water, trapped moisture, or salt accumulations in the asphalt or concrete are the elements providing conductive paths to the conduit ground system.

There are four different types of insulation material that have been used on loop wires in concrete and asphaltic street surfaces. These materials are:

(a) Polyvinyl chloride thermoplastic (TW), usable in wet locations;
(b) Rubber, heat resistant (RH), moisture and heat resistant (RHW);
(c) Latex rubber with neoprene jacket; and
(d) polyethylene, high density or cross-linked (XHHW or XLPE).

The cross-linked or high density polyethylene material has the desirable characteristic of being resistant to liquid absorption, abrasion, and petroleum solvents. The extruded polyethylene insulation is dense, but is still
pliable enough to resist abrasion. This insulation also has the tendency to flow together when heated, thereby closing insulation pinholes. Cross-linked polyethylene insulation is obtainable on stranded Number 12 AWG wire. This insulation is rated for operation at 600 volts in wet locations and for underground feeder uses.\(^{24}\)

There are also very large differences in the losses due to the type of insulation used. Since the loop is driven with an alternating current of very high frequency, the capacitance in the system becomes very important. The type of insulation determines the capacity between the wires and between the wires and ground.\(^{25}\) Since the detector is frequency variable, the shunt capacitance effect must be considered. For a twisted parallel pair of wire with polyvinyl chloride (PVC) insulation, the capacitance is approximately 25 picofarads (PF) per foot. For polyethylene insulation, the capacitance is also 25 picofarads per foot. With 750 feet of parallel lead-in at 25 PF per foot, the total shunt capacitance is 18,750 PF. This capacitance is approximately 25 percent of the internal detector capacitance. Thus, the total inductance to which the detector can be tuned is reduced by 25 percent.

Although the total shunt capacitance of PVC and polyethylene is approximately the same, the temperature characteristics are very different. For each 10 degree Fahrenheit change, the shunt capacitance of PVC will change about 5
percent. The shunt capacitance change for polyethylene is less than 0.1 percent. For 750 feet of lead-in, the capacitance change for each 10 degree Fahrenheit temperature change will be 1 percent for PVC and less than 0.05 percent for polyethylene. Since the detector uses a tuned resonant circuit, this capacitance shift must be sensed by the detector. PVC insulation has been found to have losses that are 250 times greater than the losses encountered by using polyethylene insulation.

Wire size and spacing between the conductors account for the remaining losses. The most recommended sizes of wire to be used are either Number 12 or Number 14 AWG stranded wire with polyethylene insulation.

5.4 **Feeder Lines**

Feeder (lead-in) lines should not cross a loop nor be bundled together for more than 50 feet. This rule will reduce cross-talk between the feeder lines and the loop wires. The feeder lines should be a twisted pair with at least one turn per foot. Some feeder lines are hung on poles over the roadway so that the lines are exposed to the wind. These feeder lines must be twisted tightly with several turns per foot. If desired, the feeder lines may be shielded. For feeder lines of 100 feet or less, the type of wire used is not very important. When the feeder lines are longer than 100 feet or are exposed to the sun for more than 50 feet,
the type of insulation becomes very important. If the lines are 250 feet or less, the recommended wire is Belden 8720 or the equivalent. For lines of 250 to 750 feet, the recommended wire is Belden 8718 or the equivalent.

The feeder lines are brought off the roadway in a trench, saw slot, or conduit. The same trench may contain several feeder lines, but the trench should be at least one foot from the nearest edge of any loop\textsuperscript{29}.

The lead-in lines also have inductance. The amount of lead-in inductance for a particular loop system varies with the size and the length of the wire. The lead-in inductance is usually expressed in 100-foot increments. For the recommended Number 14 size wire, the lead-in inductance is 15 microhenries per 100 feet. The total lead-in inductance for Number 14 wire can be computed from the equation\textsuperscript{30}:

\[
L_{\text{lead-in}} = \frac{15 \times \text{Lead-in length}}{100}
\]

For the other recommended wire size, Number 12, the lead-in inductance is 22 microhenries per 100 feet. The total lead-in inductance for Number 12 wire can be computed from the equation\textsuperscript{31}:

\[
L_{\text{lead-in}} = \frac{22 \times \text{Lead-in length}}{100}
\]
The lead-in inductance can also be found in a table where the values have already been computed by the manufacturer. A good rule of thumb is that the lead-in inductance should never be more than twice the inductance of the loop\textsuperscript{32}.

5.5 **Single Loop Inductance**

Total loop inductance is the inductance as seen by the detector including the loop and the lead-in lines. The detector can be tuned to any inductance between 70 and 500 microhenries. However, for best performance, the total inductance should be between 100 and 300 microhenries\textsuperscript{33}.

Measurement of the inductance of the loop and the lead-in lines is generally very difficult. Since the inductance range of the detector is very broad, an approximate calculation is usually sufficient. An estimate for the value of inductance for a single loop can be expressed by the equation:

\[
L = \frac{5PN^2}{10 + N}
\]

where

- \(N\) is the number of turns of loop wire; and
- \(P\) is the perimeter of the loop in feet\textsuperscript{34}.

The loop inductance can also be found in a table where the values have already been computed from one of the common inductance equations.
The total single loop inductance can now be computed from the equation

\[ L_{\text{total}} = L_{\text{loop}} + L_{\text{lead-in}} \]

5.6 \textbf{Multiple Loop Inductance}

Loops may be connected in series, parallel, or a series-parallel combination, as shown in Figure 12. The total inductance for all multiple loop connections should, like the single loop, be between 100 and 300 microhenries for the best performance. Nonetheless, a total inductance between 70 and 500 microhenries is acceptable.

The total inductance of loops connected in series is found by adding all the individual inductances of all the loops. The total series inductance is found from the equation:

\[ L_T = L_1 + L_2 + \ldots + (\text{etc.}) \]

The previous equation indicates that connecting loops in series increases the total inductance.

The total inductance of two loops connected in parallel is found from the equations:

\[ L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}} \]

or
Figure 12. Loop Circuit Connections
The two preceding equations show that adding two loops in parallel decreases the total inductance.

The total inductance of three loops connected in a series-parallel combination is found from the equation:

\[ L_T = \frac{L_1 L_2}{L_1 + L_2} \]

In this equation, \( L_1 \) is in series with the parallel combination of \( L_2 \) and \( L_3 \).

Generally, two or more loops are to be connected together and returned to the detector by a single feeder line. In this situation, the feeder line should be connected midway between the loops. The mid-connection is made to keep the lead-in inductance the same for all loops; otherwise, an unbalanced condition exists at the input to the detector units\(^{36}\). Even if the total inductance is 500 microhenries or less, the lead-in length should never exceed 750 feet.

When each loop in a multiple loop configuration is connected to its own detector, a center to center spacing of \( \frac{1}{4} \) times the loop width yields good results\(^{37}\).
5.7 **Loop Installation**

Due to the effect of capacitance between wires, all turns of wire should be kept as close together as possible to keep the losses at a minimum. All wires should be placed as far as possible from metal objects to avoid drastic reductions in sensitivity. The metal objects can be conduit, sewer lids, trolley or railroad tracks, and steel road reinforcements. The conductors should not cross junctions of road where two different types of surfaces meet. The loop conductors can be damaged by the different contraction and expansion movements of the two road surfaces.

Splices are also a problem source, as making a waterproof splice is very difficult. Therefore, splices should be avoided in all cases. The loop and the lead-in should be one continuous wire\(^38\). When splicing becomes necessary, it should be done in a suitable enclosure, such as a metal or concrete pull-box. The splices should be physically and electrically secure. These splices should also be insulated carefully so that there is at least a megaohm resistance from the copper conductors to ground\(^39\).

When installing a loop in a gravel roadway, the loop must be covered with a protective jacket to prevent rocks from cutting through the insulation. The protective jacket may be a plastic water pipe, a garden hose, or some other non-metallic tubing. Since the tubing must be split after the loop has been wound, a more difficult but preferred
method has been developed. This method consists of cutting the tubing into equal segments and running the loop wires through the tube segments while winding the loop. The corners of the tube segments must be taped to complete the loop. A trench of the required size must be dug. Then, the loop and lead-in should be buried no deeper than is necessary for maintenance of the roadway. The depth of wire burial is important because both the loop sensitivity and the presence time are directly proportional to the square of the distance of the vehicle from the loop.

The installation of a loop into an asphalt or concrete roadway requires a different procedure. With a concrete saw, a ½ by 1 inch deep slot is cut into the roadway to the desired loop size. A slot is also cut from one corner of the loop, off the roadway, and back to the detector. After the slot has been cut, all sharp edges that could damage the loop wire must be removed. Then, the loop is wound in the slot as was described previously. The slot is filled with a compound that will hold the wires in position and waterproof the loop. There are some commercially available compounds that have been developed for loop sealing. Some of the products are used directly from the container, while other products must be mixed with a catalyst before using them.\(^{40}\)
CHAPTER VI

ANALYTICAL PROCEDURE FOR
SINGLE LANE TRAFFIC FLOW

6.1 Terminology for Equations in Traffic Studies

R is the distance (in feet) from the leading edge of loop 1 to the origin of the tapeswitch.

d is the distance (in feet) from the leading edge of loop 1 to the point on the tapeswitch which is traversed by the right wheels of a vehicle.

L is the distance (in feet) from the leading edge of loop 1 to the leading edge of loop 2.

θ is the angle (in degrees) of the tapeswitch with the curb.

t_1 is the time (in seconds) when a vehicle crosses the leading edge of loop 1, as recorded on channel 1 of the event recorder.

t_2 is the time (in seconds) when the right front wheel of a vehicle crosses the tapeswitch, as recorded on channel 2 of the event recorder.

t_3 is the time (in seconds) when a vehicle crosses
the leading edge of loop 2, as recorded on channel 3 of the event recorder.

\[ t_d \] is the time (in seconds) a vehicle takes to travel the distance (d).

\[ t_L \] is the time (in seconds) a vehicle takes to travel the distance (L).

\[ P_n \] is the lateral placement (in feet) of the \( n^{th} \) vehicle from the curb.

\[ P \] is the average or mean lateral placement (in feet) of all observed vehicles from the curb.

\[ \lambda \] is the length (in feet) of each loop.

\[ T \] is the time duration or pulse length (in seconds) for each pulse, as measured on channels 1 and 3 of the event recorder.

\[ N \] is the total number of cars observed.

\[ a_n \] is the length (in feet) of the \( n^{th} \) vehicle.

\[ a \] is the average or mean length (in feet) of all vehicles observed.

\[ v_n \] is the speed (in feet per second) of the \( n^{th} \) vehicle.
v is the average or mean speed (in feet per second) of all vehicles observed.

\( v_n' \) is the speed (in miles per hour) of the \( n^{th} \) vehicle.

\( v' \) is the average or mean speed (in miles per hour) of all vehicles observed\(^{42}\).

\( S_n \) is the spacing (in feet) between two successive vehicles.

\( S \) is the average or mean spacing (in feet) between the vehicles observed.

\( H_n \) is the headway (in seconds) between two successive vehicles.

\( H \) is the average or mean headway (in seconds) between the vehicles observed.

\( V \) is the volume (in vehicles per hour) for the lane observed.

\( D \) is the density (in vehicles per mile) for the lane observed\(^ {43}\).

6.2 Determining Lateral Placement of Vehicles from the Curb with a Tapeswitch

Refer to Figures 13 and 14. The time at which a vehicle in the single lane crosses the leading edge of
Figure 13. Vehicle Lateral Placement
NOTE: The pulses displayed above are ideal; actual pulses may be distorted

Figure 14. Time Pulses on Event Recorder
Loop 1 (0) is represented by $t_1$. The time $t_1$ is measured on Channel 1 of the event recorder. The time at which the right front wheel of the same vehicle crosses point (d) on the tapeswitch is represented by $t_2$. The time $t_2$ is measured on Channel 2 of the event recorder. Every second pulse on Channel 2 represents the right rear wheel of the vehicle crossing the same point (d) on the tapeswitch. Therefore, these pulses have no additional effect on the lateral placement of the vehicle. The time at which the same vehicle crosses the leading edge of Loop 2 (L) is represented by $t_3$. The time $t_3$ is measured on Channel 3 of the event recorder.

The time that a vehicle takes to travel from point (0) to point (d) is denoted by $t_d$ and is found from the equation:

$$t_d = t_2 - t_1$$

The time that a vehicle takes to travel from point (0) to point (L) is denoted by $t_L$ and is found from the equation:

$$t_L = t_3 - t_1$$

A proportional equality can now be established among the following parameters: $d$, $t_d$, L, and $t_L$. This relationship can be expressed as:
Solving the equation for \( d \), we have:

\[
\frac{t_d}{t_L} = \frac{d}{L}
\]

From Figure 13, \( x \) is the horizontal distance from the origin of the tapeswitch (R) to the point where the right front wheel of a vehicle crosses the tapeswitch (d). The value of \( x \) can be found from the equation:

\[
x = d - R
\]

Substituting in this equation the expression for \( d \), we have:

\[
x = \frac{L \cdot t_d}{t_L} - R
\]

Remembering from trigonometry that the tangent of the angle \( \theta \) in a right triangle is equal to the vertical leg divided by the horizontal leg, we have:

\[
\tan \theta = \frac{P}{x}
\]
Solving this equation for $P$ yields:

$$P = x \tan \theta$$

Substituting the expression for $x$, the equation for the lateral placement of single lane vehicles from the curb becomes $^{44}$:

$$P = \left( \frac{L}{t_L} t_d - R \right) \tan \theta$$

6.3 **Equations in Traffic Engineering Studies**

Vehicle Travel Time between Loop 1 and Tapeswitch (in sec.):

$$t_d = t_2 - t_1$$

Vehicle Travel Time between Loop 1 and Loop 2 (in sec.):

$$t_L = t_3 - t_1$$

Lateral Placement of Vehicles from Curb (in ft.) $^{45}$:

$$P = \left( \frac{L}{t_L} t_d - R \right) \tan \theta$$

Speed (in fps):

$$v_n = \frac{L}{t_L}$$

Speed (in mph):

$$v_n' = 0.682 \ v_n$$

Average Speed between Two Successive Vehicles (in fps):

$$\bar{v}_n = \frac{v_n + v_{n+1}}{2}$$
Vehicle Length (in ft.): \[ a_n = L \frac{T}{t_L} - l \]

Headway (in sec.): \[ H_n = t_{n+1} - t_n \]

Average Headway (in sec.): \[ H = \frac{\sum H_n}{N-1} \]

Spacing (in ft.): \[ S_n = \bar{v}_n H_n \]

Average Spacing (in ft.): \[ S = \frac{\sum S_n}{N-1} \]

Volume (in veh./hr.): \[ V = \frac{3600}{H} \]

Density (in veh./mi.): \[ D = \frac{5280}{S} \]
CHAPTER VII

THE PORTABLE LOOP-TAPESWITCH EXPERIMENT

7.1 Objective of the Experiment

A traffic engineer must sometimes install temporary portable loops in the roadway to determine certain traffic flow parameters in a minimum amount of time. One method of constructing a portable loop is to fabricate a multiturn loop in flexible plastic tubing, and secure the loop to the roadway by a strong inconspicuous tape.

The objective of this experiment is to build and test a system combining two multiturn portable loops and a tape-switch. This system, together with an event recorder and the associated electronic circuitry, can be used to determine traffic flow parameters quickly and reasonably accurate.

7.2 Recommended Materials

(A) One 100-foot roll of 4-inch, heavy duty, gray-colored pressure sensitive tape*.

(B) Two 100-foot rolls of #14 AWG, stranded, polyvinyl

* Use black-colored vinyl pressure sensitive tape on asphalt surfaces
chloride, thermoplastic, or polyethylene insulated wire.

(C) Three 25-foot lengths of #14 AWG, 2 conductor, shielded cable.

(D) Two 3/8-inch I.D., 20-foot lengths of flexible plastic tubing.

(E) Two one-channel loop detectors (or one two-channel loop detector).

(F) Two plug-in connectors for the loop detector(s).

(G) One 4 foot by 4 foot section of wood (or four 2 inch by 4 inch wooden boards nailed together to form a 4 foot by 4 foot frame).

(H) Four 2-inch nails.

(I) One roll of $\frac{1}{2}$ inch plastic electrical tape.

(J) One terminal strip (ten or more terminals).

(K) One 5-foot roadway switch (Tapeswitch).

(L) Two end protection plates for roadway switch.

(M) One can of adhesive for roadway switch.

(N) One 12 VDC/115 VAC power converter.

(O) One 12 volt storage battery.
(P) One 6 volt battery.

(Q) One event recorder with three or more channels and multiple speeds.

(R) One roll of chart paper for event recorder.

(S) One bottle of recorder ink.

(T) One inkwell filler.

(U) Two stopwatches.

(V) Two 28 VDC, 0.5 ampere relays.

(W) One standard 115 volt plug.

(X) One 5-foot length of standard 115 volt cable.

(Y) One 50-foot tapemeasure.

(Z) One piece of chalk.

7.3 Procedure

7.3.1 Portable Loop Construction

Referring to Figure 15 for loop shape and dimensions, construct loop 1 and loop 2 according to the procedure described below.

(A) Construct a 4 foot by 4 foot wooden frame from plywood.
Figure 15. The Portable Loop-Tapeswitch Test
(B) Put a 2-inch nail in each corner of the wooden frame.

(C) Allowing a one-foot extension, tape the #14 wire to a point near the lower right nail.

(D) Wind the wire clockwise around the nails on the frame four times, as tight as possible.

(E) Extend the exit loop wire off the frame adjacent to the entry wire.

(F) Cut the exit wire even with the entry wire.

(G) Split the 20-foot length of flexible plastic tubing on one side.

(H) Put the four turns of wire inside the tubing, removing each section of the loop from each nail as needed.

(I) Tape the tubing tightly every 2 to 4 inches with a plastic electrical tape, including the junction of the extending wire with the loop ends.

(J) Twist the two extending wires together so that the wire pair has at least two to five turns per foot.

(K) Tape the twisted wire pair about two inches from its end with the plastic electrical tape.

(L) Solder the twisted wire pair with 25 feet of the
shielded lead-in wire.

(M) Tape very tightly the connection in step L.

(N) Enclose the lead-in wire extending from each loop to the curb in plastic tubing. The remaining lead-in wire does not require enclosure in plastic tubing.

(O) Tape the section of the lead-in wire enclosed in tubing every 2 to 4 inches.

7.3.2 A-C Power Supply Assembly

Referring to Figures 15 and 16, assemble the 115 volt A-C power supply according to the procedure described below.

(A) Connect the positive terminal of the 12 volt storage battery to the positive terminal on the 12 VDC/115 VAC power converter.

(B) Connect the negative terminal of the storage battery to the negative terminal on the power converter.

(C) Connect a standard 115 volt plug to 5 feet of standard two-conductor 115 volt cable.

(D) Connect the plug end of the 115 volt cable to the output receptacle on the power converter.

(E) Connect the "hot" wire from the exposed end of the 115 volt cable to the 115 volt terminal on the terminal strip.
Figure 16. Recorder Interfacing Circuit
(F) Connect the ground wire from the exposed end of the 115 volt cable to the ground terminal on the terminal strip.

(G) Keep the switch on the A-C power supply in the "Off" position until power is required.

7.3.3 Loop Detector Connections

Referring to Figures 15 and 16, install the loop detector system according to the procedure described below.

(A) Connect each detector's loop, power, and ground leads from their terminals on the terminal strip to their plug-in connector.

(B) Connect each plug-in connector to its loop detector.

(C) Connect the two leads from the loop 1 feeder line to the loop 1 terminals on the terminal strip.

(D) Connect the two leads from the loop 2 feeder line to the loop 2 terminals on the terminal strip.

(E) Connect the shielded lead from each loop feeder line to the ground terminal on the terminal strip.

7.3.4 Recorder Interfacing Connections

Referring to Figures 15 and 16, connect the recorder
interfacing circuit according to the procedure described below.

(A) Connect the positive side of the coil in loop detector 1 (LD1) to the positive side of the coil of one of the 28 VDC relays (R1).

(B) Connect the positive side of the coil in loop detector 2 (LD2) to the positive side of the coil of the other 28 VDC relay (R2).

(C) Connect the positive terminal of the 6 volt battery to one side of a normally closed contact on each relay, R1 and R2.

(D) Connect the other side of the normally closed contact on relay R1 to channel 1 (PEN 1) on the event recorder.

(E) Connect the other side of the normally closed contact on relay R2 to channel 3 (PEN 3) on the event recorder.

(F) Connect the negative side of the loop detector coil (LD1) to the negative side of the coil on relay R1.

(G) Connect the negative side of the loop detector coil (LD2) to the negative side of the coil on relay R2.

(H) Splice a 25-foot length of the two-conductor cable to the two leads of the tapeswitch.

(I) Connect the positive terminal of the 6 volt battery to one of the leads of the tapeswitch.
(J) Connect the other lead of the tapeswitch to channel 2 (PEN 2) on the event recorder.

(K) Connect the common terminal on the event recorder to the negative sides of relays R1 and R2.

(L) Connect the negative side of relays R1 and R2 to the negative terminal on the 6 volt battery immediately preceding the beginning of the experiment in order to conserve the battery.

7.3.5 Event Recorder Preparation

Before the experiment is conducted, the event recorder must be prepared for proper operation according to the procedure described below.

(A) Install the recorder gears which provide a chart speed of 720 inches per hour. A higher chart speed may be used; however, 720 inches per hour is the minimum chart speed for two loops positioned 15 feet or less apart.

(B) Do not prime the recorder pens which will not be used in the experiment.

(C) Clean the three pens to be used, using the pen point cleaner.

(D) Fill the recorder inkwell with the ink designed for the recorder pens, using the inkwell filler.
(E) Install the recorder chart paper designed for the recorder, tightening the chart to remove paper slack and assuring constant chart speed.

(F) Place each of the recorder pens on the zero reference line of its channel.

(G) Connect the 115 volt terminal on the event recorder to the 115 volt terminal on the terminal strip.

(H) Connect the ground terminal on the event recorder to the ground terminal on the terminal strip.

7.3.6 Installation of the Portable Loops and Tapeswitch System

Referring to Figure 15, install the loops and tapeswitch according to the procedure described below.

(A) Establish an experiment station off the roadway, disguising the electronic equipment.

(B) Position the two portable loops on the roadway in the shape and at the dimensions shown in Figure 15, using the tape measure and chalk.

(C) Attach each loop firmly to the roadway with the heavy-duty four-inch pressure sensitive tape.

(D) With the tape measure and chalk, scale the horizontal and vertical sides of the triangle formed by the
tapeswitch, as shown in Figure 15.

(E) With the piece of chalk, draw a heavy line where the tapeswitch is to be positioned.

(F) Put a layer of the roadway switch adhesive on the chalk line.

(G) Lay the tapeswitch on the adhesive, making sure that the tapeswitch is placed exactly as shown in Figure 15.

(H) Secure the tapeswitch firmly to the roadway with the heavy-duty four-inch pressure sensitive tape.

(I) Bring all wires back to the experiment station.

7.3.7 Tuning the Loop Detectors

Before the experiment is conducted, the loop detectors must also be prepared for proper operation according to the procedure described below.

(A) Turn the A-C power supply switch to the "On" position.

(B) Tune each of the loop detectors to its loop by adjusting the coarse and fine tuning control on each detector until its output meter reads center scale. See the manufacturer's manual.

(C) Test the operation of each loop detector by noting
whether its indicator light flashes "on" only when a vehicle is passing over its loop.

(D) If a loop detector does not function as described in step C, increase the gain control until such operation is evident.

(E) Put the mode switch on each loop in the "S" (short presence) position.

7.3.8 Equipment Operation

Immediately preceding and during the course of the experiment, the procedure described below should be followed.

(A) Turn the event recorder switch to the "On" position to test whether the pens are writing adequately on the moving chart. A twenty to thirty second test is sufficient.

(B) Turn the event recorder switch to the "Off" position to conserve chart paper, since the chart is moving at a fast rate.

(C) Each time the first vehicle of a platoon approaches loop 1, turn the event recorder switch to the "On" position.

(D) Each time the last vehicle of a platoon leaves loop 2, turn the event recorder switch to the "Off" position.

(E) Run the experiment for 30 minutes. If the experiment is run for a longer period than 30 minutes, a large
volume of chart paper will be compiled.

(F) Turn the switch on the A-C power supply to the "Off" position.

(G) Remove the two leads from the 6 volt battery.

(H) Remove all equipment from the roadway and the experiment station.

(I) Remove the chart paper from the event recorder.

7.3.9 Spot Speed Measurements*

At the same time that the portable loop-tapeswitch system is being tested, the data should be validated by means of a spot speed technique. The spot speed technique is described below.

(A) Measure the distance between a marker on one side of the portable loop-tapeswitch system and a marker on the other side of the system. In the stopwatch method, a distance of about 90 feet is desirable because of the long human response time in using stopwatches.

(B) Put an observer with a stopwatch at each marker.

(C) When a vehicle is at the first marker, the first

*Only the speed measurements are to be validated, because these values alone give a good indication of the accuracy of the portable loop-tapeswitch system.
observer records the entrance time.

(D) When the same vehicle is at the second marker, the second observer records the exit time.

(E) Subtract the entrance times from the exit times, and record the time differences in Table 3.

7.3.10 Analytical Procedure

After the experiment is completed, the data on the chart paper should be analyzed according to the procedure described below.

(A) Referring to Figure 14, note the times $t_1$, $t_2$ and $t_3$ on the chart paper, and record these times.

(B) Compute the times $t_d$ and $t_L$ from the equations given in Section 6.3, and record these times in Table 2.

   NOTE: An easier and more efficient way to find $t_d$ and $t_L$ is to measure these times directly on the chart paper with an engineering scale*, and record the times in Table 2.

(C) Measure the pulse lengths (T) produced by loop 1 on channel 1 of the event recorder. The pulse lengths produced by loop 2 on channel 3 will be the same as those produced by loop 1, due to the nearly constant vehicular speed

* For a chart speed of 720 inches per hour, use the 50 divisions per inch scale. Each division represents 0.1 second.
between loop 1 and loop 2. Record the pulse lengths of loop 1 in Table 2.

(D) Compute the traffic flow parameters from the equations given in Section 6.3, and record these values in Table 4.

(E) Compute the stopwatch spot speeds from the data in Table 3, and record these values in Table 5.

(F) Subtract the speeds obtained from the stopwatch method from the speeds obtained from the portable loop-tapeswitch method, and record these values in Table 6. A minus difference indicates that the portable loop-tapeswitch speed is below the stopwatch speed.

7.4 Data

The data obtained from this experiment are presented in the following tables, Table 2 and Table 3. Table 2 contains the portable loop-tapeswitch data and Table 3 presents the spot speed data obtained using the stopwatch technique.
TABLE 2
PORTABLE LOOP-TAPESWITCH DATA

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>$t_d$ (sec.)</th>
<th>$t_L$ (sec.)</th>
<th>$T$ (sec.)</th>
</tr>
</thead>
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* Vehicle did not activate tapeswitch
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PORTABLE LOOP-TAPESWITCH DATA

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*Vehicle did not activate the tapeswitch.
TABLE 3

SPOT SPEED (STOPWATCH) DATA

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Figure 17. Section of the Actual Chart Taken from the Event Recorder after the Experiment
7.5 Results

The results of the experiment are summarized in the following tables, Tables 4 and 5. Table 4 presents the values of traffic flow parameters using the portable loop-tapeswitch system while Table 5 presents the values of spot speeds obtained using stopwatches. In Table 6, a comparison of speed measurements between the portable loop-tapeswitch system and the stopwatch method are presented.
TABLE 4

VALUES OF TRAFFIC FLOW PARAMETERS,
USING THE PORTABLE LOOP-TAPESWITCH SYSTEM

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* Vehicle did not actuate the tapeswitch.
TABLE 4 (continued)

VALUES OF TRAFFIC FLOW PARAMETERS, USING THE PORTABLE LOOP-TAPESWITCH SYSTEM

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Mean                  18.4        18.4        2.8
Variance              14.0        7.2         1.3
Std. Deviation        3.7         2.7         1.1

* Vehicle did not actuate the tapeswitch.
### TABLE 5

VALUES OF SPOT SPEEDS, USING STOPWATCHES

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### TABLE 6 (continued)

**SPEED MEASUREMENT COMPARISON**

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<th>Vehicle No.</th>
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Mean of Difference in Speeds ($\bar{x}$) -2.834

Variance ($S_x^2$) 8.78

Standard Deviation ($S_x$) 2.96
7.6 Statistical Analysis: The t-Test for Matched Pairs

\[ \mu_x = \text{the population mean of the difference in speeds between the portable loop-tapeswitch method and the stopwatch method.} \]

\[ \mu_0 = 0 \]

Null Hypothesis \((H_0)\): There is no difference in speeds between the portable loop-tapeswitch method and the stopwatch method, \( \mu_x = 0 \).

Alternative Hypothesis \((H_a)\): \( \mu_x \neq 0 \).

Let the level of significance \((\alpha) = 0.05\).

Therefore, \( \alpha/2 = 0.025 \) for a two tail test.

From Table 6:

\[ \bar{x} = -2.834 \text{ mph} \]

\[ s_x = 2.96 \text{ mph} \]

\[ N = 50 \text{ vehicles} \]

\[ t_{\text{calculated}} = \frac{\bar{x} - \mu_0}{s_x/\sqrt{N}} \]

\[ = \frac{-2.834 - 0}{2.96/\sqrt{50}} \]

\[ = -6.77 \]

\[ |t|_{\text{calculated}} = 6.77 \]
From t-tables:

\[ \pm t(\alpha/2, n-1) = \pm t(0.025, 49) = \pm 2.01 \]

\[ 6.77 >> 2.01 \quad \text{Reject } H_0 \]

Therefore, there is a difference in speeds between the portable loop-tapeswitch method and the stopwatch method.
CHAPTER VIII
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary

8.1.1 Loop Operation and Dimensions

Loop detectors are dependent on an electrical property called inductance. All loop detectors use a coil with one or more turns of wire to detect the change of loop inductance in the presence of a vehicle. The width of the loop must be at least 4 feet to detect high-bed vehicles. The length of the loop may be any value from 4 feet to 100 feet. The loop operating frequency is generally between 10 and 150 kilohertz.

8.1.2 Methods of Loop Detection

Loop detectors can sense the presence of vehicles by four different methods:

(a) Phase shift detection;

(b) Voltage level change detection;

(c) Frequency change (heterodyne) detection; and

(d) Impedance comparison detection.
8.1.3 Types of Loop Detectors

The four types of loop detectors are:

(a) Passage detectors;
(b) Continuous presence detectors;
(c) Extended presence detectors; and
(d) Analog detectors.

8.1.4 Loop Sensitivity

Loop sensitivity is defined as the smallest percentage change of the inductance at the detector terminals which will cause the detector to actuate. One of the equations for loop sensitivity is:

\[ S = \frac{2\Delta f}{f_v} \times 100 \]

Loop sensitivity is also defined as the total inductance change, and can be expressed by the equation:

\[ S = \frac{\Delta L}{L_T} \times 100 \]

The length of the lead-in has an influence on the loop sensitivity; the longer the length of the lead-in, the lower will be the loop sensitivity.
8.1.5 Loop Circuit Bandwidth

The bandwidth of the loop circuit is defined as the difference between the two frequencies on either side of the resonance curve. The voltage across the parallel-tuned circuit is reduced to 70.7 percent of the voltage at resonance. The equation for the loop circuit bandwidth is:

$$B.W. = f_2 - f_1$$

8.1.6 Resonant (Operating) Frequency

The resonant or operating frequency of a loop amplifier is that frequency when the inductive reactance of the circuit equals the capacitive reactance of the circuit. The general equation for the resonant frequency is:

$$f_0 = \frac{1}{2\pi \sqrt{LC}}$$

8.1.7 Loop Quality Factor (Q)

The Q or quality factor of a resonant loop circuit is an indication of the lost or dissipated energy taken from the oscillating circuit. The Q is also defined as a measure of the frequency selectivity of a resonant network, such as a roadway loop. The following equations are used to find the Q of a loop circuit:

(a) \[ Q = \frac{f_0}{B.W.} = \frac{f_0}{f_2 - f_1} \]
(b) \[ Q = w \left( \frac{W_S}{P_L} \right) = 2\pi f_0 \left( \frac{W_S}{P_L} \right) \]

(c) \[ Q_S = \frac{wL}{R_S} = \frac{2\pi f_0 L}{R_S} \] (Series circuit)

(d) \[ Q_p = \frac{R_p}{wL} = \frac{R_p}{2\pi f_0 L} \] (Parallel circuit)

(e) \[ Q_t = \frac{Q_S Q_P}{Q_S + Q_P} \] (Series-Parallel circuit)

The \( Q \) of a loop can be found easily from equations (c) and (d). The loop parameters \( R_S, R_p, f_0 \) and \( L \) are determined either with available meters or by derived equations. The equation (e) can then be used to find the total loop \( Q \).

The length of the feeder line also has an influence on the loop \( Q \); the longer the length of the feeder wire, the lower the loop \( Q \). As the loop \( Q \) becomes smaller, the sensitivity of the loop decreases.

A good recommendation in loop amplifier design is to standardize a \( Q \) of 5 and an operating frequency of 10 kilohertz among all loop detector manufacturers. Another recommendation is to replace the loop when its leakage resistance to ground decreases to 10,000 ohms.
8.1.9 **Wire Selection**

Loop construction must contain wire having insulation that is able to withstand severe environmental conditions. Some of these conditions are:

(a) Shifting of the road surface;
(b) Moisture, petroleum solvents, and oils seeping through the road surface; and
(c) Sharp rocks and pebbles.

The recommended wire size for loop construction is either Number 12 or Number 14 AWG stranded wire with either polyvinyl chloride or polyethylene insulation. However, due to losses resulting from temperature changes, the polyvinyl chloride insulation has losses that are 250 times greater than the polyethylene insulation.

8.1.10 **Feeder Lines**

The feeder lines (lead-in) also have inductance. The inductance is measured in 100-foot increments. Number 14 wire has about 15 microhenries of inductance per 100 feet. Number 12 wire has about 22 microhenries of inductance per 100 feet. The lead-in inductance should never be more than twice the loop inductance.
8.1.11 Loop Inductance

The inductance of a loop is difficult to measure; however, the loop inductance can be measured from the equation:

\[ L = \frac{5PN^2}{10 + N} \]

8.1.12 Loop Installation

There are certain rules to be considered in loop installation. These rules are stated below:

(a) Due to the effect of capacitance, the wires of the same loop should be as close together as possible.

(b) All wires should be placed as far from metal objects as possible.

(c) Splices should be avoided.

8.1.13 Determining Lateral Placement of Vehicles from the Curb with a Tapeswitch

The time \( t_d \) that a vehicle takes to travel from Loop 1 to the tapeswitch is computed from the equation:

\[ t_d = t_2 - t_1 \]

The time \( t_L \) that a vehicle takes to travel from Loop 1 to Loop 2 is computed from the equation:
The lateral distance of vehicles from the curb is computed from the equation:

\[ p = \frac{L t_d}{t_L} (-R) \tan \theta \]

8.1.14 Other Equations in Traffic Studies

Speed (in fps): 
\[ v_n = \frac{L}{t_L} \]

Speed (in mph): 
\[ v_n' = 0.682 v_n \]

Average Speed between Two Successive Vehicles (in fps):
\[ \bar{v}_n = \frac{v_n + v_{n+1}}{2} \]

Vehicle Length (in ft.):
\[ a_n = L \frac{T}{t_L} - \ell \]

Headway (in sec.):
\[ H_n = t_{n+1} - t_n \]

Average Headway (in sec.):
\[ H = \frac{\sum H_n}{N-1} \]

Spacing (in ft.):
\[ S_n = \bar{v}_n H_n \]

Average Spacing (in ft.)
\[ S = \frac{\sum S_n}{N-1} \]

Volume (in veh./hr.):
\[ V = \frac{3600}{H} \]

Density (in veh./mi.):
\[ D = \frac{5280}{S} \]
8.1.15 The Portable Loop-Tapeswitch Experiment

Two multiturn portable loops can be used with a tapeswitch to determine traffic flow parameters. The construction and testing of this equipment for easy and quick use in determining traffic flow parameters with reasonable accuracy is the basis of the research in this thesis.

8.2 Conclusions

8.2.1 Advantages of Building a Portable Loop-Tapeswitch System

The advantages of building a portable loop-tapeswitch system are described as follows:

(a) The portable loop-tapeswitch system can usually be built at less cost than buying a commercially-sold traffic analyzer.

(b) The portable loop-tapeswitch system can be used to determine all traffic flow data, while most traffic analyzers sold commercially determine many, but not all, traffic flow data.

8.2.2 Comparison of Vehicular Speeds from the Portable Loop-Tapeswitch Method with the Stopwatch Method

The statistical analysis discussed in Section 7.6 indicates only that there is a difference in vehicular speeds between the portable loop-tapeswitch method and the stopwatch
method. Whether vehicular speeds obtained by the portable loop-tapeswitch method are "actually" lower or higher than the vehicular speeds obtained by the stopwatch method could not be validated by the experiment in this thesis. Therefore, the portable loop-tapeswitch system could not be calibrated.

8.2.3 Effectiveness of the Tapeswitch

The tapeswitch was occasionally not triggered while the portable loops were actuated. This incidence was due to some vehicles swinging slightly to the left to avoid passing over the apparati. Some drivers may have been conscious of the tape in the right lane. The two loops were actuated because the vehicles still passed within the loops' magnetic fields (approximately two feet around the loops). However, the tapeswitch must be struck directly by the vehicle's wheels, thus accounting for the lack of some tapeswitch pulses on the event recorder. Ninety-two percent of the vehicles, however, did actuate the tapeswitch.

8.2.4 Importance of High Density Traffic Flow During the Experiment

The lack of vehicle platooning at the time of the experiment resulted in insufficient data for computing headways, spacings, density, and volume. For safety reasons, the equipment had to be installed during a low traffic density period. During this period, the time gap between
vehicle arrivals was very long. Keeping the event recorder operating at 720 inches per hour between vehicle arrivals to obtain platooning information would not be wise during low traffic density periods. Speed, vehicle length, and lateral placement, however, can be determined anytime.

8.3 Recommendations

8.3.1 Distance Between Portable Loops

The two portable loops should be placed as close together as possible on the roadway without crosstalk between the two loops. If the distance between the loops is between four and six feet, crosstalk is nil. When the loops are separated by such a short distance, there is less chance for a vehicle to change its speed. Thus, the speed measurements are more accurate. There is also a much higher probability of detecting close-following (tailgating) vehicles. A longer distance between loops was used in this experiment due to the longer time required for the event recorder to distinguish between two pulses.

8.3.2 Use of a Computer and Data Recorder

A computer should be used to determine the vehicle travel time between loop 1 and the tapeswitch \( t_d \), the vehicle travel time between loop 1 and loop 2 \( t_L \), and the pulse length of the loop pulses \( T \). These times are
generally fractions of a second, and are difficult to determine manually. The speed and accuracy of a computer will determine these times quickly and precisely.

The computer can also be used to compute the traffic flow parameters. A computer program can be written for the desired computations. The data from the loop detectors and the tapeswitch can be recorded onto a data recorder during the experiment. Then, the data from the tape in the data recorder can be fed into the computer at a convenient time to obtain the desired results. A data recorder was not available for the experiment, so the event recorder was utilized.

8.3.3 Use of a Radar Unit

A radar unit, rather than stopwatches, should be used to measure the spot speeds. The radar unit would give more accurate speed readings than can be obtained with the stopwatch method, and would require fewer personnel. The radar speeds can be more effectively compared to the speeds obtained with the portable loop-tapeswitch system to test the reliability and accuracy of the latter system. A radar unit was not available at the time of the experiment, so stopwatches were used.

8.3.4 Camouflaging the Equipment

The electronic equipment should be concealed from the
driver's vision. If the cable connections are long, the electronic equipment can be hidden behind bushes near the roadway. The portable loops and the tapeswitch should be attached to the roadway with a tape whose color matches the color of the pavement. If the drivers do not see the equipment, they will not be tempted to change lanes nor decrease speed. Thus, the data would not be biased.
APPENDIX
FOOTNOTES TO CHAPTERS


9. Ibid.
10. Ibid.


17. Pinnell et al., op. cit., p. 24.


21. Ibid., p. 25.


23. Pinnell et al., op. cit.

24. Ibid., pp. 21-22.


27. Miller, loc. cit.

28. Ibid.


32. Miller, loc. cit.


36. Ibid., pp. 18-19.


38. Miller, *loc. cit.*


44. Byrne, loc. cit.

45. Ibid.

46. Stern, loc. cit.

47. Royer, loc. cit.
FOOTNOTES TO FIGURES

Figure No.

2. Ibid., p. 23.

3. Ibid.

4. Ibid., p. 33.


6. Ibid., p. 26

7. Ibid., p. 27.

8. Ibid.

9a. Ibid., p. 28.

9b. Ibid.

11. Pinnell et al., op. cit., p. 29.

12. Ibid., p. 20.


REFERENCES


LaBatt, Hal, "How Correct Detector Placement Solves the Motorist's Stop-or-Go Dilemma," IMSA Signal, January/February 1971, pp. 16-17.


Roseveare, R.W., "How to Install Loop Detectors," The American City, April 1966, pp. 120-121.


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Traffic and Safety Systems
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Sarasota, Florida 33577

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Thompson Electronic Supplies, Incorporated
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