DESIGNING AN INDUCTIVE SENSOR FOR ROAD TRAFFIC MONITORING SYSTEMS AND CONTROL

By

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
June 2004

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ALFIAN HADI BIN FAUZI (1544)

ABSTRACT

The purpose of this study is to design an inductive sensor, which detect a vehicle on the road. The main objectives are to design an inductive sensor using an enameled copper wire and interface it to an electronics circuit. The analyses of experiments will mainly the important part of this project. Then, a demonstration will be held to demonstrate the sensing process using a working model.

This sensor can change some work from manual to automatically. Examples of situation that can implement this sensor is to control the barrier automatically on the main gates on the roads, to monitor traffic on a narrow curved portion of the road and to count the number of vehicles from a particular point per unit time.

At present, there are a lot of sensors available in the market that uses inductive sensor. Many methods can be used in detecting the presence of vehicle and a complete circuit of inductive sensor has also been developed. The result from these methods will assist in the future work of this project.

ACKNOWLEGDEMENT

Before I go any further, I would like to thank God with the blessings that help me to go through the process of doing this project smoothly. Also, I would like to thank Mr Zuki, Universiti Teknologi Petronas (UTP) Final Year Project Coordinator (EE) for all the guidance and support.

I would like to express my greatest appreciation to my supervisors, Dr Nazir Ahmed Arain for all their guidance, support and his time spent for me during these two semesters in completing my Final Year Project. I have learned a lot from him and he gave me many suggestions and advises to me about this project.

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CHAPTER 1

INTRODUCTION

This report is written for Final Year Research Project (EEB 5043) course, which is compulsory to be undertaken by all final year Electrical and Electronics Engineering students. The project is required to be completed within 2 semesters.

1.1 Background of study

Monitoring road traffic volume has been a basic element of highway program administration for over seven decades. The collection of historical traffic volume data is used for a variety of purposes, such as forecasting when traffic patterns will require public investments to maintain an acceptable level of service. But in Malaysia there still have not implement widely this road monitoring system. [6]

For this Final year project, author has designed a sensor that will help the road users when they drive. This sensor is an inductive sensor, made of enameled copper wire. This inductive sensor consists of a set of inductive loops. For this project, author has use an enameled copper wire which acts as inductive sensor. What this sensor does is, it senses a vehicle that passes through it. Author tries to design the sensor so that when the vehicle passes the sensor, it will produce a signal. This sensor embedded in the road's surface. This signal can be connected to other device or controller in order to control some system. [6]

1.2 Problem Statement

As we know in our country, the rate of accident is high. Our country still doesn't implement road monitoring system although we know that it very important to help road users. According to statistic by JPJ (Jabatan Pengangkutan Jalan), the accidents always happen at curved road. Sharp turning on one way or two-way traffic roads, the vehicles coming from opposite directions are not visible to the drivers coming from either direction. A signaling system or a sensor is required that can alert the drivers about the vehicles coming from either side of the road. Since this sensor produces signal when detecting a vehicles, it can be applied to solve this problem. Thus it can reduce the rate of accidents. We can make a conclusion that by having this sensor, it will help the road users while they driving.

1.3 Objectives and Scope of Study

The aim of this project is to design an inductive sensor that can detect the presence of vehicles. The objectives of this project are as follows:

- To study and design an inductive sensor that can be use to detect vehicle as to monitor and control traffic
- To built an electronic circuit to interface with inductive sensor.
- To make a working model at the end of the project to demonstrate the sensing of the vehicle.

The scope of this study will cover:

- Focused on the developing the inductive sensor for vehicle detection.
- The study was limited to vehicles detection on road.
- In developing the sensor, enameled copper wire is used as the inductive loop.

- Some basic principles that related to an inductor will be use as the guide to finish this study.
- An electronic circuit will be attached to the detector circuit.
- This project will involve with electrical work such as designing the circuit of sensor.
- Involve some mechanical work in order to make the model.

The scope of the project is divided into 2 parts. First is conceptual design and the second one is embodiment design. In conceptual design, the students must complete several main task such as define the problem; gather the information, generate as many concepts and evaluation of the concepts. In second part, the embodiment of the design is carry out, such as product architecture, design configuration and design parameters

CHAPTER 2

LITERATURE RIVIEW / THEORY

2.1 Inductance

Inductance is a factor of goodness for a magnetic circuit. The higher the inductance, the better the flux linkage per ampere. Any circuit in which a change of current is accompanied by a change of flux, and therefore by an induced e.m.f., is said to be inductive or to possess self inductance or merely inductance. The inductance depends on the number of turns of the energizing coil, the length and the cross-sectional area of the magnetic circuit and the material from which the magnetic circuit is made (iron core or air core) [4].

2.1.1 Characteristics of Inductance

Inductance is the characteristic of an electrical circuit that opposes the starting, stopping, or changing of current flow. The symbol for inductance is L. The basic unit of inductance is the henry (H); 1 henry is equals to the inductance required to induce 1 volt in an inductor by a change of current of 1 ampere per second.

An analogy of inductance is found in pushing a heavy load, such as a wheelbarrow or car. It takes more work to start the load moving than it does to keep it moving. Once the load is moving, it is easier to keep the load moving than to stop it again. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change in velocity. Inductance has the same effect on current in an electrical circuit as inertia has on the movement of a mechanical object. It requires more energy to start or stop current than it does to keep it flowing. [12]

2.1.2 Electromotive Force

Electromotive force is developed whenever there is relative motion between a magnetic field and a conductor. EMF is a difference of potential or voltage which exists between two points in an electrical circuit. In generators and inductors, the EMF is developed by the action between the magnetic field and the electrons in a conductor. (An inductor is a wire that is coiled, such as in a relay coil, motor, or transformer.) Figure 1 shows EMF generated in an electrical conductor.

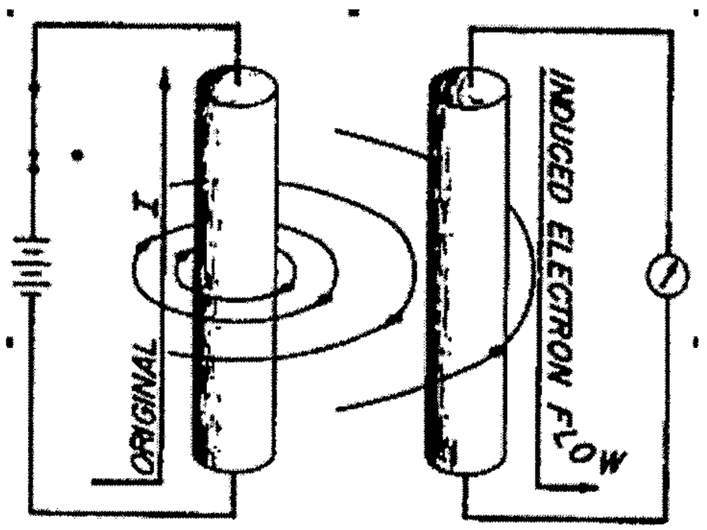


Figure 1: Generation of an EMF in an Electrical conductor [12]

2.1.3 Types of inductor and inductance

Since inductors are devices which promote inductance, they are designed to have a great ability to hold magnetic energy. Inductors are generally made to have fixed value of inductance but some are variable. [4]

Inductors fall into two categories-those with an air core and those with a ferromagnetic core. The air core has the advantage that it has a linear B/H characteristic which means that the inductance L is the same no matter what current is in the coil. However, the relative permeability of air being 1 means that the values of inductance attained is very low. The ferromagnetic core produces very much higher values of inductance, but the B/H characteristic is not linear and therefore the inductance L varies indirectly with the current. However, many of the sintered ferromagnetic materials have almost linear characteristics and they are therefore almost ideal. [12]

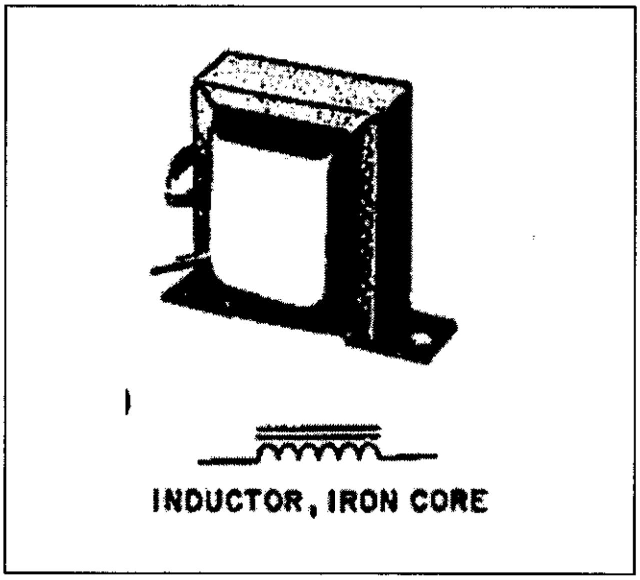


Figure 2: Inductor, Iron Core [12]

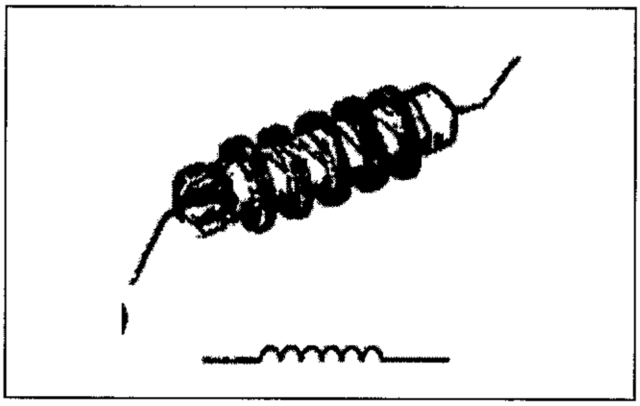


Figure 3: Inductor, Air Core [12]

2.1.4 Factors Affecting Coil Inductance

Several physical factors affect the inductance of a coil. They are the number of turns, the diameter, the length of the coil, the type of core material, and the number of layers of winding in the coil. Inductance depends entirely on the physical construction of the circuit. It can only be measured with special laboratory instruments.

The first factor that affects the inductance of the coil is the number of turns [4]. Doubling the number of turns in the coil will produce a field twice as strong; if the same current is used. A field twice as strong, cutting twice the number of turns, will induce four times the voltage. Therefore, inductance varies by the square of the number of turns.

Referring to the formula to calculate the inductance, all the factors that affect the inductance is inside the formula. [4]

$$\text{Magnetic field Strength} = \frac{IN}{l} \quad \text{(2.1)}$$

And

$$\text{total flux} = \Phi = BA = \mu_0 HA$$

$$= 4\pi \times 10^{-7} \times \frac{IN}{l} A \quad \text{(2.2)}$$

$$L = \frac{N\Phi}{I} \quad \text{(2.3)}$$

Substitute equation 2 inside 3

$$\text{Inductance} = L = 4\pi \times 10^{-7} \times \frac{AN^2}{l} \text{ henrys}$$

[4]

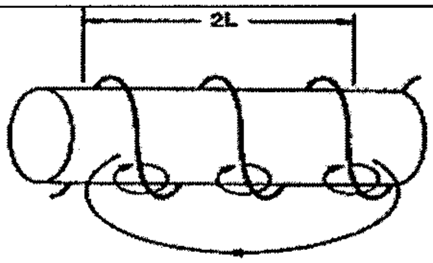
Hence the inductance is proportional to the square of the number of turns and the cross sectional area and inversely proportional to the length of the magnetic circuit.

The second factor is the coil diameter. Actually, the inductance of a coil increases directly as the cross-sectional area of the core increases. Recall the formula for the area of a circle: A = pi r squared. Doubling the radius of a coil increases the area by a factor of four.

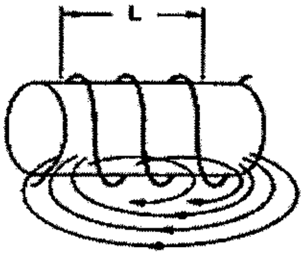
$$A = \pi r^2$$

Where r = radius of a coil

The third factor that affects the inductance of a coil is the length of the coil. Coil with a small turns, rather widely spaced, making a relatively long coil. A coil of this type has fewer flux linkages due to the greater distance between each turn. Therefore, a short length of coil has a relatively low inductance. Coil with many turns has closely spaced turns, making a relatively short coil. This close spacing increases the flux linkage, increasing the inductance of the coil. Doubling the length of a coil while keeping the number of turns of a coil the same halves the inductance. [12]



(A) WIDELY SPACED



(B) CLOSELY WOUND

FIGURE 6-8. Inductance Factor (Coil Length).

Figure 4: Inductor Factor (Coil Length) [12]

The fourth factor is the type of core material used with the coil. The magnetic core of coil with a soft iron core is a better path for magnetic lines of force than the nonmagnetic core of coil with an air core. The soft-iron magnetic core's high permeability has less reluctance to the magnetic flux, resulting in more magnetic lines of force. This increase in the magnetic lines of force increases the number of lines of force cutting each loop of the coil, thus increasing the inductance of the coil. The inductance of a coil increases directly as the permeability of the core material increases. [12]

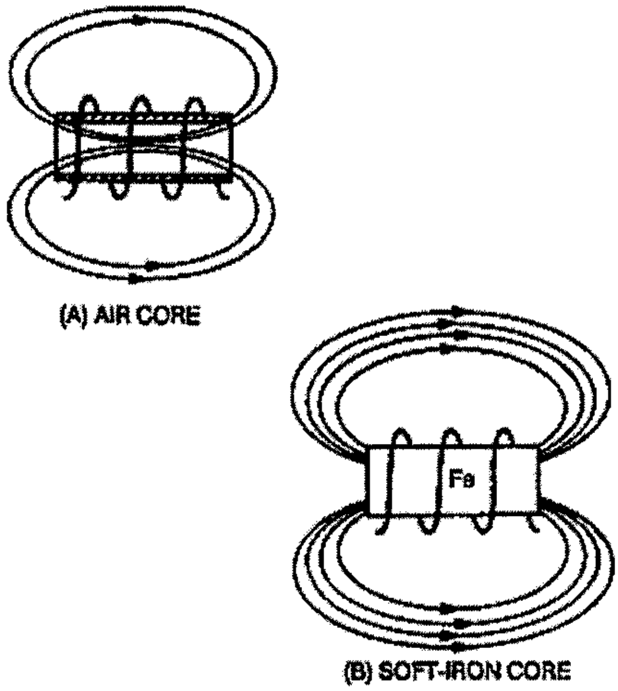


FIGURE 6-9. Inductance Factor (Core Materials).

Figure 5: Inductor Factor (Core Materials) [12]

The fifth factor is the number of layers of windings in the coil. Inductance is increased by winding the coil in layers.

2.2 DETECTOR

If we want to collect information about the flow of road traffic, we have to do measurement. The only devices in the beginning of road traffic study were a stopwatch and manual counters. But now we can use the existence of many detectors. Traffic detectors are used to detect the presence and the passing of a vehicle. Detection is used to adapt traffic to the traffic flow, to count the number of traffic units and to measure traffic flow parameter. [6]

2.3 THE LOOP DETECTOR

The inductive loop detector is a vehicle detector that is used most for permanent installation. A coil with a few windings of copper wire is installed under the road surface. The shape of loop is mostly rectangular. The important electrical properties of the coil are self inductance *L* and the loss R. The loop is connected to an alternating current source with a frequency of 40 to 120 kHz [6][11]. The loop creates an electromagnetic field above the road. When a vehicles enters this field the following changes occurs:

1) The electromagnetic field generates Eddy current in the metal of vehicles. These current itself generate an electromagnetic field that work against the loop field. The Eddy currents cause an energy loss in the metal of the car. This loss is proportional to the square root of the frequency. The loss expresses itself with an increase of the loss resistance and a decrease of self inductance L. [6]

$$\text{Energy loss} \propto f^2$$

2) The ferrous metal of the car will increase the flux density of the filed. This effect shows itself in an increase of the self inductance L. [6] (the principles that will be use in this project later)

3) The presence of the car will increase the capacity of the loop. In practice this effect can be neglected, especially when the loop is connected symmetrically.[6]

The changes in the loop properties, mainly caused by the Eddy currents, are: [6]

1. An increase of the loss resistance *R*: +5% to +15%
2. A decrease of the self-inductance L: –1% to –6%

2.4 LOOP CONFIGURATION

Many different loop sizes and shapes have been used. The application determines which loops will perform best. Especially the length in the driving direction has a large influence on the detection performance. The specifications of various manufacturers show the following figures:

Function	Loop Length
Detection of bicycles	0.5m
Axle counter	0.5-0.8m
Detection passenger cars	1.0-2.5m
Detection articulated trucks	2.0-4.0
Separation of truck and trailer	1.2-1.3m
Traffic flow detection	At least two vehicles lengths

Table 1: Specification of loop length [6]

Not only vehicles have influence on the loop parameters. Also changes in the environment are detected like falling rain. To prevent the detection of such slow changes, a differentiator is added to the detection circuit. This differentiator blocks slow changes like a stationary vehicle, will not be detected anymore after a given amount of time. This time is called the recovery time and depends on the chosen circuit and the magnitude of the constant change. The time can vary from a few minutes to more than one hour. [6]

The loop detector gives a signal as long as a vehicle is in the range of the loop. With two loops at a short distance from each other, the speed and the length of the vehicles can be measured.

The detector is robust and reliable, because the loop is under the road surface and does not suffer from wear by passing wheels. Only deformation of the surface and new layers of asphalt can disturb the action of the loop detector. [6]

Long loops can be used to detect the absence of vehicles on the road section. This function is particularly useful in combination with intersection control. It is possible to use the analogue output of this detector. The output signal can be used to indicate the number of vehicles inside the loop area. When the loop length is equal to the size of bus, the signal level is maximal only when a bus covers the loop. [6]

The absence of a vehicle is used with the detector to calibrate the detector and to compensate for an environmental change (temperature). With the long loop this can be a problem in dense the traffic situation. When the loop is continuously occupied by vehicles, this calibration may fail and the output will not be accurate. [6]

2.5 UNWANTED INFLUENCED

Environmental properties, like temperature have influenced on the loop parameter. Also when the loop is covered with rain puddle, the parameter changes a lot and a vehicle is wrongly detected. All environmental properties together with the properties of the electronic circuit cause a voltage level inside the level inside the detector to zero level.
In the most electronics circuits a differentiating element(R-C network) is applied to eliminate the variable influences of the environment. This network allows to pass, but

very slow occurring changes, caused by temperature, water etc, and change the zero level to reflect the new situation. [6]

Loops that are installed close together can cause unwanted influences. When one of the loops detects a vehicle, the change can be transferred to other loop with mutual inductance. One solution to this problem is to keep a minimum distance between the loops. If that is not possible, the detectors are tuned to different frequencies and are only selective to their own frequency. Because the loop detectors are designed to be used at a short distance from each other, for instant double loop in each lane on a multi lane motorway most detector are selective to their own frequency. [6]

Also slow motion of the road surface, leading to permanent deformation cause rather large changes in L and R. This deformation even can leads to breaking of the wires. The causes can be cracks in the surface, subsiding ground, pushing away by heavy trucks, especially in curves. [6]

CHAPTER 3

METHODOLOGY

In completing this project, some methodology had been conducted, namely:

3.1 Literature search

This project began with literature research. The topic searched is not only in the inductive sensor area only, the more general topics of detectors and sensor was searched. The objectives of this literature research are:

- To gather knowledge, information and data on related websites regarding inductive sensor.
- To find some electric circuit that already designed by designer to do as reference.

3.2 Secondary sources

To acquire relevant information and data as project is concerned

3.3 Laboratory Experiment

A lot of experiments were done in order to complete this project. These experiments are important since this project involve research and development process. The results of this experiment will help author to continue with other tasks according to the project planning.

3.4 Designing Circuit

This is the last step in completing this project. The results of the experiments were analyzed and decisions from these results have been done. In designing the circuit, it must be interrelated with the results of experiment or else it will not be the same as what I plan to do.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Vehicles Detector

There is a wide range of sensor available for the vehicle detection. Some of the most common are:

1) Video Image Processors (VIP)

A video image processor (VIP) is a combination of hardware and software which extracts desired information from data provided by an imaging sensor. This imaging sensor can be a conventional TV camera or an infrared camera. A VIP can detect speed, occupancy, count, and presence. Because the VIP produces an image of several lanes, there is potential for a VIP to provide a wealth of traffic information such as vehicle classification and incident detection. A VIP generally operates in the following manner: the operator selects several vehicle detection zones within the field of view (FOV) of the camera. Image processing algorithms are then applied in real time to these zones in order to extract the desired information, such as vehicle speed or occupancy. [11]

Advantages of VIPs are that they are mounted above the road instead of in the road, the placement of vehicle detection zones can be made by the operator, the shape of the detection zones can be programmed for specific applications, and the system can be used to track vehicles. Disadvantages are the need to overcome detection artifacts caused by shadows, weather, and reflections from the roadway surface. The disadvantages can be overcome through design and installation of the hardware and design of the software algorithms. [11]

2) Infrared Detector

There are two types of infrared (IR) detectors, active and passive. Active infrared sensors operate by transmitting energy from either a light emitting diode (LED) or a laser diode. An LED is used for a non-imaging active IR detector, and a laser diode is used for an imaging active IR detector. In both types of detectors the LED or laser diode illuminates the target, and the reflected energy is focused onto a detector consisting of a pixel or an array of pixels. The measured data is then processed using various signal processing algorithms to extract the desired information. Active IR detectors provide count, presence, speed, and occupancy data in both night and day operation. [11]

3) Ultrasonic Detector

There are two types of ultrasonic sensors available, presence-only and speed-measuring. Both types operate by transmitting ultrasonic energy and measuring the energy reflected by the target. These measurements are processed to obtain measurements of vehicle presence, speed, and occupancy. [11]

The advantages of ultrasonic are that they provide all-weather operation. Their disadvantages include their need to be mounted in a down-looking configuration as perpendicular as possible to the target (as opposed to side-mounting), a difficulty in identifying lane-straddling vehicles and vehicles traveling side by side, and susceptibility to high wind speeds. Some of these disadvantages may be compensated for through more sophisticated data processing techniques.[11]

4) Microwave/Millimeter wave radars

Microwave detectors have been used extensively in Europe, but not in the United States. They operate by measuring the energy reflected from target vehicles within the field of view. By processing the information received in the reflected energy, the detectors measure speed, occupancy, and presence. [11]

5) Piezoelectric

Piezoelectric detectors are very accurate vehicle detectors, but they do not detect presence of a stationary vehicle, unless it has stopped with its wheels on the detector. The piezoelectric sensor consists of a long strip of piezoelectric material enclosed in a protective casing. It can be embedded flush with the pavement, and when a car passes over it, compressing the piezoelectric material, a voltage is produced. This sets off the controller.

The piezoelectric detector has the advantage of indicating exactly when and where a vehicle passed by because it is a line detector perpendicular to the path of the vehicle. A series of two of them may be used to measure vehicle speed. A disadvantage is that for a permanent installation, they must be embedded in the pavement. Every time the roadway is repaved, or if a pothole appears, the sensor would need to be replaced. [11]

6) Photoelectric

Photoelectric devices commonly consist of two components, the light source and the detector. These may both be in the same place, or placed across from each other. When placed across from each other, the detector is activated whenever something obstructs the illumination from the light source. When placed in the together, the detector is activated when light from the light source is reflected from a target and back onto the detector. [11]

7) Inductive loop detectors

Loop detectors are the most widely used technology for vehicle detection in the United States. A loop detector consists of one or more loops of wire embedded in the pavement and connected to a control box. The loop may be excited by a signal ranging in frequency from 10 KHz to 200 KHz. This loop forms an inductive element in combination with the control box. When a vehicle passes over or rests on the loop, the inductance of the loop is reduced. This causes a detection to be signaled in the control box.

The advantages of inductive loop detectors are that they are an established technology in the United States, they have a well-defined zone of detection, and they are generally reliable. Disadvantages are that the detectors are very sensitive to the installation process, they can only be installed in good pavement, and they must be reinstalled every time a road is repaved. [11]

4.2 Theory of operation (Inductive Loops)

Inductive-loop detector systems operate by sensing disturbances to the inductance of an inductive loop that were built into the road. From the previous chapter, it is stated that inductor falls into two groups; with an air core and with soft iron core. Both type of core will give different value of inductance when we put it inside an inductive loop. The iron core will give more inductance compared to air core. So, when there is no vehicles pass through the loops, the inductor is said to be an air core. But when a conductive object (vehicles made of metal) enters the area of the wire loop, the inductor now is an iron core, thus resulting the inductance to increase. When vehicles enter the area of loops, the inductance of the loops will increase.

For this project, an AC voltage is used because we can use the frequency of AC voltage to increase the inductive reactance of the loops.
Please refer to the formula:

$$\text{Inductive reactance} = X_L = 2\pi f L$$

Higher the frequency, the higher the inductive reactance.

This system operates by sensing the disturbances to the electromagnetic field over the inductive loops. When a conducive object vehicles made of metal) enters the area of the loop, the magnetic field generated by alternating electrical current in the signal detector circuit induces weak electrical currents in the conductive objects(vehicles). Based on the research, the loop may be excited by a signal ranging in frequency from 10 kHz to 200 kHz typically around 20000 to 30000 Hz.[12] Since this sensor need high frequency voltage, a circuit needs to be design in order to increase the frequency. The electrical currents induced in the object generate their own magnetic field that works in opposition to the magnetic field generated by the sensor inductive loops(due to Lenz's Law) This opposition changes the resonant frequency of the sensor by reducing the effective inductance of the sensor loops. This change in resonant frequency (an increase in frequency as the inductance decreases) is detected by the circuit in the signal controller, which tells the signal control electronics that a vehicle is present. Before that, some experiments are done to check whether this theory is right or not. Also some experiments were done to analyze the result so I can proceed with next step.

4.3 Experimentation

Many experiments were done in order to check and analyze the results of the experiments. This experiment is important because based on the results; some analysis will be done and will proceed to the next experiment.

4.3.1 Experiment 1: To understand the process of inductive loop

Procedure of Experiment 1

- The experiment was setup same with the circuit below.

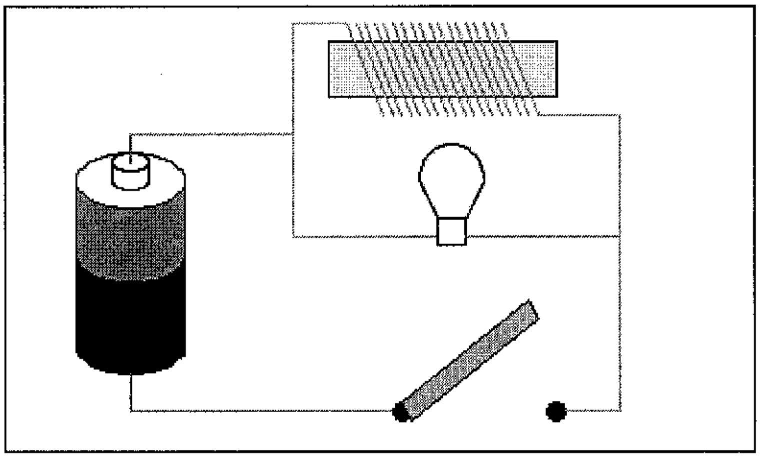


Figure 6: To check the behavior of inductor

Apparatus

- Battery
- Light bulb
- Coil of wire (inductor)

Discussion of Experiment 1

If the inductor (coil) is taken out from this circuit, what happens is a normal flashlight. Close the switch will make the bulbs lights up. With the inductor in the circuit as shown, the behavior is completely different. The light bulb is a resistor (the resistance creates heat to make the filament in the bulb glow). The wire in the coil has much lower resistance (it's just wire), so when turning on the switch will makes the bulb to glow very dimly. Most of the current should follow the low-resistance path through the loop. What happens instead is that when closed the switch, the bulb burns brightly and then gets dimmer. When open the switch, the bulb burns very brightly and then quickly goes out.

The reason for this strange behavior is the inductor. When current first starts flowing in the coil, the coil wants to build up a magnetic field. While the field is building, the coil inhibits the flow of current. Once the field is built, then current can flow normally through the wire. When the switch gets opened, the magnetic field around the coil keeps current flowing in the coil until the field collapses. This current keeps the bulb lit for a period of time even though the switch is open. [7]

4.3.2 Experiment 2: To check the effect of iron core to the inductive loop

Procedure of experiment 2

- The experiment was setup in the electrical laboratory 1.
- Experiment was setup like the figure below.
- LCR meter is used to measure the value of inductance of the loops
- Iron core is used in order to check the effect of iron core

Apparatus

- LCR meter
- Iron core
- Enameled copper wire (inductive loops)

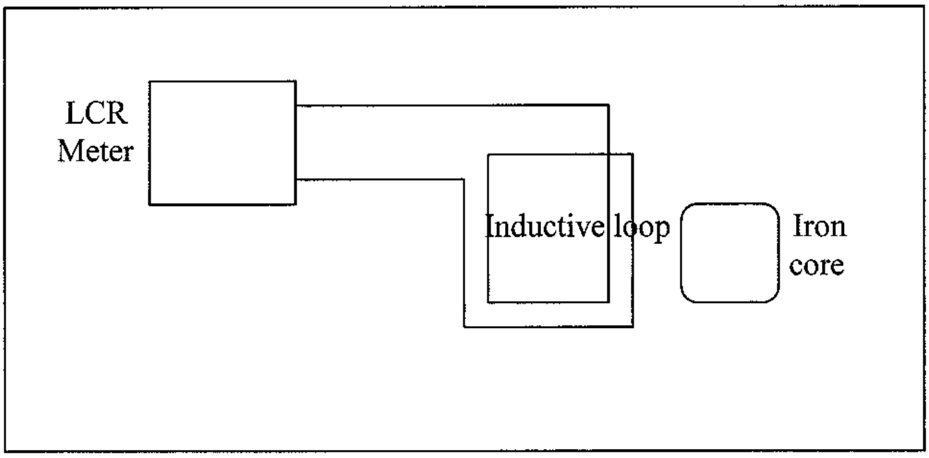


Figure 7: To check the effect of iron core

Results

SWG	With air core	With iron core
24	14.2 μH	15.1 μH
27	14.4 μH	15.1 μH
35	15.3 μH	16.1 μH

Table 2: Results of Experiment 2

Discussion of Experiment 2

The purpose of this experiment is to measure the inductance of inductance loop. The LCR meter will measure the inductance. From the results, it shows that when we put an iron core inside the loops, the inductance of the loops will increase. The results are same with different SWG of the enameled copper wire. 6 turns of loop is used for this experiment in order to compare the results of different SWG used. The meter shows inductance in micro Henry. When using air core, the inductance of the loop is 14.2 μH for SWG 24. When using iron core, the inductance increased to 15.1 μH. This proves that the presence of the iron core changes the value of inductance. Further experiment need to be done to select the best parameter of the loop. The right number of SWG, length of the detector (inductive loop), number of turns, and other parameter will make the sensor operate and perform better.

Conclusion of Experiment 2

As conclusion, putting an iron inside the inductive loop will increase the inductance. In this project, the iron will be altering with the vehicles an act as iron core since all vehicles made from iron.

4.3.3 Experiment 3: To check the sensitivity of the enameled copper wire

Procedure of Experiment 3

- This experiment was conducted same with experiment 2. But for this experiment, the size or diameter of the enameled copper wire is to be analyzed.

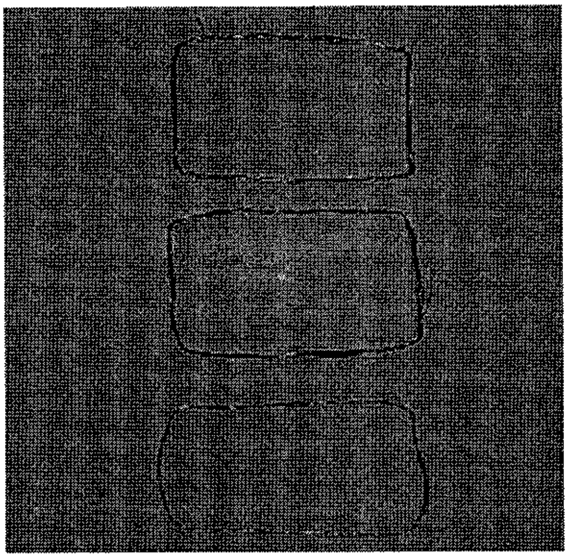


Figure 8: Enameled copper wire with different SWG

Discussion of Experiment 3

The size or diameter of the enameled copper wire is one of the factor that affecting the loops inductance.[6] The bigger size of the wire, bigger the value of the inductance. By referring to the Standard Wire Gauge (SWG) table, we can get some information that can use in this project. The most important information that we can get is the maximum current can the enameled copper wire can conduct without damaging it. Other than that, we can get the diameter of the wire according to the SWG and the resistance per meter of the wire.

Conclusion of Experiment 3

Since we know that the big diameter of enameled copper wire will give more inductance, The SWG that is suitable to use is SWG 16. This SWG is available in the laboratory and the biggest they have. Refer to the appendix for SWG table. According to the SWG table, approximate resistance for this SWG is 8.24x 10^{-3} Ω/m. The current that this wire can hold is 6.23 A at 3 A/mm^2 and 10.38 A at 5 A/mm^2.Please refer to SWG table at appendix 6 for more details.

4.3.4 Experiment 4: To check the effect of iron core to the magnetic field of the inductive loop using DC voltage

Procedure of Experiment 4

- The setup of the experiment was like in the figure below

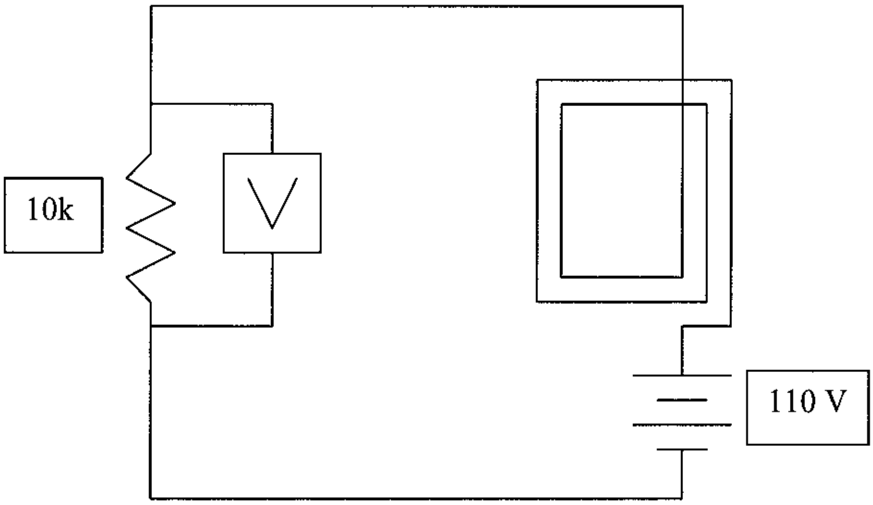


Figure 9: Circuit to check the effect of iron core in DC voltage

- DC supply to the loop is 110V
- Resistance value = 10kΩ

Discussion of Experiment 4

When DC voltage is connected to the circuit, it will generate magnetic field around the loops. When iron core enters the areas of loop, it will change the flux. According to the Lenz law, any changed in the flux linked with a coil (loops) is accompanied by an emf induced in that coil, direction of which always such as to oppose the change responsible for inducing the emf namely growth of current in L. In other words the induced e.m.f. is acting in opposition to the current and therefore to the applied voltage. But since the supply voltage is DC, the inductance of the inductive loops is not big compared to the inductance when an AC voltage used.

Calculation of Experiment 4

We can calculate the inductive reactance of the inductive loops by using the formula:

$$\boxed{X_L = 2\pi f L}$$

By referring to the circuit in experiment 4, we can analyze the effect of voltage supply to the inductive loops.

Using DC voltage

$V = IR$

$V = IR_{copper} + IR$

$V = Ircopper + IR + IX_L$

$V_{DC} = I\,(Rcopper + R + X_L)$

$= I\,(Rcopper + R + 0\,)$

$I = V_{DC} / (R\ copper + R\,)$ .... Equation for DC Voltage

Using AC voltage

$V = IR$

$V = Ircopper + IR + X_L$

$V = Ircopper + IR + 2\pi f L$

$V_{AC} = I\,(X_L + R + Rcopper)$

$I = V_{AC} / (R + X_L + Rcopper)$ .... Equation for AC voltage

For DC Voltage

For DC voltage supply, when an iron core (metal) is placed inside the area of inductive loops, the current I of the circuit is not change. This is because DC voltage not increases the inductive reactance. The frequency, f of DC voltage is zero and thus inductive reactance becomes zero. When this reactance become zero, it will not give any changes to the current, I although an iron core is placed inside the inductive loops.

For AC voltage

Meanwhile for AC voltage supply, the current was changed when an iron core is placed inside the area of inductive loops. The change of current is caused by increased in resistance of the circuit. The formula to calculate the reactance can be used since AC voltage has frequency. Higher frequency of AC voltage will increase the reactance of the circuit thus increase the resistance.

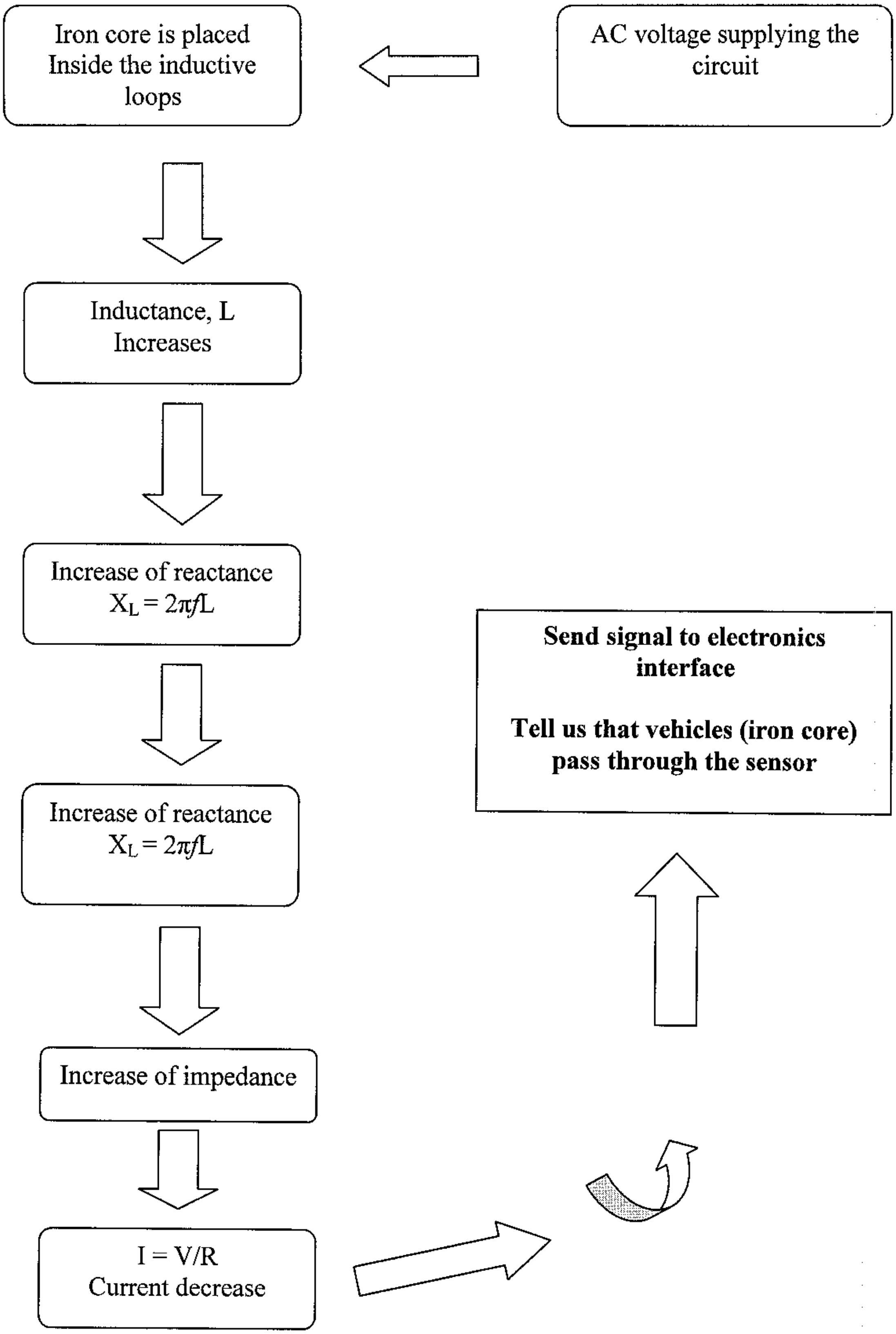
$$\boxed{\text{Impedance of the circuit} = R + R\text{ copper} + X_L}$$

When X_L increases, the impedance of the circuit also increases.
By referring to the formula below:

$$I = V_{AC} / (R+X_L + R\text{copper})$$

Current I of the circuit will decrease when we put iron core inside the inductive loops. This iron core will increase the inductance of the inductive loops. Thus increase the reactance and impedance of the circuit. These changes will act as a detector. When there is a change to the current flowing through the loops, it will indicate that a metal passes the inductive loops.

As conclusion, an AC voltage will be use in this project because it will increase the reactance of the inductive loops. When the reactance is increase, the process of detection will work properly because the present of frequency. Below is flowchart that illustrates the process of detection of vehicles when using an AC voltage.



Flow chart to illustrate the process of detection

4.3.5 Experiment 5: Use a Power MOSFET to drive a high frequency to inductive loops

Procedure of Experiment 5

- The circuit of this experiment is shown below

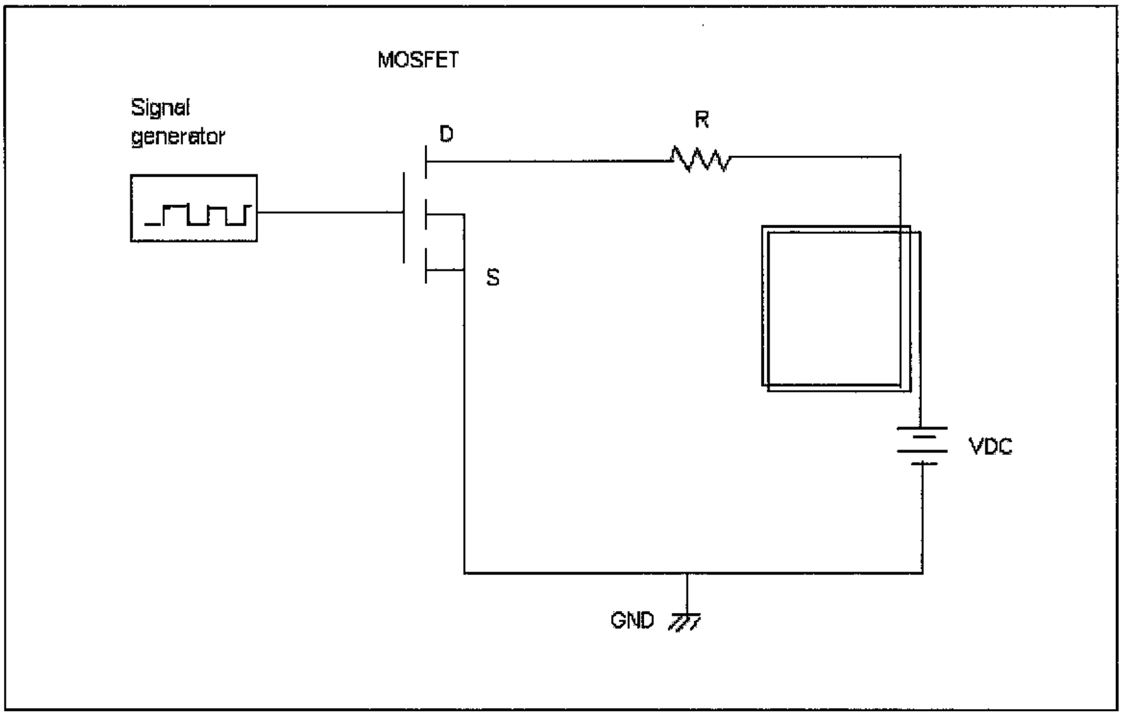


Figure 10: Circuit to check the effect of iron core in AC voltage (high frequency)

Discussion of Experiment 5

Since the main objective of the experiment have been achieved , the next step that need to do is continue with experiment but now using AC voltage supply with high frequency. To get the high frequency, a power MOSFET can be used. This power MOSFET will produce a voltage that contained high frequency and the frequency can be adjusted using signal generator. The IRF 9620 power MOSFET is used. The data sheet for this power MOSEFT is attached in the appendix. Please refer to the data sheet for reference.

The frequency that is suitable to make sure that the sensor will sense or response to the steel object is about 40 – 120 kHz. [12]. The signal generator will supply pulses that can vary the frequency. When it connects to a MOSFET, it will turn on and off the MOSFET simultaneously. This will produce an AC voltage. So to vary the frequency, we have to vary the frequency of the signal generator. After produce an AC voltage with high frequency, Author can check the effect when putting the iron core inside the inductive loops. Since the inductance reactance $X_L = 2\pi f L$, the response should be greater compare to the one we use 50Hz.

Power MOSFET Drives

A power MOSFET drives must be use in order to on the Power MOSFET. This drives circuit is available in the data sheet of the power MOSFET. In this experiment, the IRF 9620 Power MOSFET is used and the drives circuit is presented in the data sheet. The input of this drives is connected to the signal generator and the output of the drives is connected to the inductive loops circuit. Please refer to data sheet in appendix for more details.

Results of Experiment 5

When the power MOSFET drives can produces high frequency, the circuit will detect a vehicles when current flowing inside the circuit changes. The current I changes because the increase of inductance caused by the iron core (vehicles). The change of current can be measured by putting voltmeter parallel across the resistor. When the iron core is inside the inductive loops, the current will decrease causing the voltmeter to decreases too. This voltmeter will measure the voltage across the resistor. By using Ohm's Law, when current decrease, the voltage also decrease. So, when the voltage across the resistor is decrease, this will indicates that a vehicle is inside the inductive loops. As conclusion, the decrease or increase of voltage will tell us whether this circuit is working as sensor or not. This circuit must be connected to one circuit that can response to this change and then send a signal to output. The output can be signaling board or other electronic interface as long as it will indicate that a vehicle is detected.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

5.1.1 Accomplishments

At this stage, the important characteristics of this project have been achieved. The detection of a vehicle using an inductive loop has been achieved. The scope and main procedures to be taken have been finalized. It has been decided that an AC voltage supply will be used as the source voltage. This AC voltage must have a frequency that range from 40 to 120 kHz. Also it has been finalized that the SWG of 16 will be used because it gives the most sensitive response to the presence of metal

A conclusion can be made according to the results of all experiment that have been done. The proper experimental procedures to shows the detection process have been developed. A few experiments have been done to investigate the characteristic and changes when to the inductive loop when iron core is presence. The important part of this project that is detection process has been achieved. To accomplish the project, some further experiments have to be done. Progress will resume to complete the experiments and to further improving it before developing a complete circuit for the sensor.

As conclusion, the first two objectives of this project have been successfully achieved. The first objective, that is to study and design an inductive sensor that can be use to detect vehicle as to monitor and control traffics user have been achieved by author. A circuit that can detect vehicles using inductive loops was built by author and it is called an inductive sensor. The second objectives that is to build an electronic circuit to interface with inductive sensor is still in progress but author will try to achieved it within the period given. To complete the last objectives of this project, author will demonstrate the sensing process of the sensor during the presentation. This working model will show how the sensing process occurred until it will send a signal to tell output indicate that it sense a vehicle.

5.2 Recommendation

To accomplish the second objective the project, some further experiments have to be done. Progress will resume to complete the experiments and to further improving it before developing a complete circuit for the sensor. For now, the circuit of the sensor is still not complete in the part of the indicating the present of vehicles. But the process of detecting vehicle is successfully done. For the future work, the electronic circuit for the detector has to be built. This electronic circuit will receive a signal from the sensor and then send this signal to output indicator. The output might in terms of light, speaker or signaling board. This circuit will be interface with the sensor in order to give a good signal.

I recommend that this project will be continued by new student in next semester since I don't have time to complete it. What they have to do is to complete this project by continuing from where I have done and improve certain part from my project that is not satisfied by supervisors. All the data relevant and literature review that I have done is attached to this report. So I hope that there will be a student who will continue this project for next semester. I hope that this project will successful.

CHAPTER 6

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CHAPTER 7

APPENDICES

Appendix 1

COLLISION COUNTERMEASURES SYSTEMS TASK - PHASE 1 SUMMARY REPORT

1. INTRODUCTION

The purpose of the Collision Countermeasures Systems (CCS) Task is to analyze the roadside infrastructure and traffic impacts of the following CCS:

1. Roadway-mounted friction/ice detection and warning systems.

2. Cooperative warning of the presence of oncoming vehicles on curves.

3. Driver warning on a minor road in the presence of vehicles on a major road.

4. Driver warning on a major road in the presence of vehicles on a minor road.

5. Approaching vehicle warning for drivers making a left-hand turn and warning of vehicles turning left ahead.

The purpose of Phase I of the CCS Task is to collect information on the sensor technologies available or being developed that can be used in the above countermeasures systems, to describe various deployment concepts, and to evaluate the various concepts' impacts on the existing traffic flow and infrastructure.

This document is a summary of the work performed in Phase 1 of this task. Section 2 of this report describes the survey, Section 3 describes the different types of sensors, and Section 4 describes the different deployment concepts. Section 5 discusses the traffic and infrastructure impacts of the deployment concepts described in Section 4, and Section 6 contains conclusions and recommendations.

2. SURVEY METHOD

2.1. Extensive literature search

The survey began with an extensive literature search. The first topic searched was collision countermeasure systems, but as this topic did not yield much information, the more general topics of detectors, sensors, and radars were searched. Relevant technologies for sensors had already been identified as being in the categories of microwave, millimeter wave, and laser radar, along with ultrasonic, piezoelectric, infrared, video, and inductive loop detectors. The literature on these subjects was searched to determine the most up-to-date developments in the field and to determine which technologies would be most useful for the collision countermeasure systems evaluated in this report. During the literature search, another technology which may be useful for collision countermeasure systems was discovered. It is a spread-spectrum wideband radar and will be discussed in Section 3.2.8.

2.2. Phone survey of relevant sensor manufacturers

The telephone survey consisted of determining which manufacturers produced sensors which could be used in the proposed collision countermeasure systems and then requesting data sheets on them. The results of this survey were then to be used to compare the different technologies from a performance and cost benefits perspective. The sensor manufacturers were also asked to supply their opinions on the tradeoffs between the different types of sensor technologies.

2.3. Phone survey of relevant state and local Departments of Transportation

Various Departments of Transportation (DOT's) with experience in the relevant collision countermeasure systems were interviewed to determine the results of their efforts. This ensured that work would not be duplicated and that future work would build on the results and experience of past research. Their opinions on the different advantages and disadvantages of the various sensor technologies were also discussed.

2.4. Phone survey of research institutions

Research institutions with relevant experience were interviewed to ensure that previous work on the collision countermeasure systems to be evaluated in this report could be incorporated and time would not be wasted reproducing existing results.

2.5. Phone survey of auto manufacturers working on related topics.

The survey of auto manufacturers was limited by the fact that not many have ever investigated any roadway-based collision countermeasure systems. However, at least one of the manufacturers (Nissan in coordination with MITI) had implemented one of the systems to be evaluated in this report and a paper describing the system was acquired.

2.6. Summary

A large amount of information was collected through the various surveys described in this section. In addition to that information, a report entitled "Potential Safety Applications of Advanced Technology"1 was provided by the Federal Highway Administration (FHWA), and a working report2 on a project being conducted by Hughes was obtained from Pete Mills of FHWA. The safety report, Reference 1, described many different types of sensor technologies, as well as several collision countermeasure deployment concepts. The Hughes working report, Reference 2, is a very detailed analysis of sensor technologies, and will include the results of extensive testing of the sensors both in the lab and in real world environments. The final data are currently being reduced.

3. SENSOR TECHNOLOGIES

Three different types of sensors are needed for the four collision countermeasure systems to be discussed in this report. They are: friction/ice detectors, vehicle detectors, and speed/acceleration detectors. Table 1 contains the different technologies that can be used for the different collision countermeasure systems.

TABLE 1

SENSOR TECHNOLOGIES AND APPLICATIONS

REQUIRED FUNCTIONALITY	APPLICABLE SENSORS	APPLICABLE COUNTERMEASURE SYSTEMS
FRICTION/ICE	**ROADWAY WEATHER**	**I**

DETECTION	INFORMATION SYSTEMS	
VEHICLE DETECTION	MICROWAVE MILLIMETER WAVE LASER INFRARED VIDEO ULTRASONICS PIEZOELECTRICS SPREAD-SPECTRUM	II, III, IV, V
SPEED / ACCELERATION DETECTION	MICROWAVE MILLIMETER WAVE LASER INFRARED VIDEO ULTRASONICS PIEZOELECTRICS SPREAD-SPECTRUM	V

I. FRICTION/ICE DETECTION AND WARNING SYSTEMS
II. COOPERATIVE WARNING OF THE PRESENCE OF ONCOMING VEHICLES ON CURVES
III. DRIVER WARNING ON A MINOR ROAD IN THE PRESENCE OF VEHICLES ON A MAJOR ROAD
IV. DRIVER WARNING ON A MAJOR ROAD IN THE PRESENCE OF VEHICLES ON A MINOR ROAD
V. APPROACHING VEHICLE WARNING FOR DRIVERS MAKING A LEFT-HAND TURN AND WARNING OF VEHICLES TURNING LEFT AHEAD

3.1. Friction/ice detectors

A friction/ice detector generally refers to the in-pavement sensors used to detect the freezing point at the surface of the roadway, the concentration of chemicals on the surface, and wetness of the surface. The in-pavement sensors are part of a larger roadway weather information system. Many of the pavement sensors measure the surface conditions by measuring the capacitance between two conductors which are almost flush with the surface of the roadway. Moisture on the roadway causes the capacitance to change, and thus the moisture and the concentration of chemicals within it can be estimated by the change in capacitance. The roadway weather information system then combines this information with data from the other sensors about the humidity, dew point, wind, temperature, and other factors to make an estimate of the roadway's present and future condition. Some pavement sensors have several sets of conductors for measuring capacitances. One of the sets of conductors may be heated incrementally. If the sensor originally indicated that the surface was dry, but after heating, it appears wet, the sensor will indicate that there is ice on the surface, and can provide a good estimate of the freezing point at the surface.

The Michigan Department of Transportation has investigated the use of a roadway weather information system built by Surface Systems, Inc. (SSI) for the prediction of preferential icing. Preferential icing describes the case in which ice appears on a bridge before it appears on the roadway. The sensors have proven to be only 20% accurate for this specific case. Therefore, they would not be useful as part of an active warning system for preferential icing. However, they may still be useful for the prediction of normal icing conditions and as part of an active warning system for drivers. An evaluation of the SSI system is contained in Reference 3. Some other systems for pavement surface detection are the Climatronics FRENSOR, the Vaisala DRS12, and AANDERAA Instruments. The Surface Systems, Inc. weather information systems seem to be one of the most widely used systems.

3.2. Vehicle detectors

There is a wide range of sensor technologies available for vehicle detectors. Some of the most common and some developing technologies are described in this section.

3.2.1. Video Image Processors

A video image processor (VIP) is a combination of hardware and software which extracts desired information from data provided by an imaging sensor. This imaging sensor can be a conventional TV camera or an infrared camera. A VIP can detect speed, occupancy, count, and presence. Because the VIP produces an image of several lanes, there is potential for a VIP to provide a wealth of traffic information such as vehicle classification and incident detection. A VIP generally operates in the following manner: the operator selects several vehicle detection zones within the field of view (FOV) of the camera. Image processing algorithms are then applied in real time to these zones in order to extract the desired information, such as vehicle speed or occupancy.

Advantages of VIPs are that they are mounted above the road instead of in the road, the placement of vehicle detection zones can be made by the operator, the shape of the detection zones can be programmed for specific applications, and the system can be used to track vehicles. Disadvantages are the need to overcome detection artifacts caused by shadows, weather, and reflections from the roadway surface. The disadvantages can be overcome through design and installation of the hardware and design of the software algorithms.

The Hughes Report will contain the results of field tests on the Econolite Autoscope 2003, the Computer Recognition Systems Traffic Analysis System, the Golden River Traffic Marksman C-CATS 810, and the Sumitomo IDET-100. Table 2 details the specifications for these VIPS. Laboratory tests have not yet been performed on these systems. The field test results should be useful in quantifying the accuracy and performance of these systems in adverse weather conditions and differing roadway environments. The results may also be used to compare VIPs with inductive loop detectors.

TABLE 2

VIDEO IMAGE PROCESSOR CHARACTERISTICS

Detector	Number of Traffic Lanes Monitored	Speed Measurement Range	Speed Measurement Accuracy	Detection Range	Vehicle Tracking
AutoScope 2003	3	0 to > 80 mph	± 2 mph	46 m (150 ft)	No
Computer Recognition Systems, Traffic Analysis System	3	0 to > 80 mph	± 2 to 5 %	46 m (150 ft)	Yes
Condition Monitoring Systems, Mobilizer	3	0 to > 80 mph	Ñ	46 m (150 ft)	Yes

3.2.2. Infrared Detectors

There are two types of infrared (IR) detectors, active and passive. Active infrared sensors operate by transmitting energy from either a light emitting diode (LED) or a laser diode. An LED is used for a non-imaging active IR detector, and a laser diode is used for an imaging active IR detector. In both types of detectors the LED or laser diode illuminates the target, and the reflected energy is focused onto a detector consisting of a pixel or an array of pixels. The measured data is then processed using various signal processing algorithms to extract the desired information. Active IR detectors provide count, presence, speed, and occupancy data in both night and day operation. The laser diode type can also be used for vehicle classification because it provides vehicle profile and shape data. The specifications for the Schwartz Electro-Optics 780D1000 active infrared radar are contained in Table 3.

TABLE 3

ACTIVE INFRARED DETECTOR SPECIFICATIONS

Detector	Instantaneous Field of View	Vehicle Classification	Speed Measurement Range	Detection Range	Response Time	Flow	Presence Hold Time
Schwartz Electro-	• 2 beams, each 1	Auto or truck	0 to > 80 mph with	1.5 - 15 m	~ 10 ms	0 to > 1800	For as long as vehicle

Optics 780D1000	mrad (El) by 9.5 deg (Az) • Beam separation in El = 10 deg		±1 mph accuracy up to 70 mph	(5 - 49 ft)		veh/h	is in FOV of detector

A passive infrared system detects energy emitted by objects in the field of view and may use signal processing algorithms to extract the desired information. It does not emit any energy of its own for the purposes of detection. Passive infrared systems can detect presence, occupancy, and count. The specifications for the Eltec passive radar systems are listed in Table 4.

Some of the advantages of infrared detectors are that they can be operated during both day and night, and they can be mounted in both side and overhead configurations. Disadvantages are that infrared detectors can be sensitive to inclement weather conditions and ambient light. The choice of detector materials and construction of the system, as well as sophisticated signal processing algorithms, can compensate for the disadvantages.

TABLE 4

PASSIVE INFRARED DETECTOR SPECIFICATIONS

Detector	Detectable Objects	Detection Range	Response Time	Maximum Speed at which vehicles are counted	Hold time
Eltec 842	Bicycle and any motorized vehicle	6.4 - 16 m (21 - 54 ft.)	< 500 ms	45 mph	True presence detector with 6 minutes maximum hold time for vehicles in FOV of detector
Eltec 833	Bicycle and any motorized vehicle	6.4 - 16 m (21 - 54 ft.)	< 500 ms	85 mph	Pulse-type counting operation with count held for up to 4 seconds

The Hughes report will contain the results of laboratory tests of the Schwartz Electro-Optics infrared laser radar detector 780D1000. The laboratory test results will include detector electrical current draw, delay time, engagement range, disengagement range, beam pattern, and operational and functional anomalies. The field tests are designed to quantify the accuracy and performance of the detectors in real-world environments. The data taken by the detectors being tested will be compared with "ground truth", measurements taken with inductive loop detectors, radar guns, and a video camera. Based on this comparison, the accuracy of the detectors will be quantified. There are plans to field test passive IR radars as well if they become available. The passive radars to be evaluated are the Eltec Passive IR Detectors 842 and 833. They were not available for laboratory testing, but are supposed to be tested in the field.

3.2.3. Ultrasonic detectors

Ultrasonic detectors have not become widely used in the United States, but they are very widely used in Japan. Japan uses ultrasonic detectors in traffic applications as much as the U. S. uses inductive loop detectors in traffic applications. There are two types of ultrasonic sensors available, presence-only and speed-measuring. Both types operate by transmitting ultrasonic energy and measuring the energy reflected by the target. These measurements are processed to obtain measurements of vehicle presence, speed, and occupancy.

The advantages of ultrasonics are that they provide all-weather operation, do not need to be approved by the FCC, and provide fixed or portable mounting fixtures above the road. Their disadvantages include their need to be mounted in a down-looking configuration as perpendicular as possible to the target (as opposed to side-mounting), a difficulty in identifying lane-straddling vehicles and vehicles traveling side by side, and susceptibility to high wind speeds. Some of these disadvantages may be compensated for through more sophisticated data processing techniques.

Presented within the Hughes report will be the results of testing the Microwave Sensors TC-30 and TC-30C and the Sumitomo SDU200 and SDU300 ultrasonic sensors both in the laboratory and in the field. The TC-30C and the SDU300 are presence detectors, and the SDU200 also measures the vehicle's speed. The specifications of these detectors are contained in Table 5, which is taken from Reference 2. The SDU200 is designed to operate only with approaching traffic. The laboratory test results will provide information regarding detector electrical current draw, delay time, engagement range, disengagement range, beam pattern, and operational and functional anomalies. The field tests are designed to quantify the accuracy and performance of the detectors in real-world environments. The results will also be used to compare ultrasonic detectors with inductive loop detectors.

3.2.4. Microwave/Millimeter wave radars

Microwave detectors have been used extensively in Europe, but not in the United States. They operate by measuring the energy reflected from target vehicles within the field of view. By processing the information received in the reflected energy, the detectors measure speed, occupancy, and presence.

Some of the advantages of microwave detectors are that they are a mature technology because of past military applications, they detect velocity directly, and a single detector can cover multiple lanes if it is placed properly and appropriate signal processing techniques are used. In addition, FCC approval is not required if it operates in the X-band or Ku-band, and the output powers are within specified limits. Some of the disadvantages are unwanted vehicle detections based on reception of sidelobe radiation, and

false detections due to multipath. Most of these disadvantages can be overcome, in whole or in part, through proper placement of the detectors, signal processing algorithms, and antenna design.

Within the Hughes report will be a presentation of the results of evaluating the Microwave Sensors TC-20, TC-26, and TC-31, the Whelen TDN-30, TDW-10, and Electronic Integrated Systems Remote Traffic Microwave Sensor (RTMS) in laboratory and field tests. Table 6, which was taken from Reference 2, lists some of the specifications for these radar systems. All of the radars operate in the X-band. The laboratory test results will include detector electrical current draw, delay time, engagement range, disengagement range, beam pattern, and operational and functional anomalies. The field tests are designed to quantify the accuracy and performance of the detectors in real-world environments. The data taken by the detectors being tested will be compared with "ground truth", measurements taken with inductive loop detectors, radar guns, and a video camera. Based on this comparison, the accuracy of the detectors will be quantified.

3.2.5. Passive Acoustic Detector Arrays

Another type of vehicle detector is the passive acoustic array. An array of microphones may be used to determine the passage of a vehicle. The signals from the microphones in the array are processed and correlated to obtain information about vehicle passage. The design of the array determines its directionality and field of detection. These types of detectors have not yet been thoroughly investigated, at least in terms of traffic related applications. Video-conferencing companies have been developing sophisticated microphone arrays for their systems, and it is possible that some of their techniques or designs could be adapted to traffic applications.

The results of field tests of an AT&T SmartSonic TSS-1 acoustic detector array will be presented in the Hughes report. The results will be compared with those from the inductive loop detectors and magnetometers in order to judge its accuracy and level of performance.

3.2.6. Piezoelectrics

Piezoelectric detectors are very accurate vehicle detectors, but they do not detect presence of a stationary vehicle, unless it has stopped with its wheels on the detector. The piezoelectric sensor consists of a long strip of piezoelectric material enclosed in a protective casing. It can be embedded flush with the pavement, and when a car passes over it, compressing the piezoelectric material, a voltage is produced. This sets off the controller. The piezoelectric detector has the advantage of indicating exactly when and where a vehicle passed by because it is a line detector perpendicular to the path of the vehicle. A series of two of them may be used to measure vehicle speed. A disadvantage is that for a permanent installation, they must be embedded in the pavement. Every time the roadway is repaved, or if a pothole appears, the sensor would need to be replaced. These types of sensors are not being tested in the Hughes report, but they are currently being tested on the Beltway in Virginia. AMP is a manufacturer of piezoelectric traffic detectors, and Table 7 contains some of the specifications for an AMP piezoelectric traffic sensor.

3.2.7. Photoelectrics

Photoelectric devices commonly consist of two components, the light source and the detector. These may both be in the same place, or placed across from each other. When placed across from each other, the detector is activated whenever something obstructs the illumination from the light source. When placed in the together, the detector is activated when light from the light source is reflected from a target and back onto the detector. There is a dearth of information on these detectors as applied to vehicle detection. They do not appear to be a competitive technology in the field of vehicle detectors at this time.

TABLE 7

PIEZOELECTRIC DETECTOR SPECIFICATIONS

Detector	Output Uniformity	Operating Temperature Range	Temperature Sensitivity	Output Level	Product Life
AMP ROADTRAX Series P	± 20%	-20Ð120¡F	±0.2%/¡F	50Ð1500 mV @ 1MW input impedance	5 million axles typical

3.2.8. Spread-spectrum wideband radars

A new wideband spread-spectrum radar has recently been developed at Lawrence Livermore Laboratory4. It is a significant development because it is very inexpensive and it has extremely accurate range discrimination. It can also penetrate many types of materials, including concrete. It has a range of about 20 feet, so it may be useful as an inexpensive, single-lane vehicle detector. It is predicted that the sensor, when made in production quantities, would cost much less than $10 per sensor. Because of their accurate range discrimination, they have a very well-defined field of detection. They could become a cheap alternative to magnetometer probes. Their ability to detect range provides additional information for future traffic control systems.

In addition, Lawrence Livermore has stated that they are developing a broad-band transmitter/receiver pair to be used with these sensors. This would eliminate the need for communication lines between the sensor and the controller.

3.2.9. Inductive loop detectors

Loop detectors are the most widely used technology for vehicle detection in the United States. A loop detector consists of one or more loops of wire embedded in the pavement and connected to a control box. The loop may be excited by a signal ranging in frequency from 10 KHz to 200 KHz. This loop forms an inductive element in combination with the control box. When a vehicle passes over or rests on the loop, the inductance of the loop is reduced. This causes a detection to be signaled in the control box.

The advantages of inductive loop detectors are that they are an established technology in the United States, they have a well-defined zone of detection, and they are generally reliable. Disadvantages are that the detectors are very sensitive to the installation process, they can only be installed in good pavement, and they must be reinstalled every time a road is repaved.

The Hughes report will contain only the results of field tests of inductive loop detectors. The loop detectors tested will be 3M microloops. The results will mainly be used as a point of comparison for the results from the other types of detectors, because inductive loop detectors are much like a standard in the United States. Sarasota is also a manufacturer of inductive loop detectors, and Table 8 displays some of their characteristics.

TABLE 8

CHARACTERISTICS OF INDUCTIVE LOOP DETECTORS

Detector	Frequency	Sensitivity	Presence Time	Inductance Range
Sarasota 215B	Provides frequency separation for adjacent loops	3 ranges Maximum 0.02% change in inductance	Maximum exceeds 1 hour for 1% change, 2 minutes for 0.05% change in loop inductance	20 Ð 700 mH
Sarasota 515A	Provides frequency separation for adjacent loops	3 ranges Maximum 0.02% change in	Preset to 2 hours, can be changed to 4 minutes	20 Ð 2000 mH

		inductance		

3.2.10. Magnetic Detectors

There are two other types of magnetic detectors which are used to detect traffic. Both of them are in the form of probes, and they both operate on the principle of a large metal object disturbing a magnetic field, just as inductive loop detectors work. There are both active and passive types. The active type is called a magnetometer. A magnetometer acts in much the same way as an inductive loop detector, except that it consists of a coil of wire wrapped around a magnetic core. It measures the change in the magnetic field caused by the passage of a vehicle. It can be used both for presence and for vehicle passage detection.

The passive type of detector simply measures a change in the flux of the earth's magnetic field caused by the passage of a vehicle. These detectors can only detect moving vehicles, so they cannot be used as presence detectors. They have a fairly large detection range and thus can be used to observe multiple lanes of traffic.

The advantage of both of these types of magnetic detectors is that they can be used where point or small-area location of a vehicle is necessary. For example, on a bridge, inductive loop detectors would be disrupted by the steel struts, and it is necessary to have a point detector. One of their disadvantages is that multiple detectors need to be installed to detect smaller vehicles, such as motorcycles.

The results of field tests of these detectors will be contained in the Hughes report. A Midian Electronics Self Powered Vehicle Detector will be evaluated and the results will be used along with the results from the inductive loop detector as a standard by which the aboveground detectors may be compared.

3.3. Acceleration detectors

For the left-turn collision countermeasure system, it is necessary to determine the acceleration of the vehicle, so that it can be determined whether or not the vehicle is slowing to make a left turn. Using Doppler information, the range rate of a vehicle may be determined, but it does not appear that any radars currently being marketed for traffic applications measure the range rate. A simple method is to have three detectors in a linear formation. Measurements from these three detectors will provide an approximation of the acceleration of the vehicle from which the system may determine whether or not to activate the left-turn ahead warning.

3.4. Projected technologies

The spread-spectrum wideband radar is a technology that could become established in the vehicle detector market. However, it is likely that inductive loop detectors (U. S.) and ultrasonic detectors (Japan) will continue to dominate the vehicle detector market and will remain the most popular form of vehicle detector technology. The final results of the Hughes report should be useful in making more accurate projections of which technologies will continue to be used and developed. Table 9 lists the majority of the sensors with their advantages and disadvantages.

4. DEPLOYMENT CONCEPTS

This section provides a brief description of the different deployment concepts which were evaluated in this task.

4.1. Friction/ice detection and warning systems

This system should consist of a sensor system to detect the condition of the pavement surface and an active warning sign to provide a speed advisory. The sensor system should be implemented so that it measures the condition of the roadway surface at the point where the vehicle is most likely to drive. Most pavement sensors detect a very small, localized area, so they should be placed in the wheel tracks wherever possible in order to provide an estimate of the relevant surface conditions. A simple processor can then use the information about the condition of the pavement in combination with the known curvature, gradient, and dry-pavement friction coefficient to calculate an advisory speed. This speed would then be displayed on the active warning sign.

The processor should have some kind of limiter to prevent advising a speed greater than the maximum advisable for that area. It might be useful if it had a set of speed bins from which it could select an advisory speed. It may also be necessary to have a separate speed advisory for trucks. The normal difference in speed limits between cars and trucks is 10 mph. However, in the case of a slippery road, the truck is likely to retain more friction than a car, and thus its advisory speed may not have to be reduced as much as that for

TABLE 9

SENSOR ADVANTAGES AND DISADVANTAGES

SENSOR	ADVANTAGES	DISADVANTAGES
MICROWAVE / MILLIMETER WAVE RADAR	**• Mature technology** **• Detect velocity directly** **• Multi-lane coverage** **• No FCC approval required if operating in X-band or Ku-band and power limits are met**	**• Sidelobe radiation** **• Multipath**

INFRARED	**• Day and night operation** **• Overhead and side mount configurations**	**• Sensitive to inclement weather** **• Sensitive to ambient light**
VIDEO IMAGE PROCESSOR	**• Roadway mounted** **• Variable detection zones** **• Vehicle tracking** **• Vehicle identification**	**• Detection artifacts caused by shadows, weather, and reflections.**
ULTRASONIC	**• All-weather operation** **• No FCC approval necessary** **• Fixed or portable mounting**	**• Mounting configuration needs to be perpendicular to target** **• Difficult identifying lane-straddling vehicles and vehicles traveling side by side.** **• Susceptible to high wind speeds**
PIEZOELECTRIC	**• Precise detection zone** **• Portable or fixed installation**	**• Embedded in pavement**
SPREAD-SPECTRUM	**• Very inexpensive** **• Aboveground installation** **• Accurate range discrimination**	**• Short range of detection**
INDUCTIVE LOOP DETECTOR	**• Mature technology** **• Well-defined detection zone** **• Accurate for counting**	**• Embedded in pavement** **• Sensitive to installation process**
MAGNETOMETER	**• Small and useful for bridges where loops won't work** **• Portable or fixed installation**	**• Embedded in pavement**

the car. This will have to be investigated more thoroughly before an actual advisory speed processor is designed.

Another possible implementation of a friction/ice detection and warning system would be to include some type of vehicle speed detector. Then, after the system makes an estimation of what the safe speed should be, it can choose whether or not to illuminate a sign saying "SLOW DOWN" based on the oncoming vehicle's speed. This would make it necessary to have a detector which measures speed, and thus adds to the complexity. However, radar sensors can detect both presence and speed, so it is possible that one radar could be used for both. Figure 1, obtained from Reference 1, illustrates the deployment concept.

The major equipment for use in this countermeasure system is: pavement sensors to cover as much of the pavement as possible and an active warning sign. This assumes that the system has access to a complete weather information system of which the pavement sensors are only a small part. The following is a summary of the potential friction/ice detection systems:

1. Use a pavement sensor to determine the condition of the pavement. Once the condition of the pavement has been determined, calculate an advisory speed and provide it to the warning sign. The sign will then determine what type of message to provide, i.e., "SLOW DOWN", or "BRIDGE MAY BE ICY," or the advisory speed.

2. Use a pavement sensor to determine the condition of the pavement. Define a class of "dangerous" conditions, and have a signal asserted if any of those conditions is met, such as icy, or wet. Supply this signal to the warning sign.

3. Same as 2, but generate an advisory speed for the dangerous condition and supply the speed to the warning sign controller.

4. Same as 1, but also use another detector to calculate vehicle speed. Supply this speed to the controller. Controller can then decide what type of warning, if any, to provide, based on a comparison of the advisory speed and the actual speed.

5. Same as 3, but also use another detector to detect vehicle speed and supply this data to the warning sign controller. Controller then decides what to do based on comparison of advisory speed and actual speed.

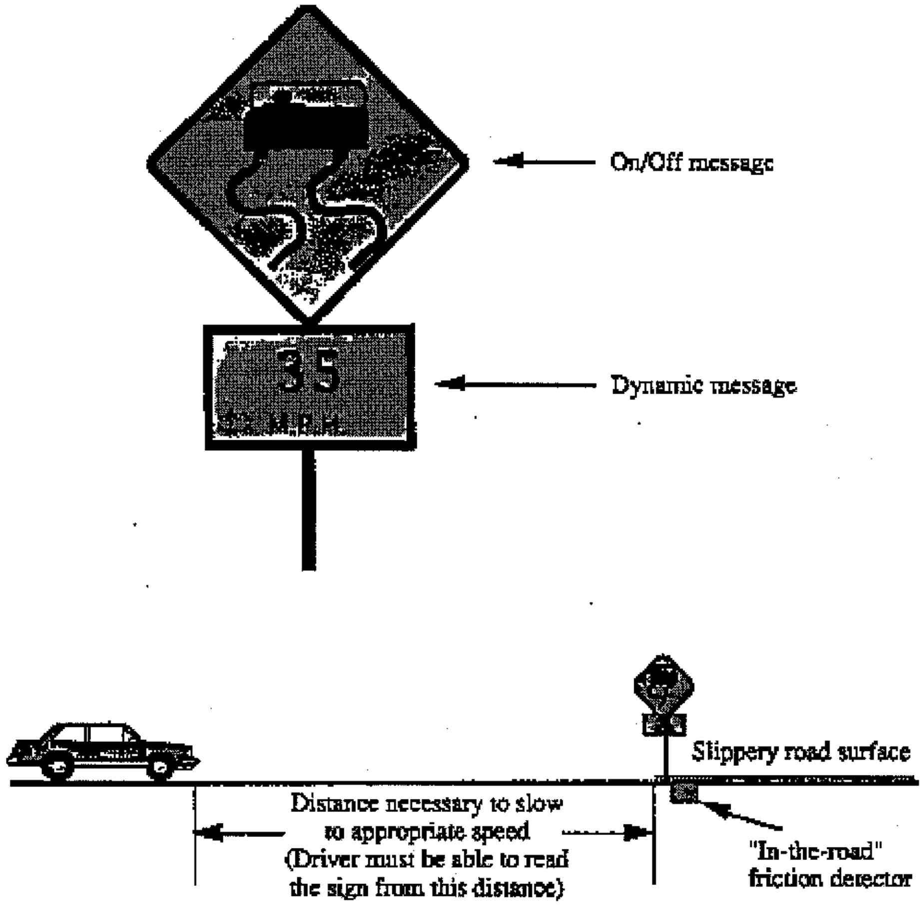


Figure 1. Road layout with an in-the-road friction detector.

4.2. Cooperative warning of the presence of oncoming vehicles on curves

A collision countermeasure system of this type is currently in operation in Japan. It has undergone extensive testing on a test track and has now been installed in actual portions of the highway. The name of the system is Guidelight. One of the Guidelight systems consists of a series of lights around the curve and an ultrasonic detector on each end of the curve. When a vehicle is detected, the lights are activated ahead of the vehicle at a rate dependent on the speed of the vehicle. The lights warn the driver of another vehicle entering the curve from the opposite direction that there is an oncoming vehicle. It is described in detail in References 5Ð8. The ISO standard being developed for "cooperative warning of the presence of oncoming vehicles on curves" is based upon the Guidelight system, so Guidelight may become the standard collision countermeasure system for this type of warning. Figure 2 shows an example of the Guidelight system, and is taken from Reference 1.

Activated by ultrasonic vehicle detectors

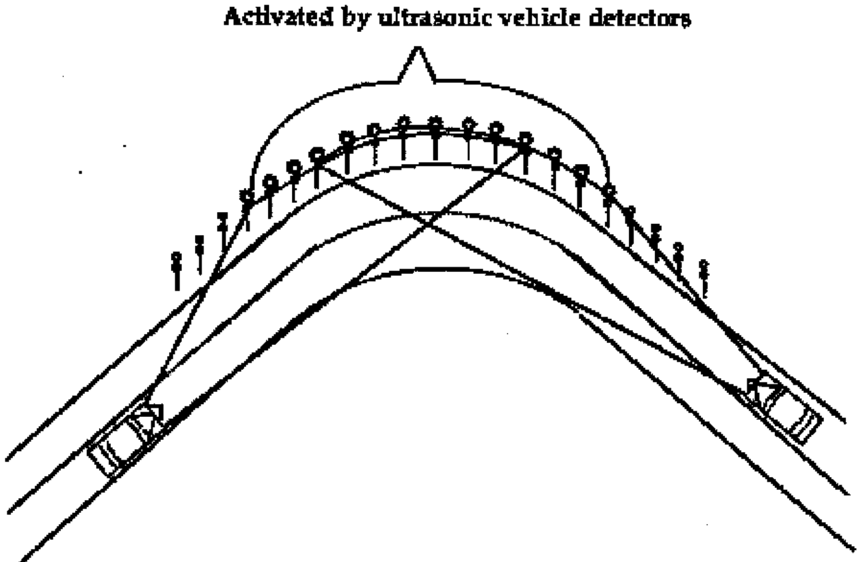


Figure 2. Schematic for Guidelight system on curves.

Figure 2. Schematic for Guidelight system on curves.

Another possible collision countermeasure system is proposed in Reference 1. It would consist of a pair of warning signs which would be activated as soon as a vehicle enters the curve in order to warn vehicles traveling in the opposite direction. A possible active warning sign would have two flashing lights on top and depict a two-way traffic road (assuming there are only two lanes) with a car in the oncoming lane. Both the flashing lights and the representation of the car will flash when the sign is activated. Figure 3 illustrates the deployment concept, and Figure 4 shows a possible active warning sign. Both figures are taken from Reference 1.

The major equipment for this countermeasure system is: vehicle detectors and a series of lights if using the Guidelight system or at least 2 warning signs if using the system described above. For hilly areas the sign could depict a straight lane with a car lighting up in the oncoming lane.

The following are possible deployment concepts:

1. In the simplest system, there should be at least 2 sensors and 2 signs. The two sensors are used to detect a vehicle entering the curve, and the active warning signs are placed inside the curve. This prevents the case of both cars entering at the same time and then passing the signs before they are activated.

2. Another option is to have four warning signs, two at the entrances to the curve and two along the curve. One set of signs should be set a good distance ahead of the curve on either side, in order to give the drivers enough advance warning that another car has entered the curve in the oncoming lane. The other set of signs should be set right within

the curve so that cars that have passed the advance warning sign will still be notified if another car has just entered the curve.

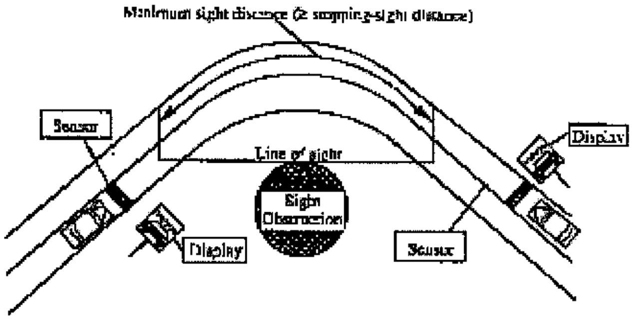


Figure 3. Schematic of a limited sight curve with a single sensor-sign pair.

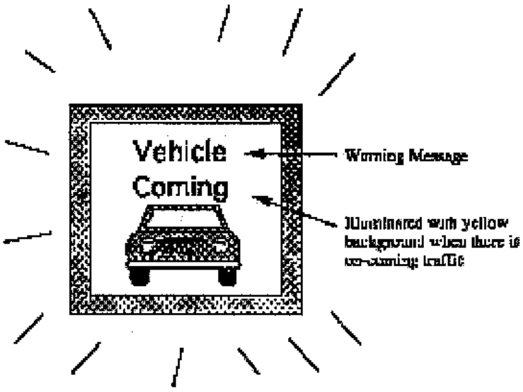


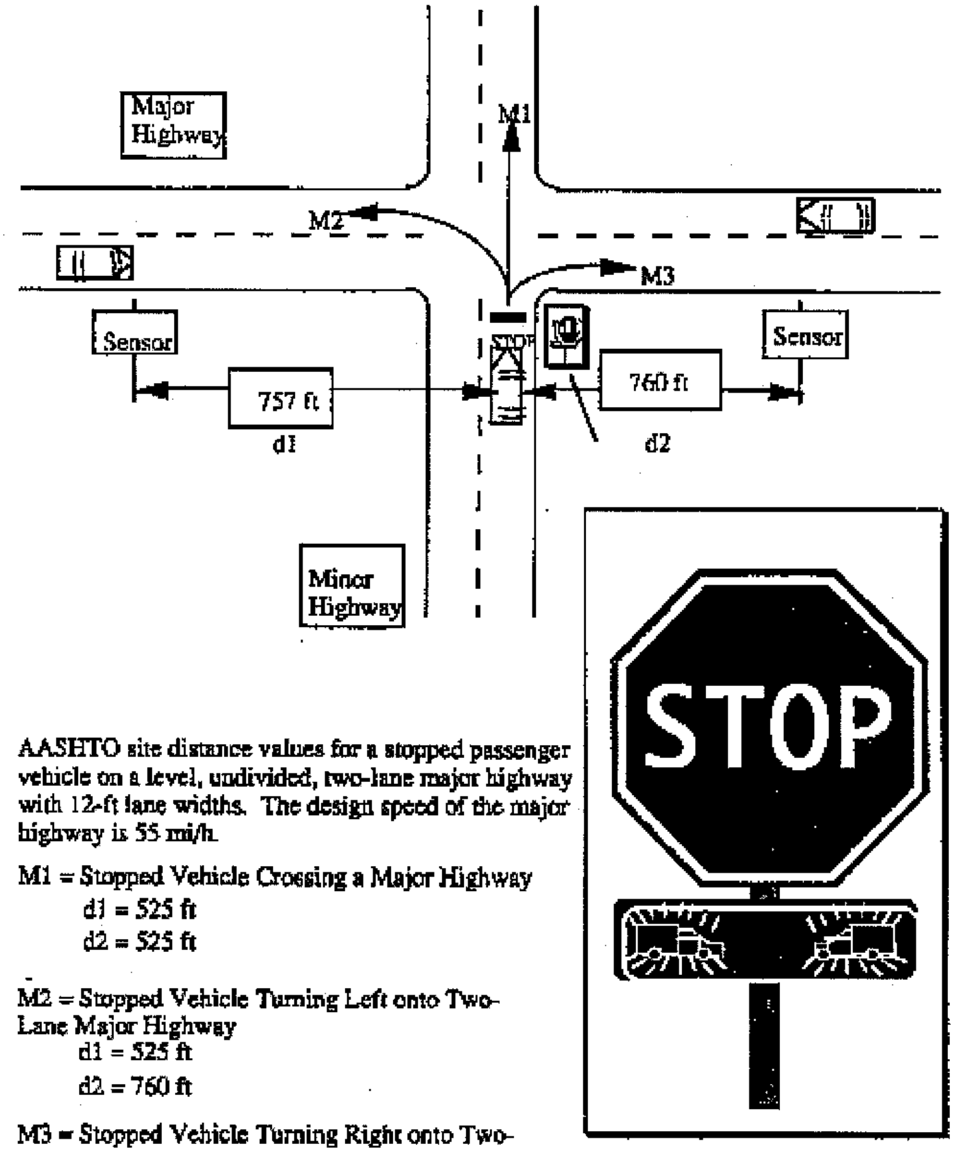
Figure 4. Warning sign on a limited sight curve.

4.3. Driver warning on a minor road in the presence of vehicles on a major road

This system is designed to enhance the driver's ability to assess the safety of entering an intersection on a major road from a minor road. There would need to be an active warning sign for the drivers on the minor road, and detectors to detect vehicles on the major road. A system of this type has already been implemented in Japan as part of the Guidelight program. A similar system is described in Reference 1.

A basic system would have two active warning signs, one on each approach to the major road. The signs should indicate not only that a car is approaching on the major road, but also from which direction.

There will also need to be as many detectors as there are lanes on the major road, and they will need to be a sufficient distance away such that the warning can be given in an adequate amount of time. The signs should be visible to the car on the minor road until he actually makes the turn. Thus, if it is in the position of most stop signs, it may not be visible as the vehicle prepares to make a turn, so there is the possibility that a vehicle appears right after the driver has moved passed the sign. In Japan, in a "T" intersection, they have placed the sign across the road, so there is no possibility of not being able to see it because of preparation for a turn. That may well be the optimum placement. The major equipment needed for this countermeasure system is: vehicle detectors for every lane on the major highway and at least one active warning sign. Figure 5 provides a detailed illustration of this deployment concept. Figure 5 was taken from Reference 1.



AASHTO site distance values for a stopped passenger vehicle on a level, undivided, two-lane major highway with 12-ft lane widths. The design speed of the major highway is 55 mi/h.

M1 = Stopped Vehicle Crossing a Major Highway
d1 = 525 ft
d2 = 525 ft

M2 = Stopped Vehicle Turning Left onto Two-Lane Major Highway
d1 = 525 ft
d2 = 760 ft

M3 = Stopped Vehicle Turning Right onto Two-Lane Major Highway
d1 = 757 ft

1 ft = 0.305 m, 1 mi/h = 1.61 km/h

Figure 5. Warning drivers on a minor road of the presence of vehicles on a major road.

4.4. Driver warning on a major road in the presence of vehicles on a minor

road

This implementation will be similar to that for the previous collision countermeasure system except that it is the vehicles on the major road that will be warned. The detectors will need to be placed on the minor road sufficiently far back to provide adequate warning to the driver on the major road. If there is a stop sign at the intersection on the minor road, then a detector could probably be placed in the intersection and right before the stop sign. If there is only a yield sign, it may be appropriate to place the vehicle detector farther back along the minor road. The sensors in the middle of the intersection should remain in either case.

The detectors will provide information as to whether there is a vehicle on any of the minor roads, and whether or not there is a vehicle in the middle of the intersection. The detector in the middle of the intersection needs to discriminate between cars crossing the intersection from the side road and cars crossing with the flow of traffic. A variety of sensor configurations can accomplish this. One radar sensor can detect directionality, and two piezoelectric sensors could also determine directionality. A smart controller would combine the information from all of the detectors to determine where the vehicle that has entered the intersection has come from. The major equipment needed for this countermeasure is: vehicle detectors to detect the vehicles on the side roads and in the intersection, and at least 2 warning signs. Figure 6 illustrates the deployment concept, and it was taken from Reference 1.

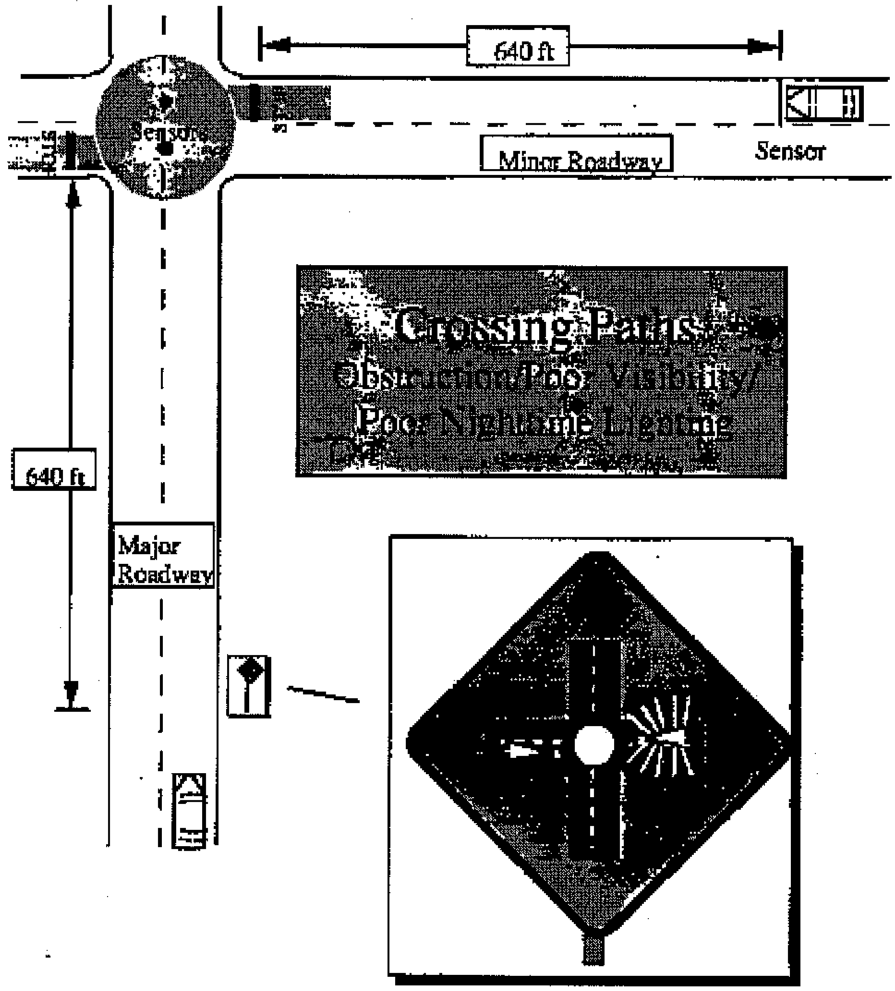


Figure 6. Warning drivers on a major road of the presence of vehicles on a minor road.

4.5. Approaching vehicle warning for drivers making a left-hand turn and

warning of vehicles turning left ahead

This system needs to perform multiple functions. First, it must identify that a vehicle is slowing down to make a left turn. It then needs to determine whether or not there is enough time to make the left turn based on the speed and location of oncoming traffic, and to activate an active warning sign appropriately.

The system must also activate a warning sign for vehicles following the driver making the left turn. An additional option is to have another sign to warn the oncoming traffic that a vehicle is making a left turn ahead. Sensors are needed to detect the acceleration of the vehicle that will be making the left turn, to detect the vehicle if it is still waiting to make a left turn, and to detect vehicles in the oncoming traffic lanes.

The most challenging aspect of this concept is to detect that a vehicle is slowing to turn left. Doppler radars can measure the range rate directly, whereas inductive loop detectors and spread-spectrum wideband sensors need to take multiple measurements and integrate them.

In an example multiple detector system for detecting the acceleration of a vehicle, a central controller would observe the timing between successive activations of the detectors. When the spacing increases above a certain threshold and indicates a predetermined amount of deceleration, the controller activates the left-turn ahead warning signal. The left-turn ahead signal will stay activated for a preset amount of time before turning off. If a speed threshold is used instead of an acceleration detector, the central controller should use memory of the most recent average speed so that the current speed can be checked against that. This would allow the system to adjust to changes in the flow of traffic. Figure 7 contains a schematic of a possible implementation of this deployment concept. It was taken from Reference 1.

The major equipment needed for this collision countermeasure system is: vehicle detectors to calculate acceleration and presence of vehicle waiting to turn left, vehicle detectors for the traffic in the oncoming lanes, one controller, and four active warning signs.

The following are three potential implementations of this collision countermeasure system:

1. A series of sensors can be set up to measure the acceleration of the vehicle. If it is decelerating at a rate greater than some threshold, then the left turn-ahead sign can be activated. In addition, there should be another sensor in the area where the vehicle would be turning left. If the sensor detects a stationary vehicle in this area, then it will also activate the left-turn ahead warning sign.

2. If congestion reaches high levels, then determining whether or not a car is slowing due to congestion or to make a left turn is more complicated. In this case, a sensor to detect slowing and a sensor to detect a stationary vehicle in the left turn position can be installed. The sensor which triggers based on a deceleration level can be deactivated in cases of heavy congestion, and so can the sensor which triggers on a stationary vehicle.

3. If there is a stop-light ahead of the left turn area, the same setup that is in example 1 can be used, but the information about the phase of the stop light should be used when deciding whether or not a car is decelerating to make a left turn.

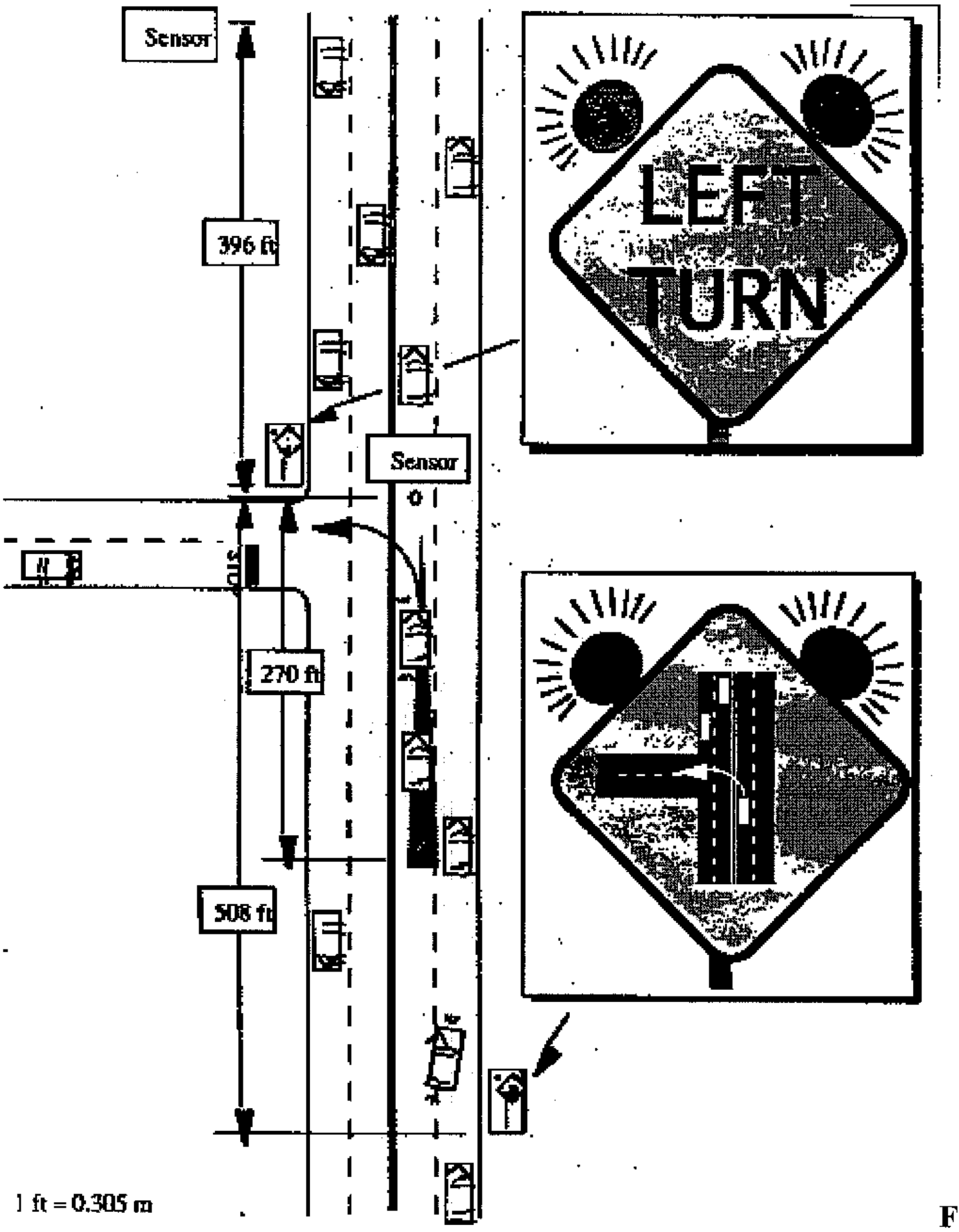


Figure 7. Approaching vehicle warning for driver making a left-hand turn and warning of vehicle turning left ahead.

5. TRAFFIC AND INFRASTRUCTURE IMPACTS

The systems discussed in this report are safety oriented systems and apply only in very specific circumstances, so it is unlikely that they will have any significant traffic flow impacts. The main traffic impact should be a reduction in the number and severity of accidents. The infrastructure impacts will be much greater, especially in the areas of installation and maintenance of the systems, and liability.

5.1. Friction/ice detection and warning systems

5.1.1. Traffic Impacts

An active friction/ice detection and warning system is a safety countermeasure system, so it is unlikely to impact the flow of normal traffic. Its main benefit is that it may reduce the number and severity of accidents occurring on icy roads.

5.1.2. Infrastructure Impacts - Installation and Maintenance

The cost of the equipment and the cost of the maintenance of the system is prohibitive if used exclusively for a friction/detection system. The friction/ice detectors are really part of a road weather information system. If the sensors serve the double purpose of providing information to the road weather information system and to active warning signs, it becomes much more cost effective. Many of roadway weather information systems have been installed throughout the world. For example, about ten of these systems have been installed by the Michigan Department of Transportation. They cost about $60,000 per installation. In addition, they have 1 man spending about 80 percent of his time year round to maintain the installations. The costs of running the system are generally paid for by the savings in deicing chemicals and reduction in overtime payments due to more accurate predictions of the road surface conditions.

5.1.3. Infrastructure Impacts - Liability

Any system designed to warn the driver of potentially dangerous pavement conditions must be very accurate to avoid the possibility of frequent lawsuits. Information obtained from Leo Defrain of the Michigan Department of Transportation indicates that using these systems to detect preferential icing on bridges is not reliable enough for an active warning system, though it may be accurate enough for active warning signs on normal roadways. Preferential icing on bridge decks is the situation in which ice forms on the deck of the bridge before it forms on the roadway. Leo Defrain has been studying detection systems for preferential icing on bridge decks at about 10 sites in Michigan. During the situations when it is essential for the system to be accurate, i.e. during preferential icing, it only operates correctly 20% of the time. This is unacceptable in any warning system because of the liability involved.

On the other hand, pavement conditions of a normal roadway are more uniform than in the preferential icing environment. The roadway weather information systems have proven to be successful in the prediction of roadway surface conditions in general and may be accurate enough for an active warning sign system.

A discussion of liability issues must really focus on the event of a real or perceived failure of the system from the driver's point of view. There are several ways in which the system could fail. It could indicate ice on the road when there wasn't, it could not indicate ice when there was, and if there were a power failure, it would indicate nothing. In any of these cases, the driver who is in an accident near one of these signs could easily sue the state.

Leo Defrain provided several examples of court cases involving road pavement conditions and the responsibility of the state in making the driver aware of them. In the first example, the types of signs used to warn of potential icing of bridges had to be changed. The original sign stated, "WATCH FOR ICE ON BRIDGE," but a driver who had an accident on the bridge sued the state based on the argument that a driver could not have watched for ice on the bridge and driven at the same time without getting in an accident. Therefore, the signs were changed to "BRIDGE MAY BE ICY".

In the second example, a major interchange that has a curve with limited sight distance in addition to being a bridge was the sight of many accidents. The bridge had two signs, one saying "LIMITED SIGHT DISTANCE, SLOW TO 45 MPH" and the other saying "BRIDGE MAY BE ICY". However, a Judge ruled that the state was responsible for warning the cars driving around the curve of stopped vehicles ahead, or else of proving that that was an impossible task.

In the third example, there was a 1.5 mile bridge with "BRIDGE MAY BE ICY" signs on either end. A driver had an accident in the middle of the bridge and said it was because he had forgotten that he was on a bridge. Therefore, the state had to put up three signs along the length of each side of the bridge to remind the driver that he was still on a bridge and that it still might be icy.

The last example again deals with a "BRIDGE MAY BE ICY" sign. It was argued that because the sign was up all year, drivers ignored it and thus could cause accidents on the bridge.

Clearly, the liability issues involved here must be fully evaluated before any of these systems are implemented. As a general rule, Mr. Defrain said that a reliability of at least 90% is desirable in any warning system. Considering the liability issues of this particular system, a reliability of 99% or greater would be best.

The above examples also indicate the importance of clearly conveying the warning to the driver through the sign, which is a human factors issue. The advent of active warning signs raises the issue of the average driver's assumption that when the warning sign is off, it guarantees safety. This is not the intended use of an active warning sign, but it is highly probable that it will often be misinterpreted in this manner. Thus, any active warning system will most likely need to err on the side of caution to ensure that there are no missed vehicle detections. This should minimize the number of lawsuits arising due to assumptions that the off state of an active warning sign guarantees safety.

5.2. Cooperative warning of the presence of oncoming vehicles on curves

5.2.1. Traffic Impacts

This collision countermeasure system is intended to reduce the number of accidents around blind curves, so its only potential traffic impact is a change in the number of collisions around blind curves.

5.2.2. Infrastructure Impacts - Installation and Maintenance

Both of these systems should be relatively inexpensive. The system described in this report may be cheaper because it does not require a sensor for speed and has fewer components than the Guidelight system. The Guidelight system has many more components to service because it consists of a string of lights around a curve, whereas the system described in this report only uses a maximum of four signs. The Guidelight system requires no cutting of the pavement because it uses ultrasonic sensors and the light elements are mounted along the guardrail. The other system may not require any cutting of the pavement either, depending on the type of sensor chosen.

5.2.3. Infrastructure Impacts - Liability

This is the most important consideration. As always, there is the potential for a suit for every malfunction or perceived malfunction of the system. Interpretation of the meaning of the active warning signs in the one system and the lights in the Guidelight system could lead to some initial difficulties. However, tests on the Guidelight system indicate that most drivers were able to understand their use or at the very least, they did not misinterpret them in a such a way as to cause an accident.

When using active warning signs, it is important to clearly convey the warning to the driver. Unless the warning sign is very clear, the driver may think that only one car is permitted to enter the curve at a time, and thus he may stop and cause a rear-end collision. This should not happen once drivers become accustomed to the sign. Because of the many possible interpretations of a sign, the simpler implementation of lights in the Guidelight system may be best.

5.3. Driver warning on a minor road in the presence of vehicles on a major road

5.3.1. Traffic Impacts

The goal of this collision countermeasure system is to reduce the number of accidents at intersections of a minor and major road. Thus, the traffic impact is hoped to be a reduction in the frequency and severity of accidents at these types of intersections. It should not have a significant effect on the traffic flow patterns unless widespread use in an urban environment is achieved.

5.3.2. Infrastructure Impacts - Installation and Maintenance

The installation of this system will require the installation of vehicle detectors in every lane of the major road, and they will need to be connected to the active warning signs on the minor road. The elements of this system are well known, so there should not be any significant or unusually high costs for the implementation of this system.

5.3.3. Infrastructure Impacts - Liability

In this collision countermeasure system it is particularly important that drivers do not interpret the unactivated signs as a guarantee that the intersection will be clear. The signs are meant to encourage the driver to look more carefully for oncoming traffic, not for the driver to blindly trust in the signs and to cross the intersection. However, someone will probably make the assumption that since the signs were not activated, the intersection was clear, and try to cross it and perhaps run into another vehicle. The probability of a missed detection in combination with a driver on a minor road crossing the intersection without looking anywhere except the signs should be estimated. It may be low enough to be tolerable. The government's responsibility for the drivers' safety in such a system should be investigated thoroughly, as well as the government's liability in the case of a malfunction of the system.

Visibility at the intersection can greatly affect the usefulness of these devices. If the driver on the minor road can see far enough in both directions on the major road, then the driver can easily discount a false alarm. In cases where visibility is at least somewhat restricted, false alarms become very important and need to be minimized, because the driver is putting his trust in the reliability of the sensors and the party responsible for the system could be liable for any errors. The warning signs are mainly designed to cause the driver to look again in cases where he may not have been very observant.

If drivers begin to take the fact of the signs in the inactive state as an indication that there is no oncoming traffic, then these signs would tend to increase the likelihood of an accident. For example, drivers who are in a hurry and who are approaching a major road from a minor road and who see that the sign is not activated may assume that the road is clear and attempt to cross it. If one of the sensors had failed, then there is potential for a fatal accident. Because some drivers depend on signs and not on their own powers of observation, when a sign fails, especially an active warning sign, many accidents could occur. When an active warning sign fails, it is not necessarily clear that it has failed, as in the case of a stop-light, so it can be a lot more dangerous.

5.4. Driver warning on a major road in the presence of vehicles on a minor

road

5.4.1. Traffic Impacts

This collision countermeasures system is also designed to reduce the number of accidents at the intersections of minor and major roads. It is not expected to affect traffic flow.

5.4.2. Infrastructure Impacts - Installation and Maintenance

The installation and maintenance of this system should be straightforward. Vehicle detectors need to be installed on the minor roads and connected to the active warning signs on the major roads. Any maintenance required should be minimal as the systems will need to be highly reliable.

5.4.3. Infrastructure Impacts - Liability

The liability issues in this countermeasure system are just as important as in the previous countermeasure system. In this case, a missed detection can result in the driver on the major road running into a driver from the minor road who has entered the intersection. Of course, this assumes a lack of visibility or the driver's assumption that a sign in the off-state guarantees that the intersection is clear.

5.5. Approaching vehicle warning for drivers making a left-hand turn and

warning of vehicles turning left ahead.

5.5.1. Traffic Impacts

This collision countermeasure system is designed to reduce the number of crossing-path accidents for vehicles making left turns. The warning of a vehicle waiting to turn left ahead is intended to make the drivers aware that they need to either slow down or change lanes. However, it probably will not impact traffic flow, because most drivers tend not to merge until necessary, especially in heavy traffic.

5.5.2. Infrastructure Impacts - Installation and Maintenance

The system will need several sensors to be installed to detect vehicles and to detect acceleration, as well as a simple processor to calculate the acceleration and to decide whether or not the car is slowing to turn left. The costs of installation could vary depending on the type of highway involved. If there is a median, sensors could be installed in the median, minimizing the interruption of traffic flow for both installation and later maintenance. If there is no median and no overhead mounting area, sensors will need to be embedded in the pavement. This involves considerably more cost and a disruption of the flow of traffic.

5.5.3. Infrastructure Impacts - Liability

Again, there is the problem of how an unactivated sign will be interpreted by the general driving public. A sign in the unactivated state does not guarantee that there is no oncoming traffic. This system and the previous system have the greatest potential for fatal accidents in that both of them are meant to aid drivers in crossing oncoming traffic. In both cases, if the driver depends exclusively on the signs, which would be an inappropriate use of them, he may cause a serious accident.

6. CONCLUSION AND RECOMMENDATIONS

This report has presented an overview of available sensor technologies for friction/ice detection, vehicle detection, and acceleration detection. A description of the five collision countermeasure systems and a summary of possible traffic and infrastructure impacts has been presented as well. Information contained in this report included data from References 1 and 2.

For the friction/ice detection sensors and the cooperative warning around curves countermeasure systems, the following are recommended for Phase 2 of the CCS task:

- **Monitor developments in implementation**

- **Monitor test results**

- **Monitor development of new sensor products**

These recommendations are based on the fact that both friction/ice detection sensors and cooperative warning around curves countermeasure systems (Guidelight) have been implemented and are being tested in the field.

The rest of the CCS are mainly concerned with intersection warnings. For these CCS, the following are recommended for Phase 2 of the CCS task:

- **Determine possible scenarios** Ñ Use maps to determine locations of intersections where these CCS apply and use data from NHTSA to determine which intersections could benefit most from the CCS, based on the number of incidents.

- **Develop system options** Ñ Drawing from the deployment concepts presented in this report, develop candidate systems which meet the specific needs of each scenario. Compare systems based on different detector technologies, determining which technologies or combination of technologies provide the best system performance in each scenario.

- **Perform first level cost analysis** Ñ For each system, analyze the costs for installation and maintenance.

- **Performance analysis** Ñ Parameterize the performance of the proposed systems based on the differing sensor technologies. Incorporate data from the Hughes report when it becomes available.

- **Recommend operational tests** Ñ Recommend operational tests for the most likely systems. Possibly incorporate the recommended tests into existing operational tests.

A final recommendation for Phase 2 is that the spread spectrum sensors described in Section 3.2.8 be investigated for potential application as traffic sensors. However, prototypes of the sensor will not be available for experimentation until sometime in 1995, so it may not be possible to experiment with them before the completion of Phase 2.

From the Phase 2 report, it will be possible to determine, for a given intersection and CCS, the best combination of sensor technologies to apply, where and how to deploy them, and the costs for installation and maintenance of the CCS. The Phase 2 report will incorporate the results from Reference 1 when they become available, using them to help determine which sensor technologies best meet the needs of each scenario and CCS.

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CHAPTER 6

INDUCTANCE

INTRODUCTION

The study of inductance is a very challenging but rewarding segment of electricity. It is challenging because at first it seems that new concepts are being introduced. However, these new concepts are merely extensions of the fundamental principles in the study of magnetism and electron physics. The study of inductance is rewarding because a thorough understanding of it will enable you to acquire a working knowledge of electrical circuits more rapidly. The Army marine engineer field is the only military occupational speciality that requires an individual to show a working knowledge of electricity, from the production and supply, through the maintenance and overhaul, to the user-end operation.

CHARACTERISTICS OF INDUCTANCE

Inductance is the characteristic of an electrical circuit that opposes the starting, stopping, or changing of current flow. The symbol for inductance is L. The basic unit of inductance is the henry (H); 1 henry equals the inductance required to induce 1 volt in an inductor by a change of current of 1 ampere per second.

An analogy of inductance is found in pushing a heavy load, such as a wheelbarrow or car. It takes more work to start the load moving than it does to keep it moving. Once the load is moving, it is easier to keep the load moving than to stop it again. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change in velocity. Inductance has the same effect on current in an electrical circuit as inertia has on the movement of a mechanical object. It requires more energy to start or stop current than it does to keep it flowing.

ELECTROMOTIVE FORCE

Electromotive force is developed whenever there is relative motion between a magnetic field and a conductor. EMF is a difference of potential or voltage which exists between two points in an electrical circuit. In generators and inductors, the EMF is developed by the action between the magnetic field and the electrons in a conductor. (An inductor is a wire that is coiled, such as in a relay coil, motor, or transformer.) Figure 6-1 shows EMF generated in an electrical conductor.

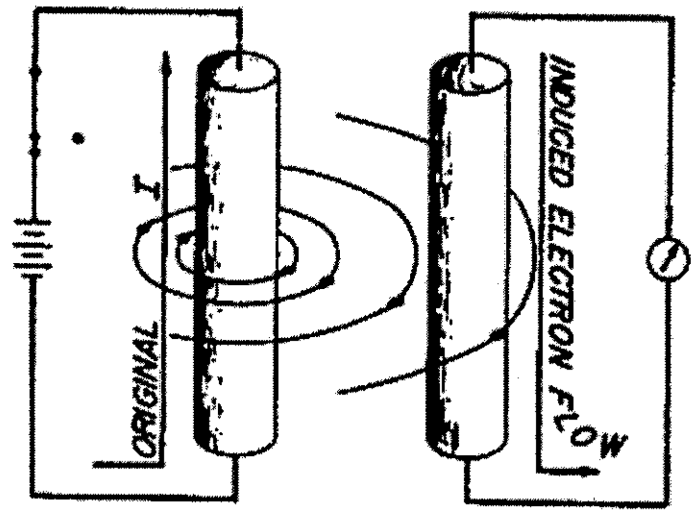


FIGURE 6-1. Generation of an EMF in an Electrical Conductor

When a magnetic field moves through a stationary conductor, electrons are dislodged from their orbits. The electrons move in a direction determined by the movement of the magnetic lines of flux (Figure 6-2).

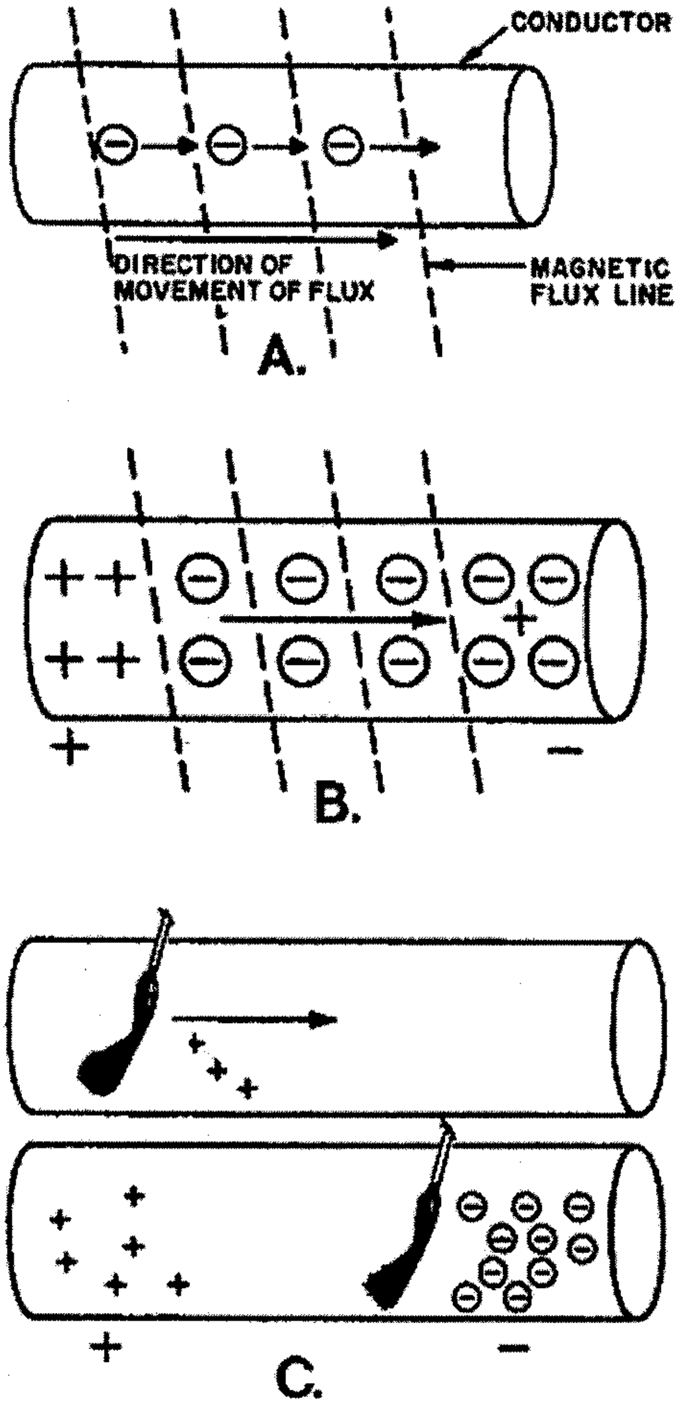


FIGURE 6-2. Current Movement and Flux Direction Relationship.

The electrons move from one area of the conductor into another area (<u>view A</u>). The area that the electrons moved from has fewer negative charges (electrons) and becomes positively charged (<u>view B</u>). The area the electrons move into becomes negatively charged. The difference between the charges in the conductor equals a difference of potential (or voltage). This voltage caused by the moving magnetic field is called electromotive force.

In simple terms, compare the action of a moving magnetic field on a conductor to the action of a broom. Consider the moving magnetic field to be a moving broom (view C). As the magnetic broom moves along (through) the conductor, it gathers up and pushes loosely bound electrons before it.

The area from which electrons are moved becomes positively charged, while the area into which electrons are moved becomes negatively charged. The potential difference between these two areas is the electromotive force.

SELF-INDUCTANCE

Even a perfectly straight length of conductor has some inductance. Current in a conductor produces a magnetic field surrounding the conductor. When the current changes direction, the magnetic field changes. This causes relative motion between the magnetic field and the conductor, and an EMF is induced in the conductor. This EMF is called a self-induced EMF because it is induced in the conductor carrying the current. It is also called counter electromotive force (CEMF).

COUNTER ELECTROMOTIVE FORCE

To understand what CEMF is and how it develops, first review a basic requirement for. the production of voltage. To magnetically produce a voltage or electromotive force, there must be --

-
- A conductor.
-
- A magnetic field.
-
- Relative motion.

Next, review some of the properties of an electrical circuit. If the ends of a length of wire are connected to a terminal of an AC generator, there would be an electrical short, and maximum current would flow. (Do not do this.) Excessive current would flow because there would be only the minimal resistance of the wire to hold back the current. This will damage the electrical system. Figure 6-3 illustrates self-inductance.

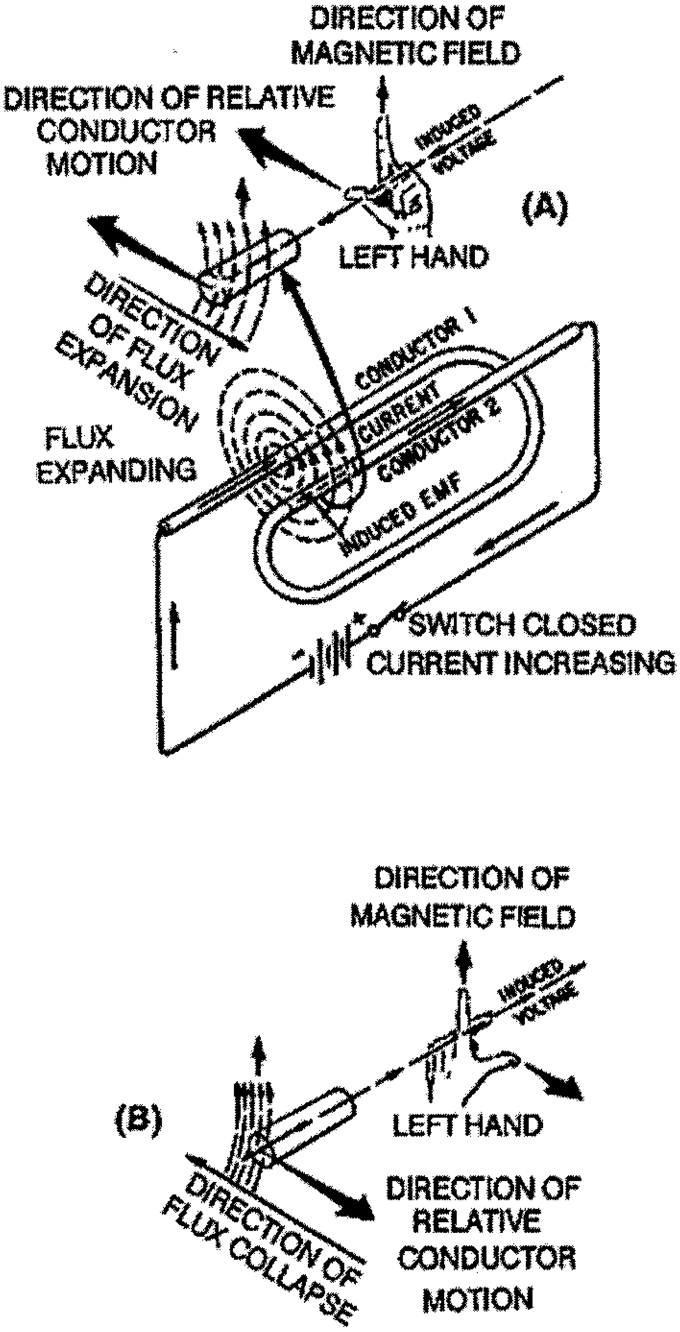


FIGURE 6-3. Self-Inductance.

If the length of wire is rolled tightly into a coil, the coil would become an inductor. Whenever an inductor is used with AC, a form of power generation occurs. An EMF is created in the inductor because of the close proximity of the coil conductors and the expanding and contracting AC magnetic fields. The inductor creates its own EMF. Since this inductor generator follows the rules of inductance, opposing a change in current, the EMF developed is actually a counter EMF opposing the power source creating it. This

CEMF pushes back on the electrical system as a form of resistance to the normal power source. CEMF is like having another power source connected in series and opposing.

This is an example of an inductive load. Unlike the resistive load, all the power in the circuit is not consumed. This effect is summarized in Lenz's Law which states that the induced EMF in any circuit is always in a direction to oppose the effect that produced it.

The direction of this induced voltage may be determined by applying the left-hand rule for generators. This rule is applied to a portion of conductor 2 that is enlarged for this purpose in Figure 6-3 view A. This rules states that if you point the thumb of your left hand in the direction of relative motion of the conductor and your index finger in the direction of the magnetic field, your middle finger, extended as shown, will indicate the direction of the induced current which will generate the induced voltage (CEMF) as shown.

View B shows the same section of conductor 2 after the switch has been opened. The flux field is collapsing. Applying the left-hand rule in this case shows that the reversal of flux movement has caused a reversal in the direction of the induced voltage. The induced voltage is now in the same direction as the battery voltage. The self-induced voltage opposes both changes in current. That is, when the switch is closed, this voltage delays the initial buildup of current by opposing the battery voltage. When the switch is opened, it keeps the current flowing in the same direction by aiding the battery voltage.

Thus, when a current is building up, it produces a growing magnetic field. This field induces an EMF in the direction opposite to the actual flow of current. This induced EMF opposes the growth of the current and the growth of the magnetic field. If the increasing current had not set up a magnetic field, there would have been no opposition to its growth. The whole reaction, or opposition, is caused by the creation or collapse of the magnetic field, the lines of which as they expand or contract cut across the conductor and develop the counter EMF (Figure 6-4).

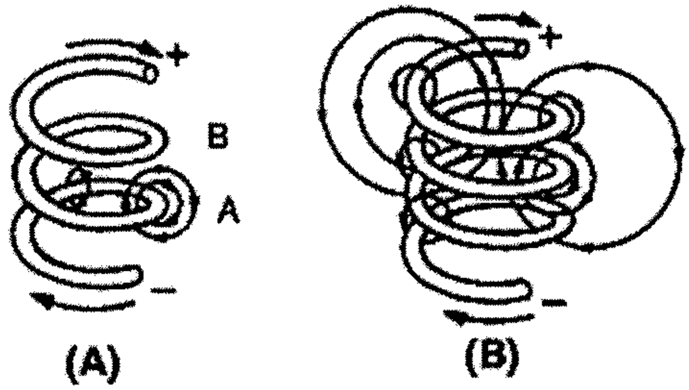


FIGURE 6-4. Inductance.

Inductors are classified according to core type. The core is the center of the inductor just as the core of an apple is the center of the apple. The inductor is made by forming a coil of wire around a core. The core material is normally one of two types: soft iron or air. Figure 6-5 view A shows an iron core inductor and its schematic symbol (represented with lines across the top of the inductor to indicate the presence of an iron core). The air core inductor may be nothing more than a coil of wire, but it is usually a coil formed around a hollow form of some nonmagnetic material such as cardboard. This material serves no purpose other than to hold the shape of the coil. View B shows an air core inductor and its schematic symbol.

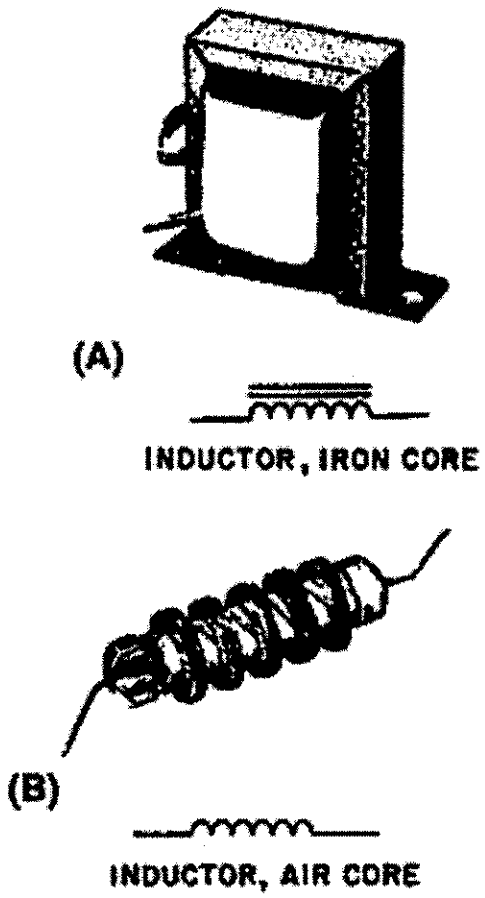


FIGURE 6-5. Inductor Types and Schematic Symbols.

FACTORS AFFECTING COIL INDUCTANCE

Several physical factors affect the inductance of a coil. They are the number of turns, the diameter, the length of the coil conductor, the type of core material, and the number of layers of winding in the coil. Inductance depends entirely on the physical construction of the circuit. It can only be measured with special laboratory instruments.

The first factor that affects the inductance of the coil is the number of turns. Figure 6-6 shows two coils. Coil A has two turns, and coil B has four turns. In coil A, the flux field setup by one loop cuts one other loop. In coil B, the flux field setup by one loop cuts three other loops. Doubling the number of turns in the coil will produce a field twice as strong; if the same current is used. A field twice as strong, cutting twice the number of turns, will induce four times the voltage. Therefore, inductance varies by the square of the number of turns.

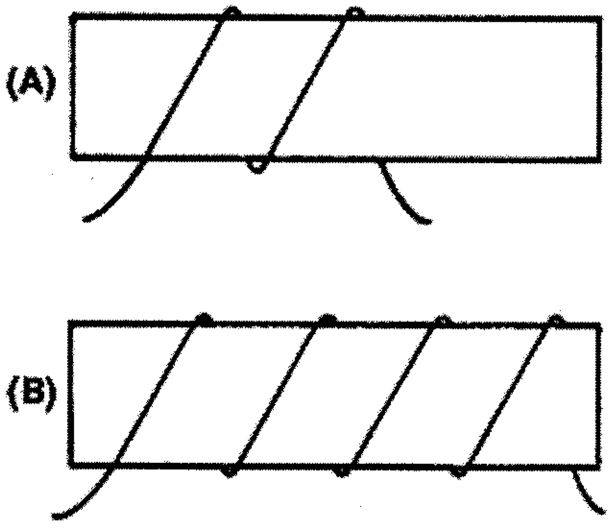
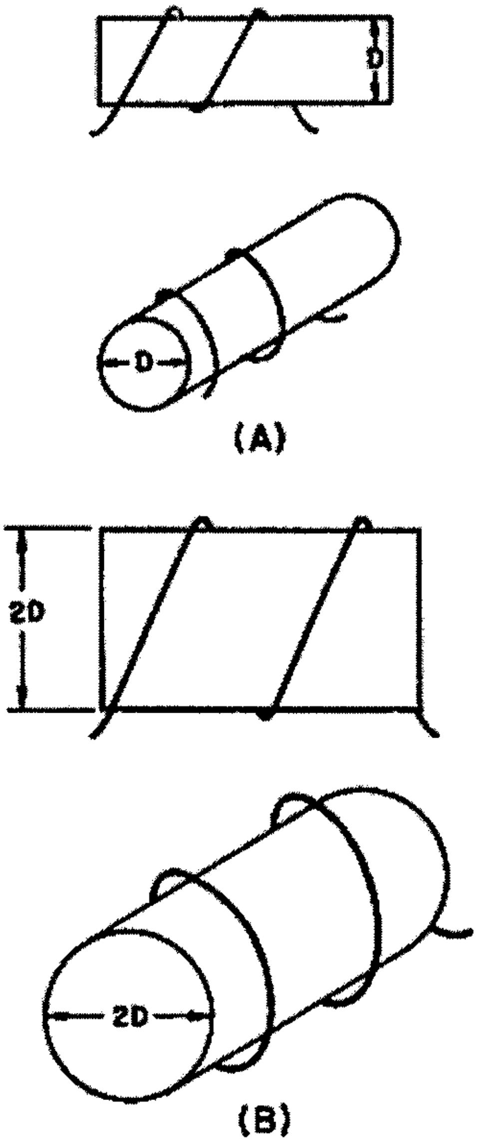


FIGURE 6-6. Inductance Factor (Turns).

The second factor is the coil diameter. In Figure 6-7, coil B has twice the diameter of coil A. Physically, it requires more wire to construct a coil of larger diameter than one of smaller diameter with an equal number of turns. Therefore, more lines of force exist to induce a counter EMF in the coil with the larger diameter. Actually, the inductance of a coil increases directly as the cross-sectional area of the core increases. Recall the formula for the area of a circle: A = pi r squared. Doubling the radius of a coil increases the area by a factor of four.

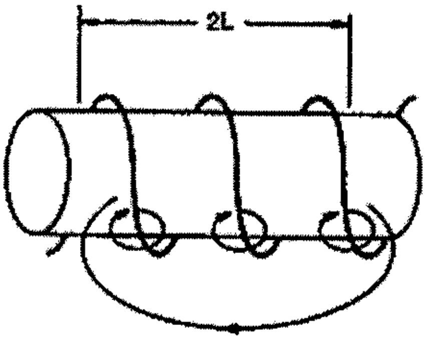


(A)

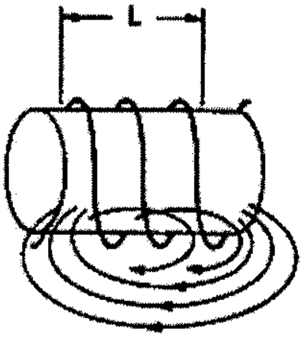
(B)

FIGURE 6-7. Inductance Factor (Diameter).

The third factor that affects the inductance of a coil is the length of the coil. Figure 6-8 shows two examples of coil spacings. Coil A has three turns, rather widely spaced, making a relatively long coil. A coil of this type has fewer flux linkages due to the greater distance between each turn. Therefore, coil A has a relatively low inductance. Coil B has closely spaced turns, making a relatively short coil. This close spacing increases the flux linkage, increasing the inductance of the coil. Doubling the length of a coil while keeping the number of turns of a coil the same halves the inductance.



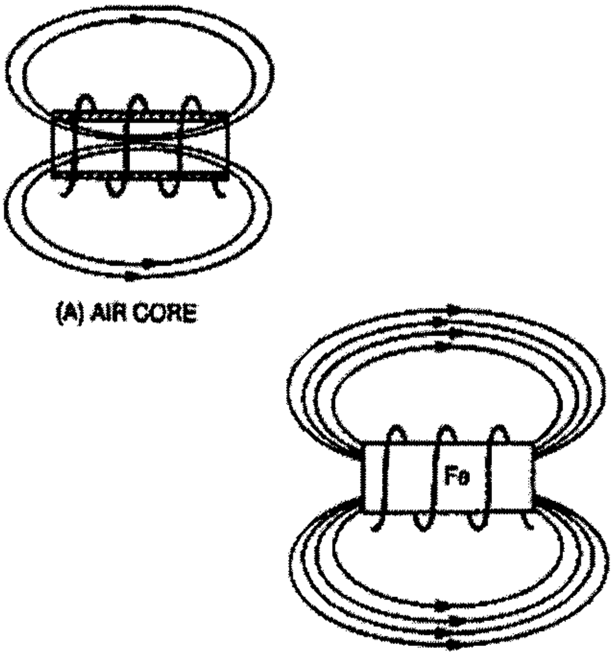
(A) WIDELY SPACED



(B) CLOSELY WOUND

FIGURE 6-8. Inductance Factor (Coil Length).

The fourth factor is the type of core material used with the coil. Figure 6-9 shows two coils: coil A with an air core and coil B with a soft-iron core. The magnetic core of coil B is a better path for magnetic lines of force than the nonmagnetic core of coil A. The soft-iron magnetic core's high permeability has less reluctance to the magnetic flux, resulting in more magnetic lines of force. This increase in the magnetic lines of force increases the number of lines of force cutting each loop of the coil, thus increasing the inductance of the coil. The inductance of a coil increases directly as the permeability of the core material increases.



(A) AIR CORE

(B) SOFT-IRON CORE

FIGURE 6-9. Inductance Factor (Core Materials).

The fifth factor is the number of layers of windings in the coil. Inductance is increased by winding the coil in layers. Figure 6-10 shows three cores with different amounts of layering. Coil A is a poor inductor compared to the others in Figure 6-10 because its turns are widely spaced with no layering. The flux movement, indicated by the dashed arrows, does not link effectively because there is only one layer of turns. Coil B is a more inductive coil. The turns are closely spaced, and the wire has been wound in two layers. The two layers link each other with greater number of flux loops during all flux movements. Note that nearly all the turns, such as X, are next to four other turns (shaded). This causes the flux linkage to be increased.

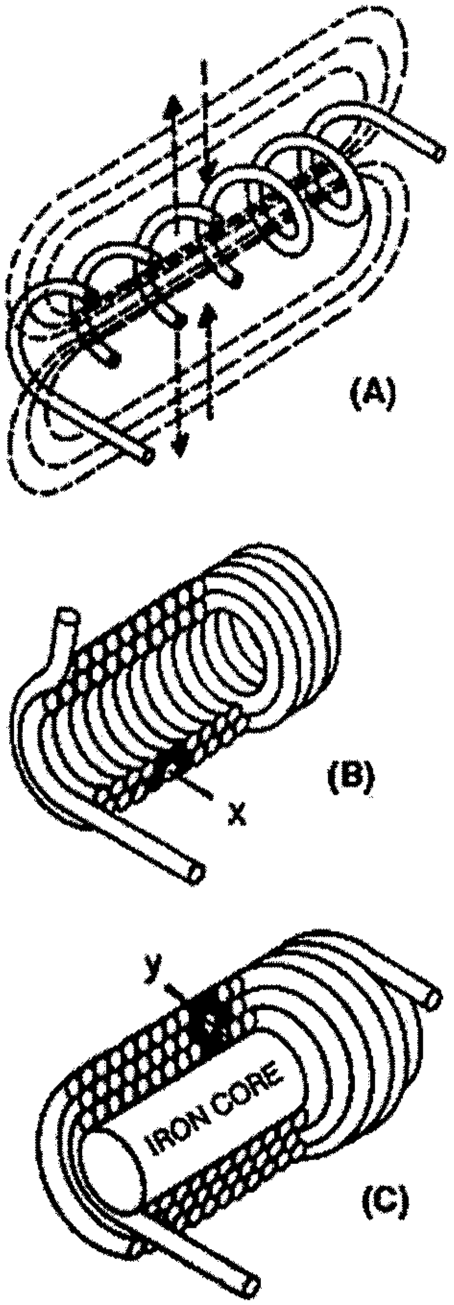


FIGURE 6-10. Coils of Various Inductances.

A coil can be made still more inductive by winding it in three layers (coil C). The increased number of layers (cross-sectional area) improves flux linkage even more. Some turns, such as Y, lie directly next to six other turns (shaded). In actual practice, layering can continue on through many more layers. The inductance of a coil increases with each layer added.

The factors that affect the inductance of a coil vary. Many differently constructed coils can have the same inductance. Inductance depends on the degree of linkage between the wire conductors and the electromagnetic field. In a straight length of conductor, there is very little flux linkage between one part of the conductor and another. Therefore, its inductance is extremely small. Conductors become much more inductive when they are wound into coils. This is true because there is maximum flux linkage between the conductor turns, which lie side by side in the coil.

UNIT OF INDUCTANCE

As stated before, the basic unit of inductance (L) is the henry (H). An inductor has an inductance of 1 henry if an EMF of 1 volt is inducted in the inductor when the current through the inductor is changing at the rate of 1 ampere per second.

POWER LOSS IN AN INDUCTOR

Since an inductor (coil) consists of a number of turns of wire and since all wire has some resistance, every inductor has a certain amount of resistance. Normally, this resistance is small. It is usually neglected in solving various types of AC circuit problems because the reactance of the inductor (the opposition to alternating current) is so much greater than the resistance that the resistance has a negligible effect on current.

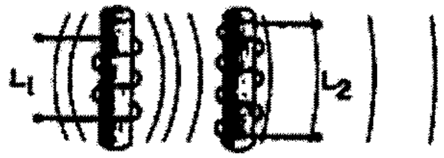
However, since some inductors are designed to carry relatively large amounts of current, considerable power can be dissipated in the inductor even though the amount of resistance in the inductor is small. This is wasted power called copper loss. The copper loss of an inductor can be calculated by multiplying the square of current in the inductor by the resistance of the winding (I^2R).

In addition to copper loss, an iron-core coil (inductor) has two iron losses. These are hysteresis loss and eddy-current loss. Hysteresis loss is due to power that is consumed in reversing the magnetic field of the inductor core each time the direction of current in the inductor changes. Eddy-current loss is due to currents that are induced in the iron core by the magnetic field around the turns of the coil. These currents are called eddy currents and flow back and forth in the iron core.

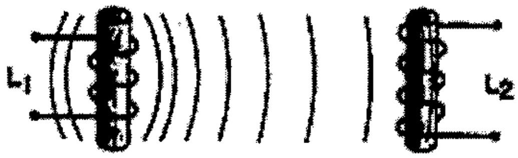
All these losses dissipate power in the form of heat. Since this power cannot be productively consumed in the electrical circuit, it is lost power.

MUTUAL INDUCTANCE

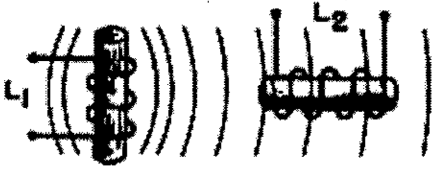
Whenever two coils are located so that the flux from one coil links with the turns of another coil, a change of flux in one causes an EMF to be induced into the other coil. This allows the energy from one coil to be transferred or coupled to the other coil. The two coils are coupled or linked by the property of mutual inductance. The amount of mutual inductance depends on the relative positions of the two coils (Figure 6-11). If the coils are separated a considerable. distance, the amount of flux common to both coils is small, and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flux of one coil links the turns of the other, the mutual inductance is high.



(A) INDUCTORS CLOSE—LARGE M



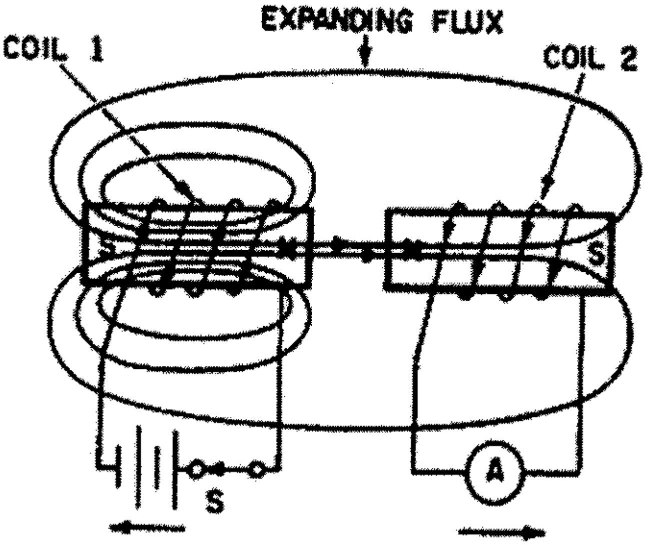
(B) INDUCTORS FAR APART—SMALL M



(C) INDUCTORS AXES PERPENDICULAR—NO M

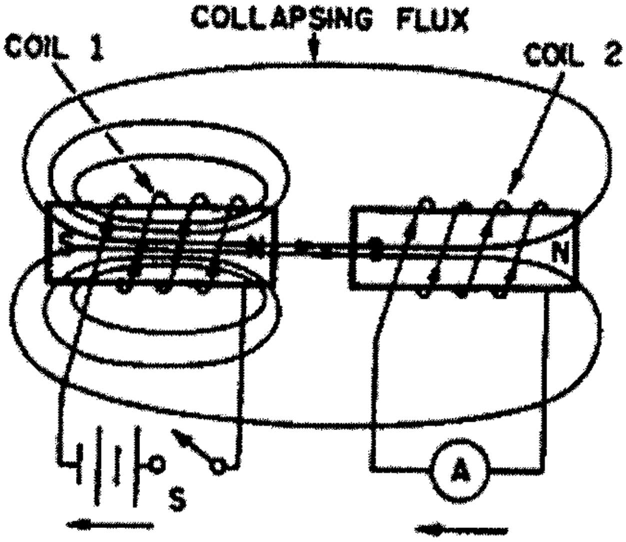
FIGURE 6-11. The Effect of Position of Coils on Mutual Inductance.

The mutual inductance can be increased greatly by mounting the coils on a common core. Two coils are placed close together (Figure 6-12). Coil 1 is connected to a battery through switch S, and coil 2 is connected to an ammeter (A). When switch S is closed (view A), the current that flows in coil 1 sets up a magnetic field that links with coil 2, causing an induced voltage in coil 2 and a momentary deflection of the ammeter. When the current in coil 1 reaches a steady value, the ammeter returns to zero. If switch S is now opened (view B), the ammeter (A) deflects momentarily in the opposite direction, indicating a momentary flow of current in the opposite direction of coil 2. This current in coil 2 is produced by the collapsing magnetic field of coil 1.



SWITCH CLOSED

(A)



SWITCH OPENED

(B)

FIGURE 6-12. Mutual Inductance.

Detection of Bicycles by Quadrupole Loops at Demand-Actuated Traffic Signals

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Abstract

Inductive loop sensors, commonly used for detection of traffic at demand-actuated traffic signals, can be configured and adjusted to detect bicycles with metal rims. This article describes how to provide reliable detection of bicycles via inductive loop sensors without generating unacceptable false-positive detection of large vehicles in adjacent lanes.

Introduction

Demand-actuated traffic signals sense the presence of traffic before changing signal phases in order to optimize traffic flow. The main disadvantage of such systems is that a defect in the sensor system can cause it to fail to detect users waiting at a left-turn lane or cross-street. Such failure can cause substantial, indeterminate delay to road users and encourages non-compliance with the signal, which affects safety. Functional operation of the traffic control devices in use is fundamental to protection of individuals' safe and legal passage. Fortunately, good engineering of traffic signal sensors allows virtually all legal vehicle traffic, including bicycles, to be detected reliably using existing technology. Although a number of advanced non-intrusive sensor systems such as video and microwave devices are beginning to be employed for vehicle detection, at the time of this writing (2003) the most reliable and cost-effective method for detecting metal vehicles is the use of inductive loop sensors in the roadway pavement. Inductive loop sensors can reliably detect bicycles with metal rims if they are properly configured and adjusted. A number of communities in the United States, including Bakersfield, California, Santa Cruz, California and Santa Clara County, California, have adopted policies to design and adjust all traffic signal sensors to detect bicycles.

Theory of Operation

Inductive-loop traffic detector systems operate by sensing disturbances to the electromagnetic field over a coil of wire built into the roadway (Figure 1). When a conductive object (typically made of metal) enters the area over the wire loop, the magnetic field generated by alternating electrical current in the signal detector circuit induces weak electrical currents in the conductive object. (The AC frequency may be between 10,000 and 200,000 Hz, typically around 20,000 - 30,000 Hz.) The electrical currents induced in the object generate their own magnetic field that works in opposition to the magnetic field generated by the sensor coil (due to Lenz's Law). This opposition changes the resonant frequency of the sensor circuit by reducing the effective inductance of the sensor coil. This change in resonant frequency (an increase in frequency as the inductance decreases) is detected by the circuit instrumentation in the signal controller cabinet, which then tells the signal control electronics that a vehicle is present.

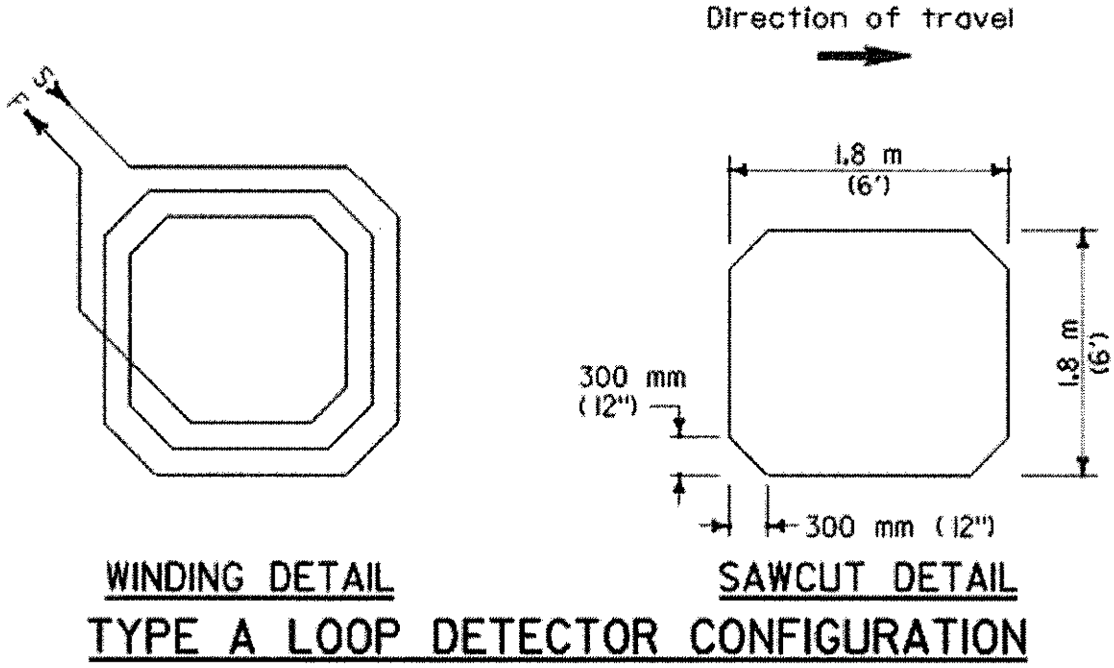


Figure 1: Basic dipole inductive loop sensor. (Source: California DOT)

A number of variables affect the degree to which the introduction of a conductive object will change the inductance of the sensor loop. These variables include:

- The size, shape, and conductivity of the object
- The 3-D orientation of the object with respect to the wires in the loop
- The 3-D position of the object over the loop
- The size and shape of the sensor loop

The combination of these variables create the potential for public confusion about the feasibility and reliability of bicycle detection via inductive loop sensors. Experiments that fail to control for some of these variables often create unreliable results, and have sometimes frustrated efforts to select reliable detection systems for cyclists by leading the engineers and facilities designers to false conclusions. Since bicycles are small vehicles and have less conductive material in them than do automobiles, they are harder to detect with inductive loops. Often the sensor loop is very large or the detector circuitry is not sensitive enough to detect the slight inductance decrease caused by the bicycle. The bicycle may not be aligned for maximum effect, or the loop may be shaped (as in Figure 1) such that large vehicles in adjacent lanes may be detected at the level of circuit sensitivity required to register a bike. Since the time and money invested by most states and municipalities toward bicycle transportation issues is very limited, traffic signal engineers often give up on the problem of bicycle detection before it is fully understood. However, this article will show that careful application of the operational theory allows optimization of inductive loop sensing systems for reliable detection of conductive (including aluminum, steel, and titanium) bicycle rims, without false detections caused by adjacent traffic.

There is a common misconception that an object must be ferrous (include iron) to activate a traffic signal loop sensor, or that a ferrous object will perform better. This misconception is fed by the observation that steel cars are detected by standard loop detectors but small aluminum bicycles (often, but not always) are not. The rationale behind this misconception is rooted in the observation that placing a ferrous core into the center of an inductor coil (such as inside an electromagnet or transformer) affects the inductance of the coil. But in such ferrous-core coil applications, the inductance of the coil is *increased* by the ferromagnetic effect of the iron, while the typical inductive-loop signal sensors used for traffic signal actuation require the vehicle to cause a *decrease* in inductance. Given the high frequencies at which signal detectors operate and the large conductive silhouette of the car, any effect the iron's properties might have to increase the inductance of the coil are overpowered by the induced electrical eddy currents in the vehicle which serve to reduce the inductance of the coil. There are some rare cases where a steel vehicle wheel positioned in the center of a loop can create a net increase in loop inductance, but most traffic signal sensor circuits will either ignore this increase or treat it as an error condition. It is simply the size and net conductivity of an automobile that makes it easier to detect than a bicycle.

There is another common misconception that because bicycles are smaller than cars, inductive detector loops cannot be designed to detect bicycles. This is absolutely incorrect; simply making the loop smaller puts the loop on a scale that allows easy detection of bicycles. Communities that design inductive loops to detect bicycles make them about six to ten feet long. Unfortunately, the North Carolina Department of Transportation has currently adopted a bicyclist-unfriendly standard loop design that is 60 feet long. This standard needs to be revised in order to allow bicycle detection. If a larger detection area is needed to bridge gaps between cars approaching a signal, the traffic engineer can instead install a second, longer loop behind the small bicycle-sensitive one, and run it on a separate detector circuit. This is standard practice in bicycle-driver-friendly communities.

Inducing Current in Bicycle Rims

Bicycle rims lend themselves well to detection by inductive loop detectors because they provide an excellent conductive loop and are located close to the ground where the loop wires are. By positioning the rims over a straight leg of the loop wire pointed in the same direction (as shown in Figure 2), the magnetic field lines around the wire pass through the profile of the wheels. The integral sum of the magnetic flux density across each wheel's profile determines the induced current around the rim loop and the opposing magnetic field it generates. The larger the area of the wheels in comparison to the area of the sensor loop, and the better the positioning of the wheels to intercept the maximum magnetic flux, the greater the percentage reduction in the sensor loop's inductance. Note that positioning the wheels at a different angle or moving them to either side from the wire reduces their effectiveness.

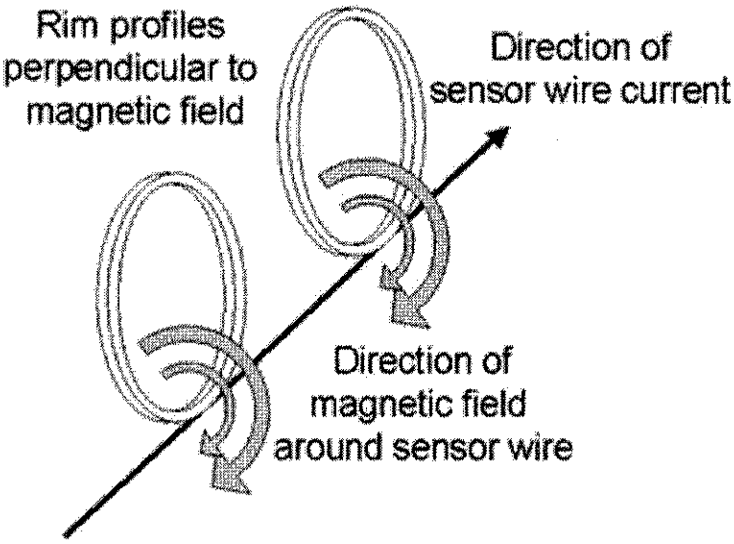


Figure 2: Magnetic field reception by bicycle rims

Improved Loop Design

Bicycles are not the only vehicles that may not be detected by an insensitive loop detector system. Oftentimes a simple dipole loop sensor, especially a large one, will not detect a small car or a motorcycle. But if the traffic signal technician turns up the sensitivity of the detector circuit to detect the small vehicle, it may also detect a large vehicle in an adjacent lane when the sensor's lane is empty. The sensitivity of the dipole loop is actually weakest at its center, and strongest over its perimeter wires, the longest stretches of which are often routed near the lane edges. This makes the dipole loop configuration vulnerable to false positive detection when adjusted to detect small vehicles.

In order to address this reliability problem, many state and local DOTs have switched to a different loop configuration, called a quadrupole loop, as shown in Figure 3. A quadrupole loop is actually two loops wired in a figure-8 pattern side-by-side, in series with a single wire. Because each loop has two magnetic poles, the sensor has a total of four poles, hence the name quadrupole. The two poles are wound in opposite directions, such that whenever the magnetic North is pointing up out of one loop, it is pointing down into the adjacent loop. This creates a tight channelization of magnetic flux from one loop over into the other, resulting in maximum sensitivity over the center of the sensor footprint with much less spillover around the sides. Also note that the center sawcut in the loop, which runs parallel to the direction of vehicle travel, has twice as many conductors in it as the edge sawcuts, and the current runs in the same direction for all of the center-sawcut conductors. This makes the center sawcut the most sensitive place over which to position the bicycle's wheels. The magnetic flux lines around the center wire cut, moving from one coil into the other, will pass through the profile of the bicycle wheels for maximum effect.

From personal experience reported by various cyclists, dipole loops that are successful in detecting bicycles have a very small "sweet spot" (only about 20 mm each side of the wire loop). Quadrapole loops have a sweet spot about four times larger. Even this is smaller than desirable. The quadrapole loop offers at least four significant advantages over the dipole: 1. Improved sensitivity; 2. Lower false positive detection; 3. A larger "sweet spot" over the center wires; 4. More logical placement of the sweet spot (in the center of the lane).

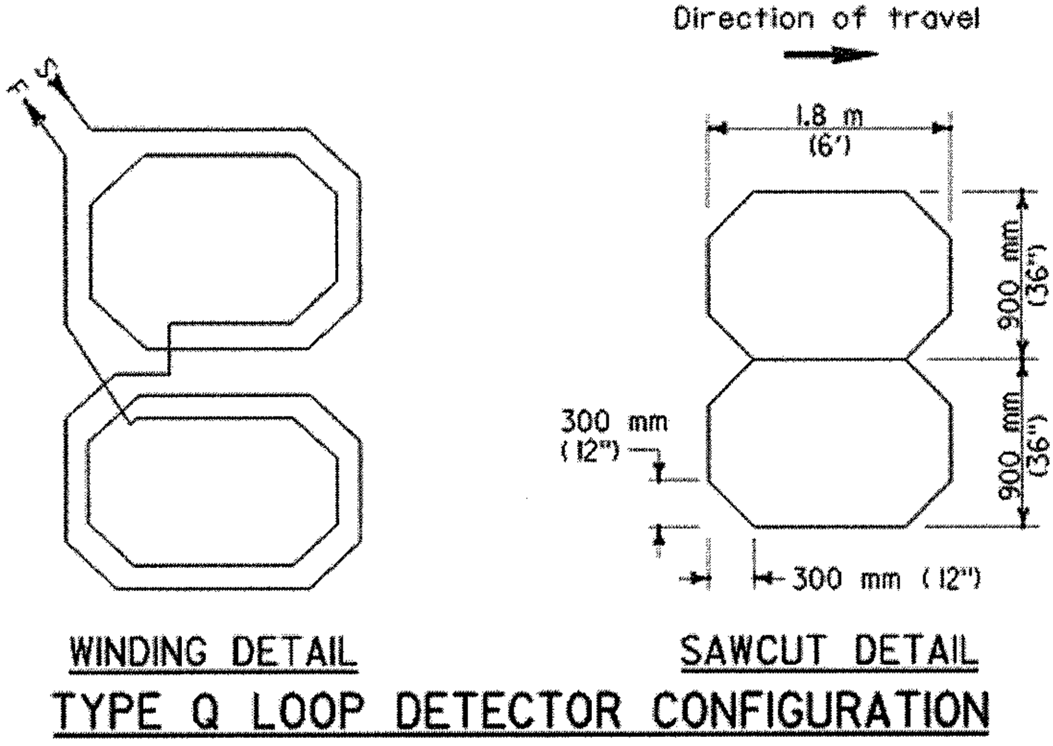


Figure 3: Small quadrupole loop sensor. (Source: California DOT)

The size of the quadrupole loop installation still has an impact on the ability of the sensor system to detect a bicycle. If the loop footprint is very long, such as the NCDOT standard of sixty feet, then the relatively small bicycle wheels will intercept a very small percentage of the magnetic flux generated by the loop. If the loop footprint is a more modest length, (for example six feet as in Figure 3) the larger relative size of the bicycle wheels in the path of the magnetic field will make them easier to detect. In fact, a small quadrupole loop at high sensitivity can usually detect a bicycle anywhere over the detector, not just over the center wire. This is the preferred performance for cyclists. As a compromise, detector circuits for loops as long as 25 feet or more can also be adjusted to detect bicycles over the center wire. If the loop is very much larger, however, there is an increased chance of false detection due to large vehicles in adjacent lanes.

In order to detect a bicycle waiting alone at a signal, the loop should be installed just behind the stop line. Note that it is important not to wire the small-footprint quadrupole in series with another loop sensor, as this will defeat the purpose of using the small loop for sensitivity. If additional, longer loop sensors are to be installed in the traffic lane behind the first one to bridge gaps between vehicles, these loops should be wired to separate detector channels.

Empirical Data

Cyclists' real-world experience with modestly-sized quadrupole (and dipole) loop detectors demonstrates that detection of bicycles with aluminum rims and frames not only is possible, but is no more difficult than with steel components. As an experiment, the author found a pair of quadrupole loop detectors in Cary, North Carolina (at the intersection of Cary Parkway and Two Creeks Drive) that happened to be adjusted sensitive enough to detect a lightweight steel-framed road bicycle (2002 Lemond Zurich) with 700c aluminum wheels positioned over the center sawcut. The author observed the signal operation to ensure it was working properly on demand, rather than on a timer, and approached the intersection repeatedly from the cross streets when no other traffic was coming, after the signal had been green for the arterial for more than 30 seconds. The signal detected the bicycle and changed the signal phase for the arterial to yellow immediately. Detection reliability was 100%. The author then repeated the experiment with a lightweight aluminum-framed soft-tail suspension mountain bicycle (1999 Gary Fisher Sugar) with 26" aluminum rims. Detection was again 100% reliable.

In cities where signal technicians regularly adjust loop sensors to detect bicycles, the technicians will often use just aluminum rims, without the rest of the bicycle, to test the sensitivity of the sensor. This is more convenient for the technicians than carrying a bicycle just for this purpose. Since the sensors can be set to detect just the aluminum rims minus the frame, the sensors can also detect bicycles with frames that are made from more exotic materials that have little or no electrical conductivity, or have shapes that do not provide a wide loop profile for interception of magnetic flux. Cyclists with carbon-fiber bicycle frames but aluminum wheels have reported being detected by sensitive quadrupole loops.

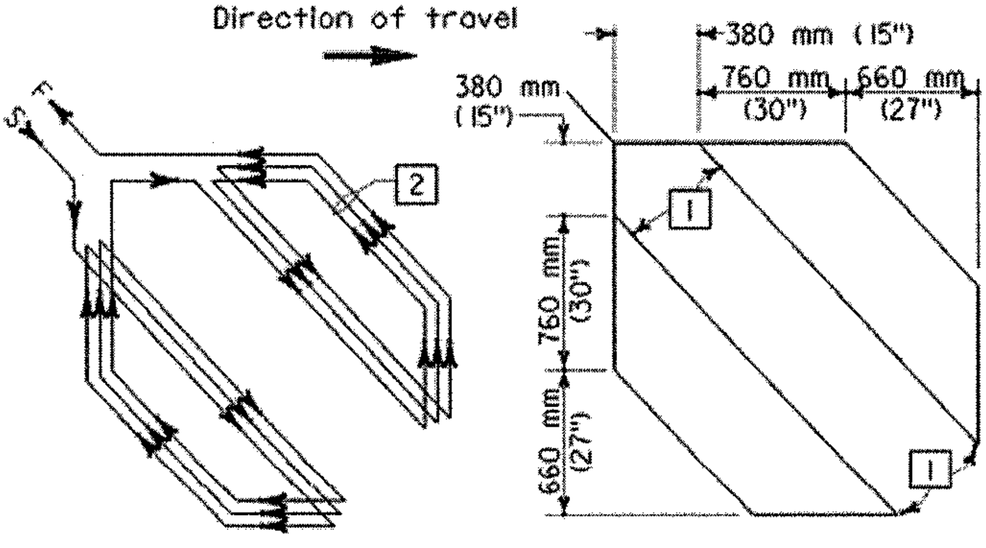
Common Rim Materials

Most quality adult bicycles feature aluminum rims, which are excellent conductors. Lower quality bicycles and some older bicycles feature steel rims. Steel rims have lower conductivity than aluminum rims, per pound, but perform adequately for detection over a properly adjusted quadrupole loop sensor. Extremely low-weight wheels constructed of carbon fiber with no metal in the rim are sometimes used by racing cyclists for competitions. Carbon fiber is a conductor, but the loop conductivity of the wheel is affected by the materials used to bond it into shape. Very few cyclists use carbon fiber wheels for general utilitarian or recreational use on public roadways, however, because of their very high cost and somewhat lower durability than metal wheels.

The Diagonal Quadrupole

A disadvantage of the conventional quadrupole loop design shown in Figure 3 is that it under marginal operating conditions (a low-conductance bicycle, a low-sensitivity setting, or a large loop footprint) it requires the bicycle wheels to be positioned in a precise location (over the center wire) for detection to occur reliably. To eliminate this requirement, the diagonal quadrupole loop (Figure 4) was developed for better detection of narrow vehicles. This loop is designed with the poles farther apart and the loops at an angle to provide fairly uniform sensitivity across the width of the sensor, making it easier for cyclists to be detected. The way the sweet spot between the two loops sweeps diagonally across the footprint of the detector virtually guarantees that either the front or back wheel will cut across the magnetic field and be detected regardless of the bicyclist's lateral position over the loop.

There are two potential disadvantages to the diagonal quadrupole. First, it can be less sensitive than the conventional quadrupole to motor vehicles with a high undercarriage, such as tractor-trailers, but this may be rectified by placing a conventional quadrupole behind the diagonal quadrupole. Second, the sawcuts are more complex and acute, and may result in faster deterioration of the pavement surface by weakening it more than the would standard quadrupole cuts, but liberal application of pavement sealant can mitigate this. The diagonal quadrupole is desirable in places where bicycle position will be laterally distributed.



WINDING DETAIL

SAWCUT DETAIL

TYPE D LOOP DETECTOR CONFIGURATION

NOTES

1 Round corners of acute angle sawcuts to prevent damage to conducto

2 Install 3 turns when only one Type D loop is on a sensor unit channel. Install 5 turns when one Type D loop is connected in series with 3 additional 1.8 m x 1.8 m (6' x6') loops on a sensor unit channel.

Figure 4: Diagonal quadrupole pattern (Source: California DOT)

Assistive Markings for Quadrupole Loops

When a roadway is repaved over the loop sawcuts, a cyclist cannot determine the location of the conventional quadrupole sensor's center wires, and as a result may not be able to position the bicycle's rims for detection. Some cyclists may not be aware of the best part of the loop for detection, or may not be aware of the function of inductive sensors in the first place. In order to address this problem, proposed Revision 2 of the 2000 edition of MUTCD specifies roadway markings to identify the center of the loop to cyclists (Figure 5), and specifies a road sign (Figure 6) to educate road users about the purpose of the markings.

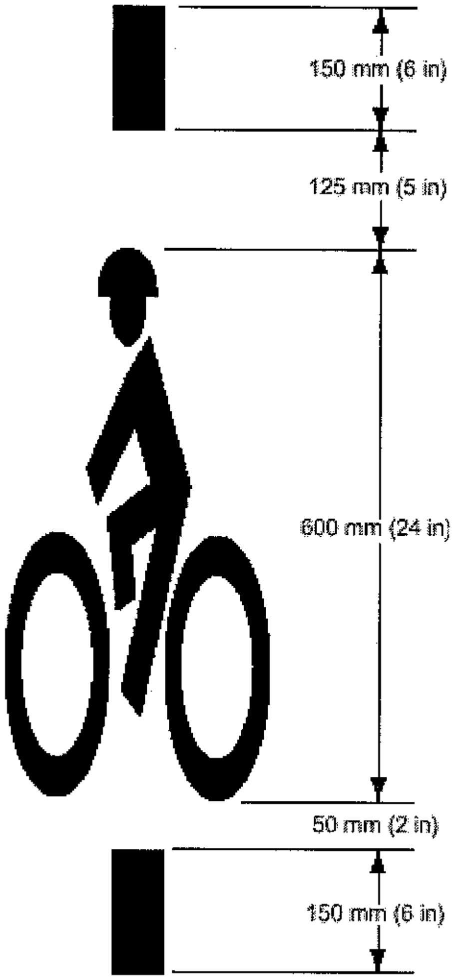


Figure 5: Stencil for marking location of most sensitive portion of traffic sensor (Source: 2000 MUTCD, Rev. 2)

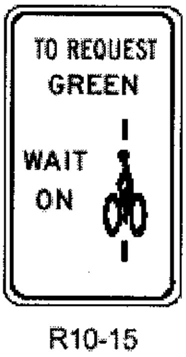


Figure 6: Informational sign describing optimum use of traffic sensor (Source: 2000 MUTCD, Rev. 2)

Detector Circuit Sensitivity

Detection of a bicycle over a well-designed quadrupole loop requires that the detector circuit be adjusted more sensitive than what is typically required for automobile detection. A bicycle can generate as little as 1% as much change in the loop inductance as an automobile does, especially for a poorly designed loop, because the car covers so much more area of magnetic flux, and has a high net conductivity. However, many commercially available detectors provide adequate sensitivity to accomplish this. According to Jim Magerkurth of US Traffic Corporation, a detector should provide an inductance change sensitivity level down to 0.0025% to reliably detect bicycles. Examples of such detectors include the US Traffic Corporation 262 series rack-mount detectors, which offer nine sensitivity levels. Shelf-mount detectors with this sensitivity include the US Traffic Corporation 921-2, 910 and 913 units. Such modern inductive loop detectors vary in price from $100 to $250. Note that some other models of detector systems on the market offer sensitivity to only 0.01% inductance change; such detectors should be avoided for bicycle-sensitive loop installations.

Good detectors can be adjusted to detect bicycles on quadrupole loops. As described by one signals expert:

> *It is always possible to set a detector's sensitivity to pick up a bicycle. The trade-off is in longer detection times and the possibility of false detections from vehicles in adjacent lanes. Most people who set signal detectors use the lowest sensitivity setting that will pick up cars reliably. I advocate using the highest setting that will avoid picking up vehicles in adjacent lanes. Digital circuits used in modern detectors can use high sensitivity settings without unacceptable increases in detection times. Unfortunately, there are still a lot of old detectors out there, and most people who work on signals use principles based on the performance characteristics of old detectors.*

- Bob Shanteau, PhD, PE, Registered Traffic Engineer (Source: Rec.Bicycles FAQ)

Summary

Detection of bicycles by demand-actuated traffic signal sensors is important at cross streets, left-turn-only lanes and other travel lanes where cyclists may become stuck, unable to get a green light. Compact (not much longer than a bicycle) quadrupole loop detectors, located near the stop line and operated by suitably sensitive detector circuits, can reliably detect most bicycles waiting at traffic signals without generating false positive detection of vehicles in adjacent lanes due to spillover. Detection does not depend on the bicycle being made of iron, but the loop conductivity of the rims is important. As the quadrupole loop footprint increases in length, the chances that it may detect large vehicles in adjacent lanes increase. Many existing quadrupole loop installations with lengths of 20 feet are able to detect bicycles but operate acceptably. Quadrupole footprints that are much longer can also be adjusted to detect bicycles, but result in progressively increased probability of spillover effects. NCDOT standards that specify very long loop sizes should be revised to include a short bicycle-sensitive loop near the stop line. Lane markings that show cyclists where to position their bicycle maximize the capability of the sensor.

For more information:

"How to Turn Signals Green"

"Traffic Signals", http://www.bikeplan.com/signal.html

Alan Wachtel, "Re-Evaluating Signal Detector Loops", *Bicycle Forum* #50

John Forester, *Bicycle Transportation*, Second Edition, MIT Press, 1994

John Allen, "Traffic Signal Actuators: Am I Paranoid?"

APPENDIX 4

Power MOSFET

FAIRCHILD
SEMICONDUCTOR TM

Application Note 558

Ralph Locher

Introduction to Power MOSFETs and their Applications

INTRODUCTION

The Power MOSFETs that are available today perform the same function as Bipolar transistors except the former are voltage controlled in contrast to the current controlled Bipolar devices. Today MOSFETs owe their ever-increasing popularity to their high input impedance and to the fact that being a majority carrier device, they do not suffer from minority carrier storage time effects, thermal runaway, or second breakdown.

MOSFET OPERATION

An Understanding of the operation of MOSFETs can best be gleaned by the first considering the lateral N-channel MOSFET shown in Figure 1.

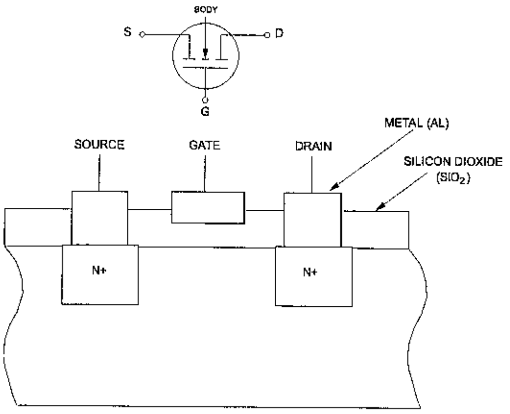


Figure 1. Lateral N-Channel MOSFET Cross-Section

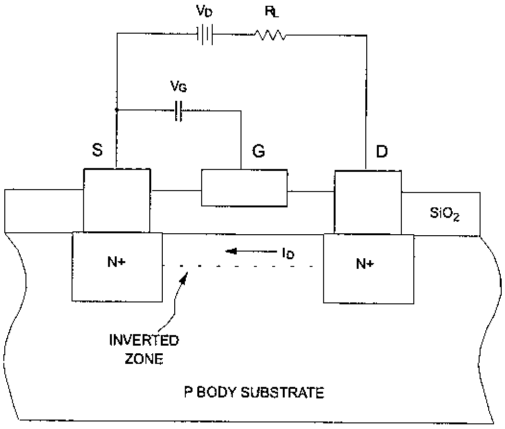


Figure 2. Lateral MOSFET Transistor Biased for Forward Current Conduction

With no electrical bias applied to the gate G, no current can flow in either direction underneath the gate because there will always be a blocking PN junction. When the gate is forward biased with respect to the source S together with an applied drain-source voltage, as shown in Figure 2, the free hole carriers in the p-epitaxial layer are repelled away from the gate area creating a channel, which allows electrons to flow from the source to the drain. Note that since the holes have been repelled from the gate channel, the electrons are the "majority carriers" by default. This mode of operation is called "enhancement" but is easier to think of enhancement mode of operation as the device being "normally off", i.e., the switch blocks the current until it receives a signal to turn on. The opposite is depletion mode, which is normally "on" device.

The advantages of the lateral MOSFET are:

1. Low gate signal power requirement. No gate current can flow into the gate after the small gate oxide capacitance has been charged.
2. Fast switching speeds because electrons can start to flow from drain to source as soon as the channel opens. The channel depth is proportional to the gate voltage and pinches closed as soon as the gate voltage is removed, so there is no storage time effect as occurs in transistors.

Rev B, October 1998

The major disadvantages are:

1. High resistance channels. In normal operation, the source is electrically connected to the substrate. With no gate bias, the depletion region extends out from the N+ drain in a pseudo-hemispherical shape. The channel length L cannot be made shorter than the minimum depletion width required to support the rated voltage of the device.
2. Channel resistance may be decreased by creating wider channels but this is costly since it uses up valuable silicon real estate. It also slows down the switching speed of the device by increasing its gate capacitance.

Enter vertical MOSFETs!
The Power MOSFET structure (also known as DMOS) is shown Figure 3.

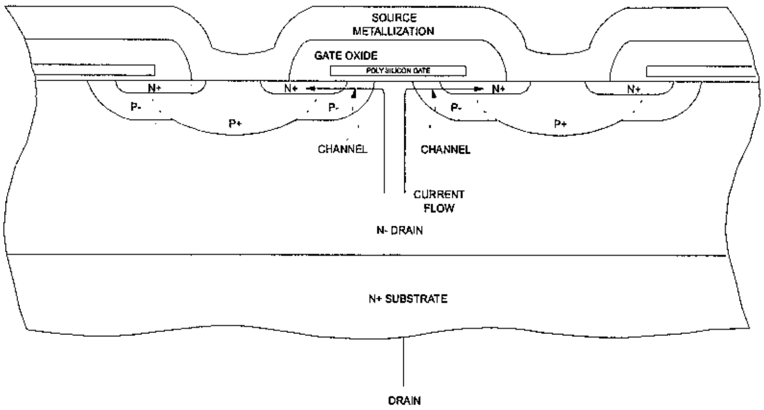


Figure 3. Vertical DMOS Cross-Sectional

The current path is created by inverting the p-layer underneath the gate by the identical method in the lateral MOSFETs. Source current flows underneath this gate area and then vertically through the drain, spreading out as it flows down. A typical MOSFET consists of many thousands of N+ sources conducting in parallel. This vertical geometry makes possible lower on-state resistances ($R_{DS(on)}$) for the same blocking voltage and faster switching than the lateral MOSFETs.

There are many vertical construction designs possible, e.g., V-groove and U-groove, and many source geometries, e.g. squares, triangles, hexagons, etc. The many considerations that determine the source geometry are $R_{DS(on)}$, input capacitance, switching times and transconductance.

PARASITIC DIODE

Early versions of MOSFETs were susceptible to voltage breakdown due to voltage transients and also had a tendency to turn on under high rates of rise of drain-to-source voltage (dV/dt). Both resulted in catastrophic failures. The dV/dt turn-on was due to the inherent parasitic NPN transistor incorporated within the MOSFET, shown schematically in Figure 4a. Current flow needed to charge up junction capacitance C_{DG} acts like base current to turn on the parasitic NPN.

The parasitic NPN action is suppressed by shorting the N+ source to the P+ body using the source metallization. This now creates an inherent PN diode anti-parallel to the MOSFET transistor (see Figure 4b). Because of its extensive junction area, the current ratings and thermal resistance of this diode exhibit a very long reverse recovery time and large reverse recovery current due to the long minority carrier lifetimes in the N-drain layer, which precludes the use of this

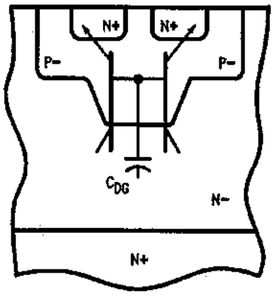


Figure 4a. DMOS Construction Showing Location of the Parasitic NPN Transistor

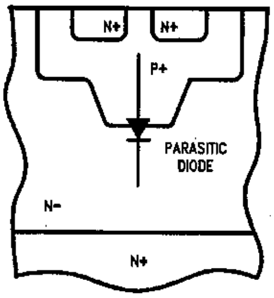


Figure 4b. Parasitic Diode

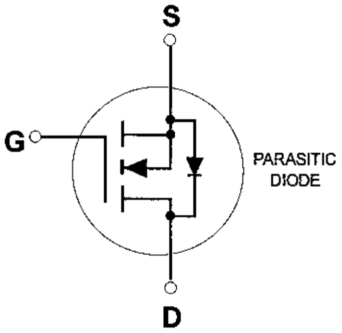


Figure 4c. Circuit Symbol

diodes except for very low frequency applications. e.g., motor control circuit shown in Figure 5. However in high frequency applications, the parasitic diode must be paralleled externally by an ultra-fast rectifier to ensure that the parasitic diode does not turn on. Allowing it to turn will substantially increase the device power dissipation due to the reverse recovery losses within the diode and also leads to higher voltage transients due to the larger reverse recovery current.

CONTROLLING THE MOSFET

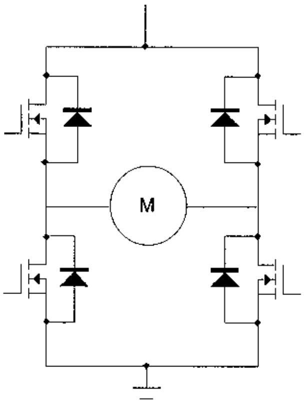


Figure 5. Full-Wave Motor Control Circuit

A major advantage of the Power MOSFET is its very fast switching speeds. The drain current is strictly proportional to gate voltage so that the theoretically perfect device could switch in 50ps - 200ps, the time it takes the carriers to flow from source to drain. Since the MOSFET is a majority carrier device, a second reason why it can outperform the junction transistor is that its turn-off is not delayed by minority carrier storage time in the base. A MOSFET begins to turn off as soon as its gate voltage drops down to its threshold voltage.

SWITCHING BEHAVIOR

Figure 6 illustrates a simplified model for the parasitic capacitances of a Power MOSFET and switching voltage waveforms with a resistive load.There are several different phenomena occurring during turn-on. Referring to the same figure:

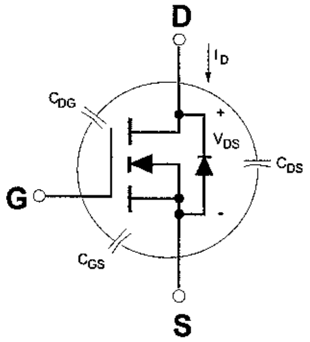


Figure 6a. MOSFET Capacitance Model for Power MOSFET

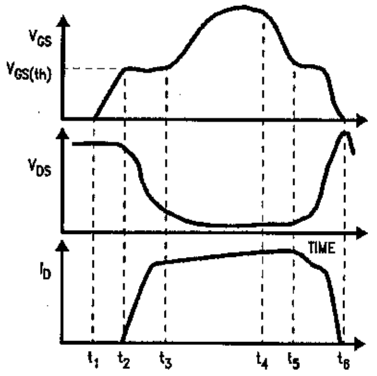


Figure 6b. Switching Waveforms for Resistive Load

Time interval t1<t<t2:

The initial turn-on delay time $t_{d(ON)}$ is due to the length of time it takes V_{GS} to rise exponentially to the threshold voltage $V_{GS(TH)}$. From Figure 6, the time constant can be seen to be $R_S x C_{GS}$.

Typical turn-on delay approximation is:

$$t_{d(on)} = R_S \times C_S \times 1n\left(1 - \frac{V_{GS(th)}}{V_{PK}}\right) \qquad (1)$$

Note that since the signal source impedance appears in the t_d equation, it is very important to pay attention to the test conditions used in measuring switching times.

Physically one can only measure input capacitance C_{iss}, which consists of C_{GS} in parallel with C_{DG}. Even though $C_{GS}>>C_{DG}$, the later capacitance undergoes a much larger voltage excursion so its effect on switching time cannot be neglected.

Plots of C_{iss}, C_{oss}, and C_{rss} for the Fairchild Semiconductor Supersot™ NDS351N are shown in Figure 7 below. The charging and discharging of C_{DG} is analogous to the "Miller" effect that was first discovered with electron tubes and dominates the next switching interval.

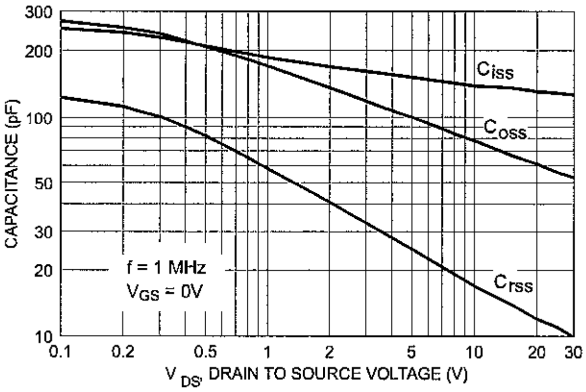


Figure 7. Typical Capacitances of NDS351N

Time interval t2<t<t3:

Since V_{GS} has now achieved the threshold value, the MOSFET begins to draw increasing load current and V_{DS} decreases. C_{DG} must not only discharge but its capacitance value also increases since it is inversely proportional to V_{DS}, namely:

$$C_{DG} \cong \frac{C_{DG}(0)}{V_{DG}^{n}} \qquad (2)$$

Unless the gate driver can quickly supply the current required to discharged C_{DG}, voltage fall will be slowed with increases in turn-on time.

Time interval t3<t<t4:

The MOSFET is now on so the gate voltage can rise to the overdrive level.

Turn-off interval t4<t<t6:

Turn-off occurs in reverse order. V_{GS} must drop back close to the threshold value before $R_{DS(on)}$ will start to increase. As V_{DS} starts to rise, the Miller effect due to C_{DG} re-occurs and impedes the rise of V_{DS} as C_{DG} recharges to V_{CC}.

Specific gate drive circuits for different applications are discussed and illustrated later in this paper.

MOSFET CHARACTERIZATION

The output characteristics (I_D vs V_{DS}) of the Fairchild Semiconductor Supersot^{TM} NDS351N are illustrated in Figures 8 and 9. The two distinct regions of operation in Figure 8 have been labeled "linear" and "saturated". To understand the difference, recall that the actual current path in a MOSFET is horizontal through the channel created under the gate oxide and then vertical through the drain. In the linear region of operation, the voltage across the MOSFET channel is not sufficient for the carriers to reach their maximum current density. The static $R_{DS(on)}$, defined simply as V_{DS}/I_{DS}, is a constant.

As V_{DS} is increased, the carriers reach their maximum drift velocity and the current amplitude cannot increase. Since the device is behaving like a current generator, it is said to have high output impedance. This is the so-called "saturation" regions. One should also note that in comparing MOSFET operation to Bipolar transistor, the linear and saturated regions are just the opposite to the MOSFET. The equal spacing between the output I_D curves for constant step in V_{GS} indicates that the transfer characteristics in Figure 9 will be linear in the saturated region.

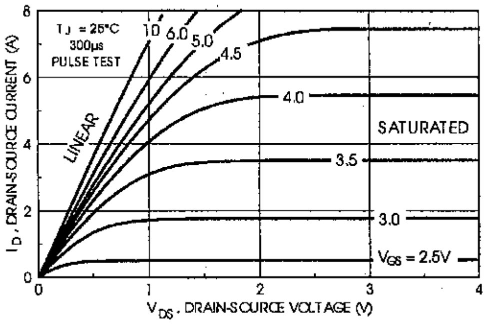


Figure 8. NDS351N Output Characteristics

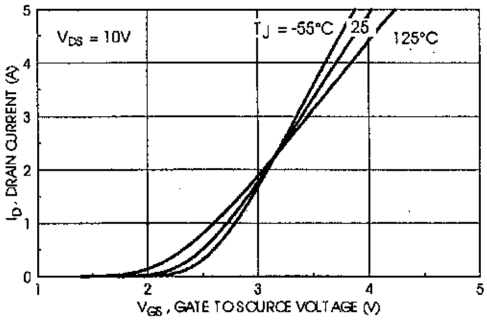


Figure 9. NDS351N Transfer Characteristics

IMPORTANCE OF THRESHOLD VOLTAGE

Threshold voltage $V_{GS(th)}$ is the minimum gate voltage that initiates drain current flow. $V_{GS(th)}$ can be easily measured on a Tektronix 576 curve tracer by connecting the gate to the drain and recording the required drain voltage for a specified drain current, typically 250µA. $V_{GS(th)}$ in Figure 9 is 1.6V. While a high value of $V_{GS(th)}$, can apparently lengthen turn-on delay time, a low value for Power MOSFET is undesirable for the following reasons:

1. $V_{GS(th)}$ decreases with increased temperature.
2. The high gate impedance of a MOSFET makes it susceptible to spurious turn-on due to gate noise.
3. One of the more common modes of failure is gate-oxide voltage punch-through. Low $V_{GS(th)}$ requires thinner oxides, which lowers the gate oxide voltage rating.

POWER MOSFET THERMAL MODEL

Like all other power semiconductor devices, MOSFETs operate at elevated junction temperature. It is important to observe their thermal limitations in order to achieve acceptable performance and reliability. Specification sheets contain information on maximum junction temperature ($T_{J(max)}$), safe operating areas, current ratings and electrical characteristics as a function of T_J where appropriate. However, since it is still not possible to cover all contingencies, it is still important that the designer perform some junction calculations to ensure that the device operates within specifications.

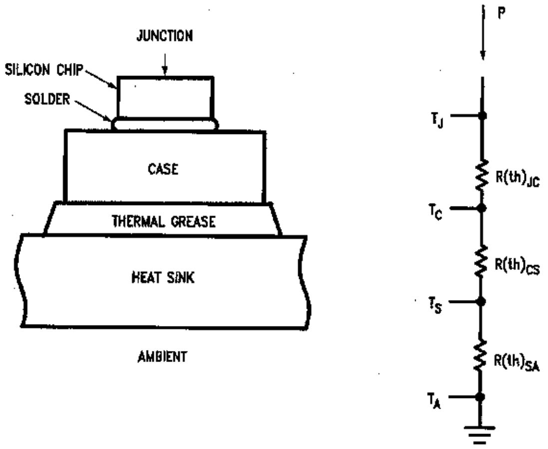


Figure10. MOSFET Steady-State Thermal Resistance Model

Figure 10 shows an elementary, steady-state, thermal model for any power semiconductor and the electrical analogue. The heat generated at the junction flows through the silicon pellet to the case or tab and then to the heat sink. The junction temperature rise above the surrounding environment is directly proportional to this heat flow and the junction-to-ambient thermal resistance. The following equation defined the steady-state thermal resistance $R_{\theta JA}$ between device junction to ambient:

$$R_{\theta JA} = \frac{T_J - T_A}{P} \qquad (3)$$

where:
T_J = average temperature at the device junction (°C)
T_A = average temperature at ambient (°C)
P = average heat flow in watts (W).

Note that for thermal resistance to be meaningful, two temperature reference points must be specified. Units for $R_{\theta JA}$ are °C/W.

The thermal model shows symbolically the locations for the reference points of junction temperature, case temperature, sink temperature and ambient temperature. These temperature reference define the following thermal resistances:

- $R_{\theta JC}$: Junction-to-Case thermal resistance.
- $R_{\theta CS}$: Case-to-Sink thermal resistance.
- $R_{\theta SA}$:Sink-to-Ambient thermal resistance.

Since the thermal resistances are in series:

$$R_{\theta JA} = R_{\theta JC} + R_{\theta CS} + R_{\theta SA} \qquad (4)$$

The design and manufacture of the device determines $R_{\theta JC}$ so that while $R_{\theta JC}$ will vary somewhat from device to device, it is the SOLE RESPONSIBILITY of the manufacturer to guarantee a maximum value for $R_{\theta JC}$. Both the user and manufacturer must cooperate in keeping $R_{\theta CS}$ to an acceptable maximum. Finally, the user has sole responsibility for the external heat sinking.
By inspection of Figure 10, one can write an expression for T_J:

$$T_J = T_A + P \times (R_{\theta JC} + R_{\theta CS} + R_{\theta SA}) \qquad (5)$$

While this appears to be a very simple formula, the major problem using it is due to the fact that the power dissipated by the MOSFET depends upon T_J. Consequently one must use either an iterative or graphical solution to find the maximum $R_{\theta SA}$ to ensure stability. But an explanation of transient thermal resistance is in order to handle the case of pulsed applications.

Use of steady-state thermal resistance is not satisfactory for finding peak junction temperatures for pulsed applications. Plugging in the peak power value results in overestimating the actual junction temperature while using the average power value underestimates the peak junction temperature at the end of the power pulse. The reason for the discrepancy lies in the thermal capacity of the semiconductor and its housing, i.e., its ability to store heat and to cool down before the next pulse.

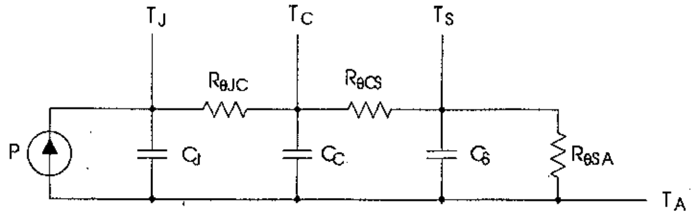


Figure 11. Transient Thermal Resistance Model

The modified thermal model for the MOSFET is shown in Figure 11. The normally distributed thermal capacitances have been lumped into single capacitors labeled C_J, C_C, and C_S. This simplification assumes current is evenly distributed across the silicon chip and that the only significant power losses occur in the junction. When a step pulse of heating power, P, is introduced at the junction, figure 12a shows that T_J will rise at an exponential rate to some steady state value dependent upon the response of the thermal network. When the power input is terminated at time t2, T_J will decrease along the curve indicated by Tcool in Figure 12a back to its initial value. Transient thermal resistance at time t is thus defined as:

$$Z_{\theta JC} = \frac{\Delta T_{JC}(t)}{P} \qquad (6)$$

The transient thermal resistance curve approaches the steady-state value at long times and the slope of the curve for short times is inversely proportional to C_J. In order to use this curve

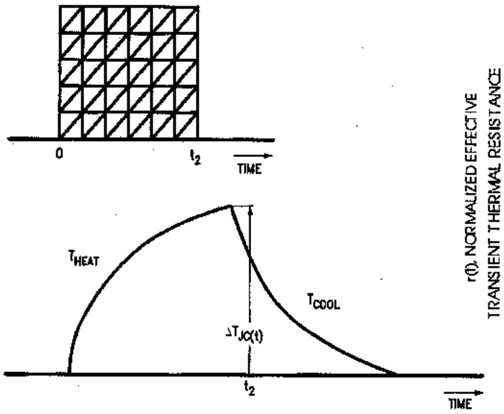


Figure 12a. Junction Temperature Response to a Step Pulse of Heating Power

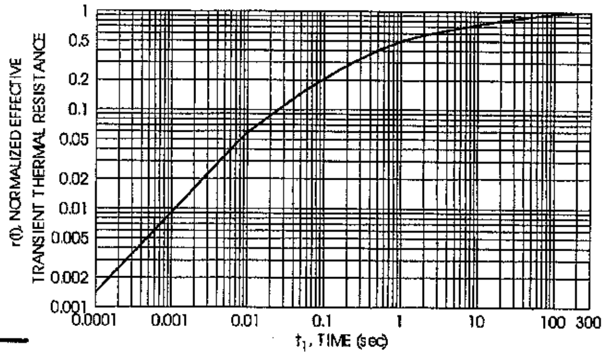


Figure 12b. Transient Thermal Resistance Curve for NDS351N

with confidence, it must represent the highest values $Z_{\theta JC}$ for each time interval that can be expected from the manufacturing distribution of the products.

While predicting T_J in response to a series of power pulses becomes very complex, superposition of power pulses offers a rigorous numerical method of using the transient thermal resistance curve to secure a solution. Superposition tests the response of a network to any input function by replacing the input with an equivalent series of superimposed positive and negative step functions. Each step function must start from zero and continue to the time for which T_J is to be computed. For example, Figure 13 illustrates a typical train of heating pulses.

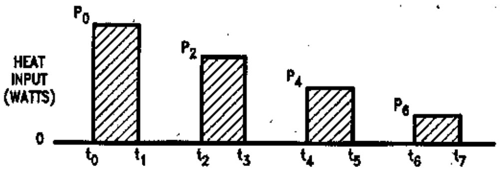


Figure 13a. Heat Input

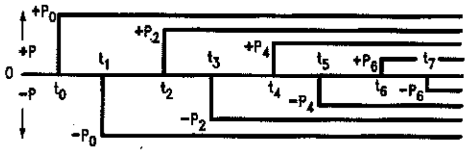


Figure 13b. Equivalent Heat Input by Superposition of Power Pulses

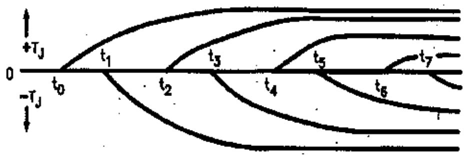


Figure 13c. Junction Temperature Response to Individual Power Pulse

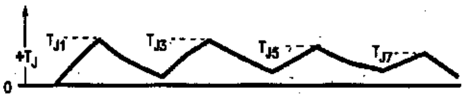


Figure 13d. Use of Superposition to Determine Peak T_J

T_J at time is given by:

$$T_J(t) = T_J(0) + \Sigma P_i \times [Z_{\theta JC}(t_n - t_i) - Z_{\theta JC}(t_n - t_i + 1)] \qquad (7)$$

The typical use condition is to compute the peak junction temperature at thermal equilibrium for a train of equal amplitude power pulses as shown in Figure 14.

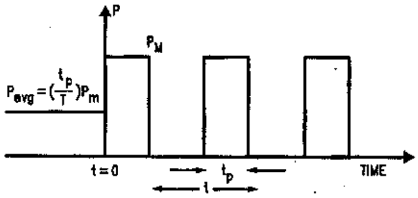


Figure 14a. Train of Power Pulses

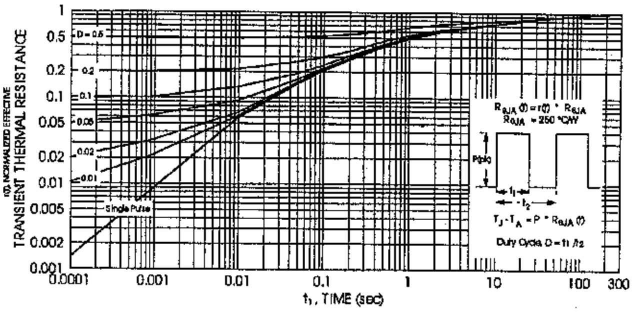


Figure 14b. Normalized r(t) for NDS351N

To further simplify this calculation, the bracketed expression in equation (G) has been plotted for all Fairchild Semiconductor Power MOSFETs, as exemplified by the plot of $Z_{\theta JC}$ in Figure 14b. From this curve, one can readily calculate T_J if one knows P_M. $Z_{\theta JC}$ and T_C using the expression:

$$T_J = T_C + P_M \times Z_{\theta JC} \qquad (8)$$

Example: Compute the maximum junction temperature for a train of 1W, 10ms wide heating pulses repeated every 100ms. Assume a case temperature of 55°C.
Duty factor=0.1
From Figure 14b: $Z_{\theta JC}$=0.14*250°C/W=35°C/W
Substituting into Equation (7):
$T_{J(max)}$=55+1*35=90°C

SAFE OPERATING AREA

The Power MOSFET is not subjected to forward or reverse bias second breakdown, which can easily occur in transistors. Second breakdown is a potentially catastrophic condition in transistors caused by thermal hot spots in the silicon as the transistor turns on or off. However in the MOSFET, the carriers travel through the device much as if it were a bulk semiconductor, which exhibits positive temperature coefficient. If current attempts to self-constrict to a localized area, the increasing temperature of the spot will raise the spot resistance due to positive temperature coefficient of the bulk silicon. The ensuing higher voltage drop will tend to redistribute the current away from the hot spot. Figure 15 shows the safe operating area of the Fairchild Semiconductor Supersot^{TM} NDS351N device.

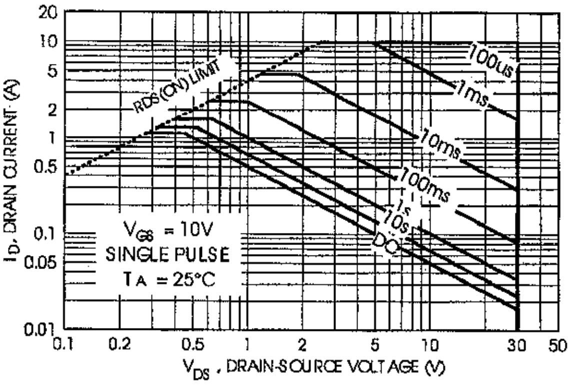


Figure 15. Safe Operating Area of NDS351N

Note that the safe area boundaries are only thermally limited and exhibit no derating for second breakdown. This shows that while the MOSFET transistor is very rugged, it may still be destroyed thermally by forcing it to dissipate too much power.

ON-RESISTANCE $R_{DS(on)}$

The on-resistance of a Power MOSFET is a very important parameter because it determines how much current the device can carry for low to medium frequency (less than 200kHz) applications. After being turned on, the on-state is defined simply as its on-state voltage divided by on-state current. When conducting current as a switch, the conduction losses P are:

$$P_C = I^2_{D(RMS)} \times R_{DS(ON)} \qquad (9)$$

To minimize $R_{DS(on)}$, the applied gate signal should be large enough to maintain operation in the linear or ohmic region as shown in Figure 8. Fairchild Semiconductor SUPERSOT™-3 NDS351N will conduct its rated current for V_{GS}=4.5V, which is also the value used to generate the curves of $R_{DS(on)}$ vs I_D and T_J that are shown in Figure 16 for the Fairchild Semiconductor Supersot NDS351N. Since $R_{DS(on)}$ is a function of T_J, Figure 16 plots this parameter at varies junction temperatures. Note that as the drain current rises, $R_{DS(on)}$ increases once I_D exceeds the rated current value. Because the MOSFET is a majority carrier device, the component of $R_{DS(on)}$ due to the bulk resistance of the N- silicon in the drain region increases with temperature as well. While this must be taken into account to avoid thermal runaway, it does facilitate parallel operation of MOSFETs. Any imbalance between MOSFETs does not result in current hogging because the device with the most current heat up and ensuing higher on-voltage will divert some current to the other devices in parallel.

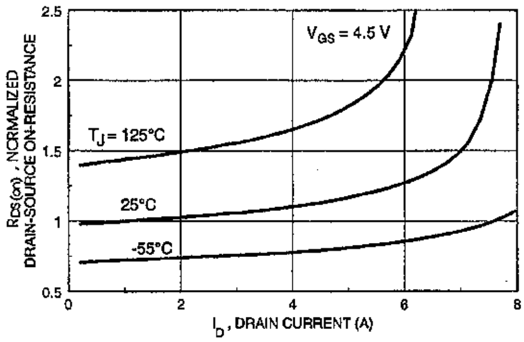


Figure 16. $R_{DS(on)}$ of NDS351N

TRANSCONDUCTANCE

Since MOSFETs are voltage controlled, it has become necessary to resurrect the term transconductance g_{FS}, commonly used in the past with electron tubes. Referring to Figure 8, g_{FS} equals to the change in drain current divided by the change in gate voltage for a constant drain voltage. Mathematically:

$$g_{fs}(Siemens) = \frac{dI_D(A)}{dV_{GS}(V)} \qquad (10)$$

Transconductance varies with operating conditions, starting at 0 for $V_{GS}<V_{GS(th)}$ and peaking at a finite value when the device is fully saturated. It is very small in the ohmic region because the device cannot conduct any more current. Transconductance is useful in designing linear amplifiers and does not have any significance in switching power supplies.

GATE DRIVE CIRCUITS FOR POWER MOSFETs

The drive circuit for a Power MOSFET will affect its switching behavior and its power dissipation. Consequently the type of drive circuitry depends upon the application. If on-state power losses due to $R_{DS(on)}$, will predominate, there is little point in designing a costly drive circuit. This power dissipation is relatively independent of gate drive as long as the gate-source voltage exceeds the threshold voltage by several volts and an elaborate drive circuit to decrease switching times will only create additional EMI and voltage ringing. In contrast, the drive circuit for a device switching at 200KHz or more will affect the power dissipation since switching losses are a significant part of the total power dissipation.

Compare to a junction transistor, the switching losses in a MOSFET can be made much smaller but these losses must still be taken into consideration. Examples of several typical loads along with the idealized switching waveforms and expressions for power dissipation are given in Figure 17 to 19.

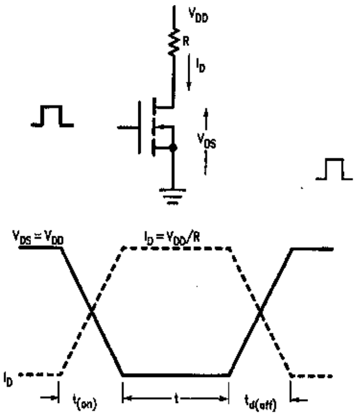


Figure17. Resistive Load Switching Waveforms

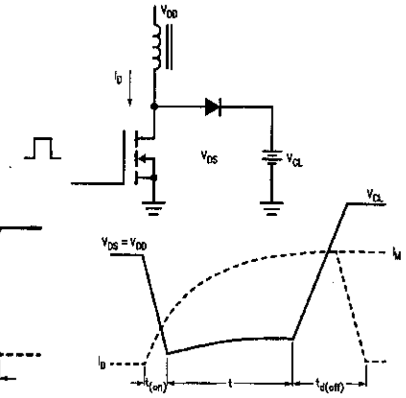


Figure18. Clamped Inductive Load Switching Waveforms

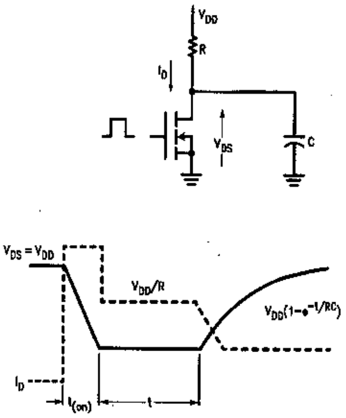


Figure19. Capacitive Load Switching Waveforms

Their power losses can be calculated from the general expression:

$$P_D = \left(\frac{1}{T}\int I_D(t) \times V_{DS}(t)dt\right) \times f_S \qquad (11)$$

where f_S =Switching frequency.

For the idealized waveforms shown in the figures, the integration can be approximated by the calculating areas of triangles:
Resistive loads:

$$P_D \approx \frac{V_{DD}^2}{R}\left[\frac{t_{on}+t_{off}}{6} + R_{DS(on)} \times T\right] \times f_S$$

Inductive Load:

$$P_D \approx \frac{V_{CL} \times I_M \times (t_{off}) \times f_S}{2} + P_C$$ where P_C = conduction loss during period T.

Capacitive load:

$$P_D = \left(\frac{C \times V_{DD}^2}{2} + \frac{V_{DD}^2 \times R_{DS(ON)}}{R^2} \times T\right) \times f_S$$

Gate losses and blocking losses can usually be neglected. Using these equations, circuit designer is able to estimate the required heat sink. A final heat run in a controlled temperature environment is necessary to ensure thermal stability.

Since a MOSFET is essentially voltage controlled, the only gate current required is that necessary to charge the input capacitance Ciss. In contrast to a 10A transistor, which may require a base current of 2A to ensure saturation, a Power MOSFET can be driven directly by CMOS or open-collector TTL logic circuit similar to that in Figure 20.

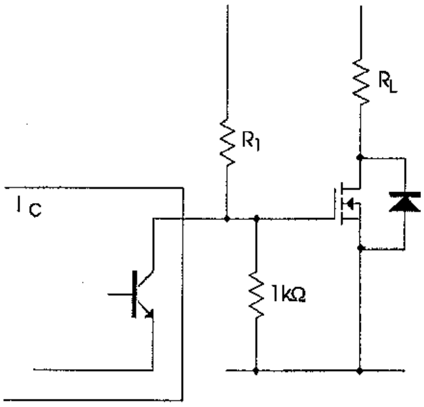


Figure 20. Open Collector TTL Drive Circuit

Turn-on speed depends upon the selection of resistor R1, whose minimum value will be determined by the current sinking rating of the IC. It is essential that an open collector TTL buffer be used since the voltage applied to the gate must exceed the MOSFET threshold voltage. CMOS devices can be used to drive the power device directly since they are capable of operating 15V supplies.

Interface ICs, originally intended for other applications, can be used to drive the Power MOSFETs, as shown below in Figure 21.

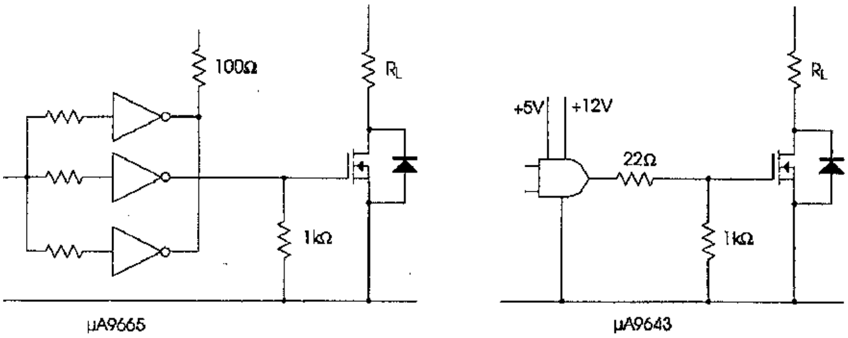


Figure 21. Interface ICs Used to Drive Power MOSFETs

Most frequently, switching power supply applications employ a pulse width modulator IC with an NPN transistor output stage. This output transistor is ON when the MOSFET should be ON, hence the type of drive used with open-collector TTL devices cannot be used. Figures 22 and 23 give examples of typical drive circuits used with PWM ICs.

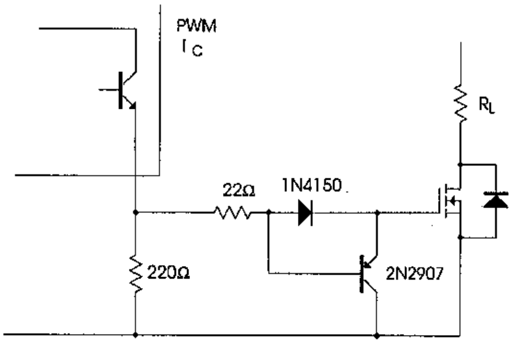


Figure 22. Circuit for PWM IC Driving MOSFET. The PNP Transistor Speeds Up Turn-Off

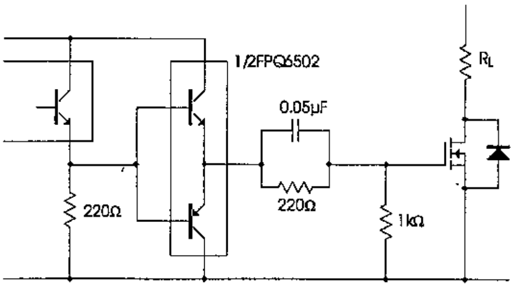


Figure 23. Emitter Follower with Speed-Up Capacitor

Isolation: Off-line switching power supplies use power MOSFETs in a half bridge configuration because inexpensive, high voltage devices with low $R_{DS(on)}$ are not available.

Since one of the power devices is connected to the positive rail, its drive circuitry is also floating at a high potential. The most versatile method of coupling the drive circuitry is to use a pulse transformer. Pulse transformers are also normally used to isolate the logic circuitry from the MOSFETs operating at high voltage to protect it from a MOSFET failure.

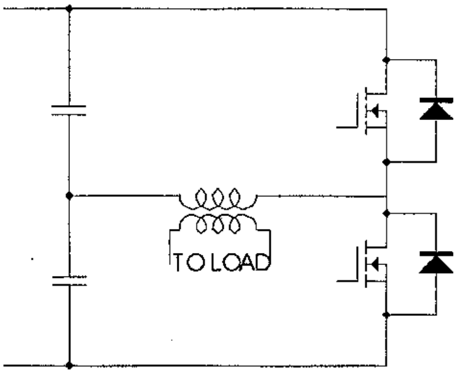


Figure 24. Half-Bridge Configuration

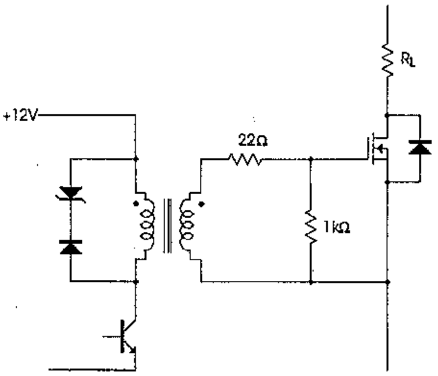


Figure 25. Simple Pulse Transformer Drive Circuit. The Transistor May Be a Part of a PWM IC if Applicable

The zener diodes shown in Figure 25 is included to reset the pulse transformer quickly. The duty cycle can approach 50% with a 12V zener diode. For better performance at turn-off, a PNP transistor can be added as shown in Figure 26.

Figure 27 illustrates an alternate method to reverse bias the MOSFET during turn-off by inserting a capacitor in series with the pulse transformer. The capacitor also ensures that the pulse transformer will not saturate due to DC bias.

Opto-isolators may also be used to drive power MOSFETs but their long switching times make them suitable only for low frequency applications.

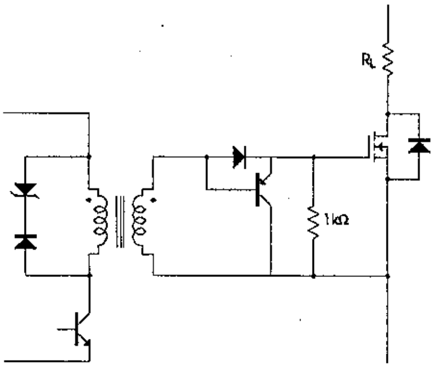


Figure 26. Improved Performance at Turn-Off with a Transistor

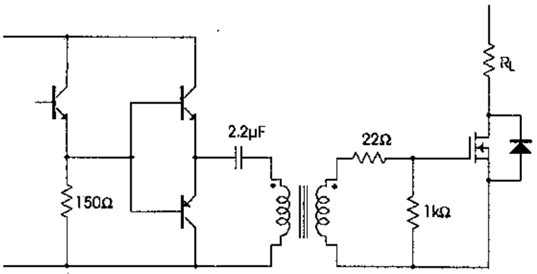


Figure 27. Emitter Follower Driver with Speed-Up Capacitor

SELECTING A DRIVE CIRCUIT

Any of the circuits shown are capable of turning a Power MOSFET on and off. The type of circuit depends upon the application. The current sinking and sourcing capabilities of the drive circuit will determine the switching time and switching losses of the power device. As a rule, the higher the gate current at turn-on and turn-off, the lower the switching losses will be. However, fast drive circuits may produce ringing in the gate circuit and drain circuits. At turn-on, ringing in the gate circuit may produce a voltage transient in excess of the maximum V_{GS} rating, which will puncture the gate oxide and destroy it. To prevent this occurrence, a zener diode of appropriate value may be added to the circuit as shown in Figure 28. Note that the zener should be mounted as close as possible to the device.

At turn-off, the gate voltage may ring back up to the threshold voltage and turn on the device for a short period. There is also the possibility that the drain-source voltage will exceed its maximum rated voltage due to ringing in the drain circuit. A protective RC snubber circuit or zener diode may be added to limit drain voltage to a safe level.

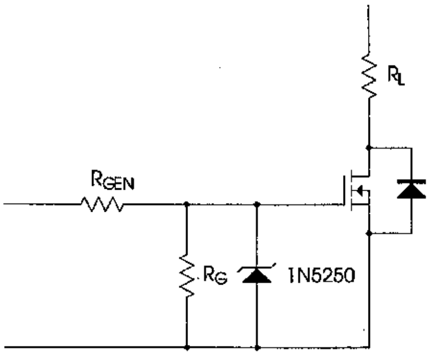


Figure 28. Zener Diode to Prevent Excessive Gate-Source Voltages

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HiSeC™
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SuperSOT™-8
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PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

APPENDIX 5

DATA SHEET

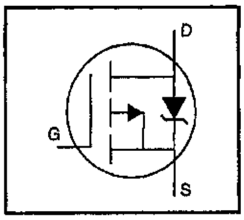
International
IOR Rectifier

PD-9.351F

IRF9620

HEXFET® Power MOSFET

- Dynamic dv/dt Rating
- P-Channel
- Fast Switching
- Ease of Paralleling
- Simple Drive Requirements



$V_{DSS} = -200V$

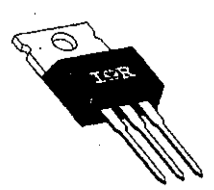
$R_{DS(on)} = 1.5\Omega$

$I_D = -3.5A$

Description

The HEXFET technology is the key to International Rectifier's advanced line of power MOSFET transistors. The efficient geometry and unique processing of the HEXFET design achieve very low on-state resistance combined with high transconductance and extreme device ruggedness.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ $T_C = 25°C$	Continuous Drain Current, V_{GS} @ -10 V	-3.5	A
I_D @ $T_C = 100°C$	Continuous Drain Current, V_{GS} @ -10 V	-2.0	
I_{DM}	Pulsed Drain Current ①	-14	
P_D @ $T_C = 25°C$	Power Dissipation	40	W
	Linear Derating Factor	0.32	W/°C
V_{GS}	Gate-to-Source Voltage	±20	V
I_{LM}	Inductive Current, Clamp	-14	A
dv/dt	Peak Diode Recovery dv/dt ③	-5.0	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting Torque, 6-32 or M3 screw	10 lbf•in (1.1 N•m)	

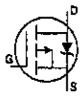
Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	—	3.1	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	—	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	—	62	

Electrical Characteristics @ $T_J = 25°C$ (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	-200	—	—	V	V_{GS}=0V, I_D=-250µA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	-0.22	—	V/°C	Reference to 25°C, I_D=-1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	1.5	Ω	V_{GS}=-10V, I_D=-1.5A ④
$V_{GS(th)}$	Gate Threshold Voltage	-2.0	—	-4.0	V	V_{DS}=V_{GS}, I_D=-250µA
g_{fs}	Forward Transconductance	1.0	—	—	S	V_{DS}=-50V, I_D=-1.5A ④
I_{DSS}	Drain-to-Source Leakage Current	—	—	-100	µA	V_{DS}=-200V, V_{GS}=0V
		—	—	-500		V_{DS}=-160V, V_{GS}=0V, T_J=125°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	-100	nA	V_{GS}=-20V
	Gate-to-Source Reverse Leakage	—	—	100		V_{GS}=20V
Q_g	Total Gate Charge	—	—	22	nC	I_D=-4.0A
Q_{gs}	Gate-to-Source Charge	—	—	12		V_{DS}=-160V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	10		V_{GS}=-10V See Fig. 11 & 18 ④
$t_{d(on)}$	Turn-On Delay Time	—	15	—	ns	V_{DD}=-100V
t_r	Rise Time	—	25	—		I_D=-1.5A
$t_{d(off)}$	Turn-Off Delay Time	—	20	—		R_G=50Ω
t_f	Fall Time	—	15	—		R_D=67Ω See Figure 17 ④
L_D	Internal Drain Inductance	—	4.5	—	nH	Between lead, 6 mm (0.25in.) from package and center of die contact 
L_S	Internal Source Inductance	—	7.5	—		
C_{iss}	Input Capacitance	—	350	—	pF	V_{GS}=0V
C_{oss}	Output Capacitance	—	100	—		V_{DS}=-25V
C_{rss}	Reverse Transfer Capacitance	—	30	—		f=1.0MHz See Figure 10

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
I_S	Continuous Source Current (Body Diode)	—	—	-3.5	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ①	—	—	-14		
V_{SD}	Diode Forward Voltage	—	—	-7.0	V	T_J=25°C, I_S=-3.5A, V_{GS}=0V ④
t_{rr}	Reverse Recovery Time	—	300	450	ns	T_J=25°C, I_F=-3.5A
Q_{rr}	Reverse Recovery Charge	—	1.9	2.9	µC	di/dt=100A/µs ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is neglegible (turn-on is dominated by L_S+L_D)				

Notes:

① Repetitive rating; pulse width limited by max. junction temperature (See Figure 5)

② Not Applicable

③ I_{SD}≤-3.5A, di/dt≤95A/µs, V_{DD}≤$V_{(BR)DSS}$, T_J≤150°C

④ Pulse width ≤ 300 µs; duty cycle ≤2%.

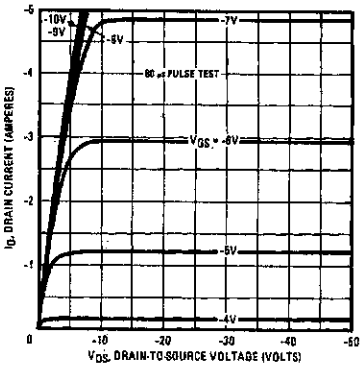


Fig. 1 — Typical Output Characteristics

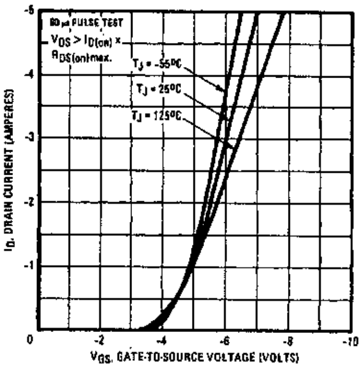


Fig. 2 — Typical Transfer Characteristics

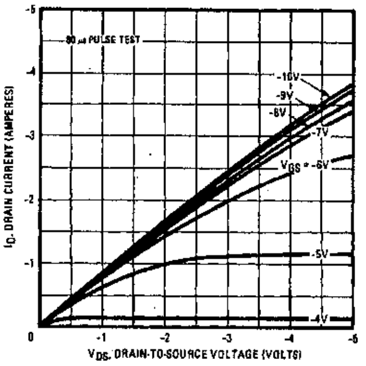


Fig. 3 — Typical Saturation Characteristics

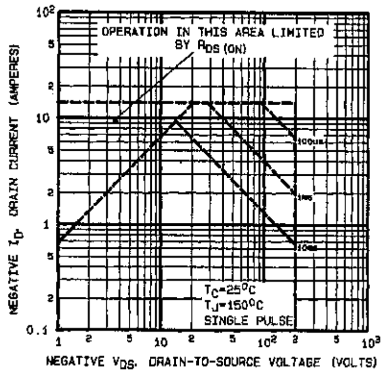


Fig. 4 — Maximum Safe Operating Area

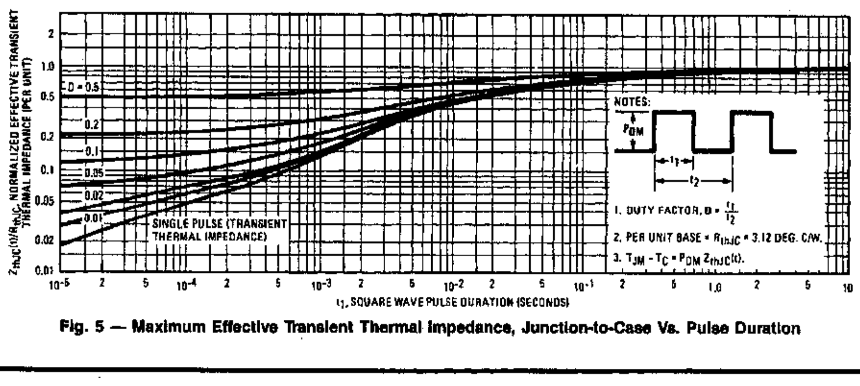


Fig. 5 — Maximum Effective Transient Thermal Impedance, Junction-to-Case Vs. Pulse Duration

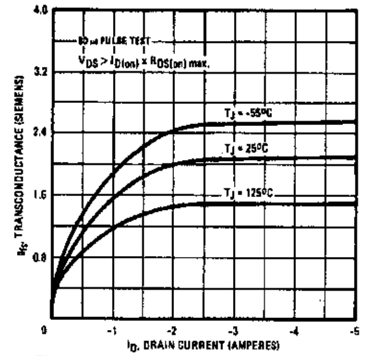


Fig. 6 — Typical Transconductance Vs. Drain Current

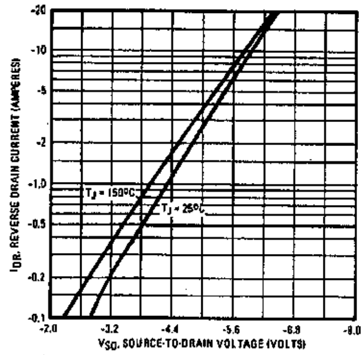


Fig. 7 — Typical Source-Drain Diode Forward Voltage

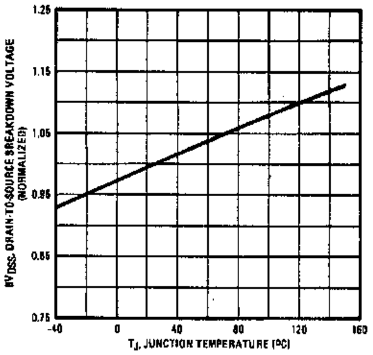


Fig. 8 — Breakdown Voltage Vs. Temperature

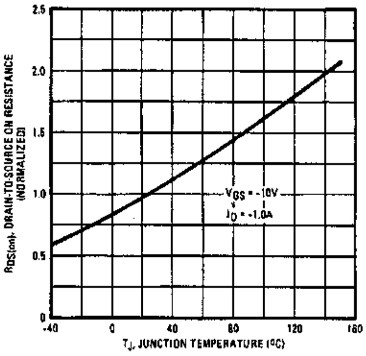


Fig. 9 — Normalized On-Resistance Vs. Temperature

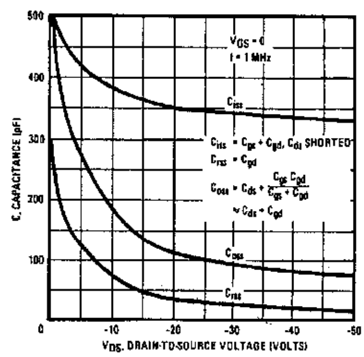


Fig. 10 — Typical Capacitance Vs. Drain-to-Source Voltage

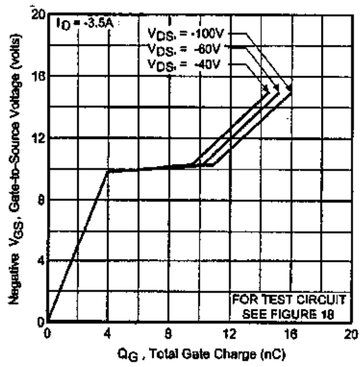


Fig. 11 — Typical Gate Charge Vs. Gate-to-Source Voltage

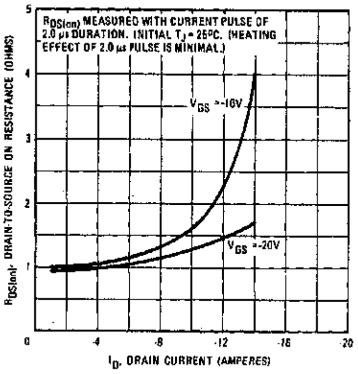


Fig. 12 — Typical On-Resistance Vs. Drain Current

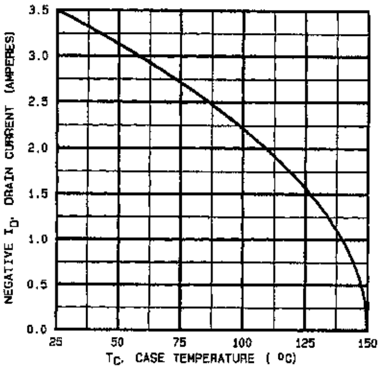


Fig. 13 — Maximum Drain Current Vs. Case Temperature

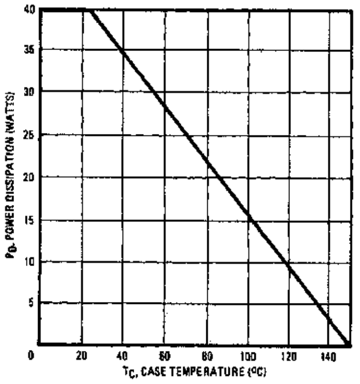


Fig. 14 — Power Vs. Temperature Derating Curve

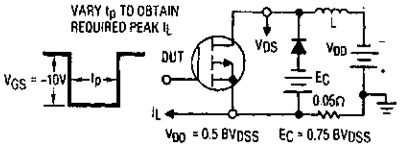


Fig. 15 — Clamped Inductive Test Circuit

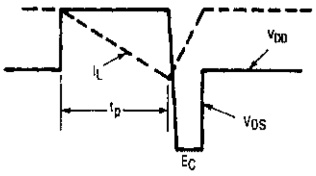


Fig. 16 — Clamped Inductive Waveforms

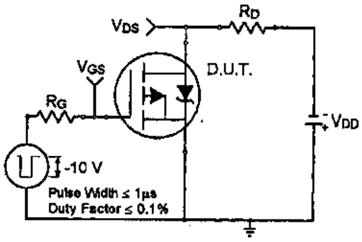


Fig. 17a — Switching Time Test Circuit

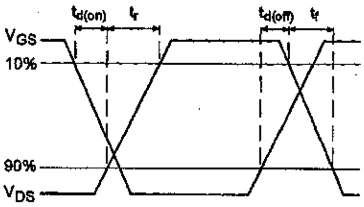


Fig. 17b — Switching Time Waveforms

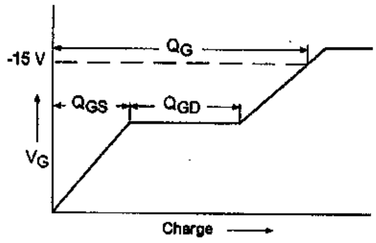


Fig. 18a — Basic Gate Charge Waveform

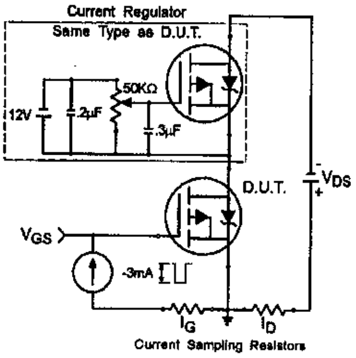


Fig. 18b — Gate Charge Test Circuit

Appendix A: Figure 14, Peak Diode Recovery dv/dt Test Circuit – See page 1506

Appendix B: Package Outline Mechanical Drawing – See page 1509

Appendix C: Part Marking Information – See page 1516

Appendix E: Optional Leadforms – See page 1525

International
IOR Rectifier

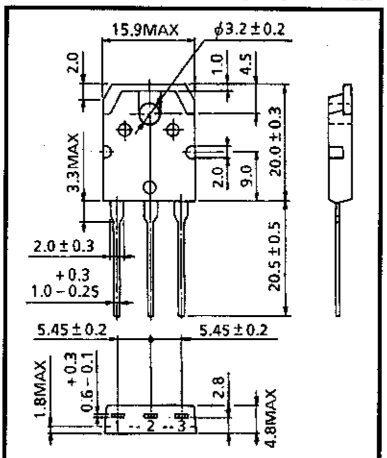
TOSHIBA INSULATED GATE BIPOLAR TRANSISTOR SILICON N-CHANNEL IGBT

GT15J101

IGH POWER SWITCHING APPLICATIONS

OTOR CONTROL APPLICATIONS

Unit in mm



1. GATE
2. COLLECTOR (HEAT SINK)
3. EMITTER

JEDEC	—
EIAJ	—
TOSHIBA	2-16C1C

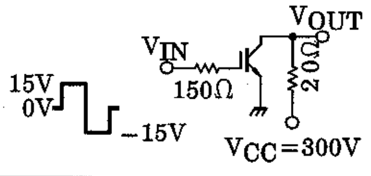
Weight : 4.6g

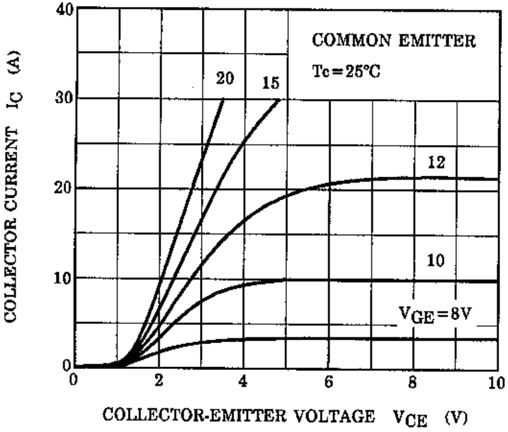
- High Input Impedance
- High Speed : t_f=0.35μs (Max.)
- Low Saturation Voltage : $V_{CE(sat)}$=4.0V (Max.)
- Enhancement-Mode

AXIMUM RATINGS (Ta = 25°C)

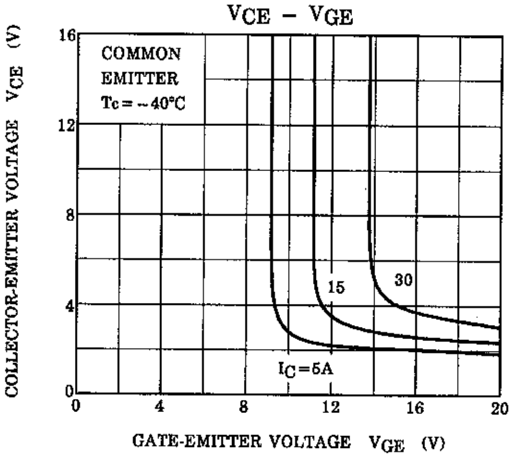
CHARACTERISTIC		SYMBOL	RATING	UNIT
ollector-Emitter Voltage		V_{CES}	600	V
ate-Emitter Voltage		V_{GES}	±20	V
ollector Current	DC	I_C	15	A
	1ms	I_{CP}	30	
ollector Power Dissipation Tc=25°C)		P_C	100	W
unction Temperature		T_j	150	°C
torage Temperature Range		T_{stg}	−55~150	°C

ECTRICAL CHARACTERISTICS (Ta = 25°C)

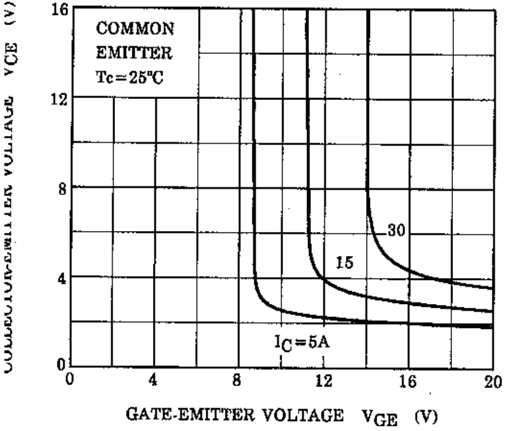
CHARACTERISTIC		SYMBOL	TEST CONDITION	MIN.	TYP.	MAX.	UNIT
ate Leakage Current		I_{GES}	V_{GE}=±20V, V_{CE}=0	—	—	±500	nA
ollector Cut-off Current		I_{CES}	V_{CE}=600V, V_{GE}=0	—	—	1.0	mA
ate-Emitter Cut-off Voltage		$V_{GE(OFF)}$	I_C=15mA, V_{CE}=5V	3.0	—	6.0	V
ollector-Emitter aturation Voltage		$V_{CE(sat)}$	I_C=15A, V_{GE}=15V	—	3.0	4.0	V
nput Capacitance		C_{ies}	V_{CE}=10V, V_{GE}=0, f=1MHz	—	1100	—	pF
witching ime	Rise Time	t_r		—	0.30	0.60	μs
	Turn-on Time	t_{on}		—	0.40	0.80	
	Fall Time	t_f		—	0.15	0.35	
	Turn-off Time	t_{off}		—	0.50	1.00	



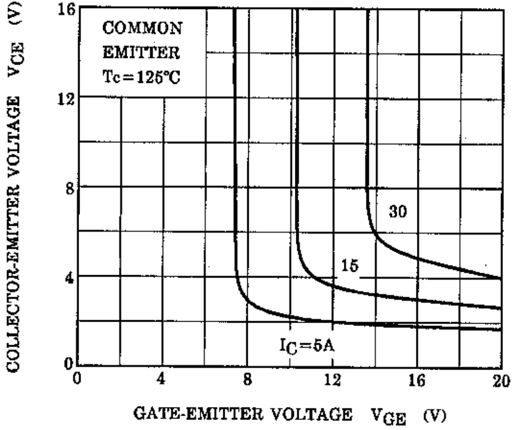
I_C – V_{CE}



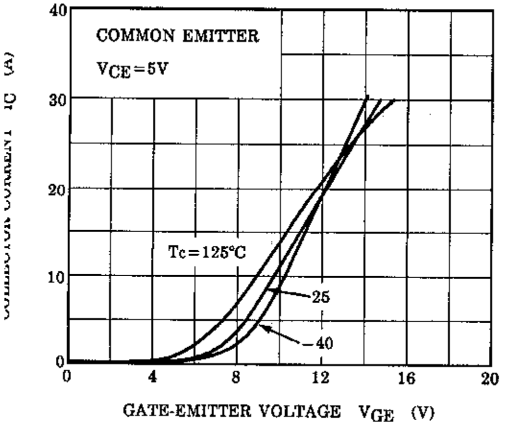
V_{CE} – V_{GE}



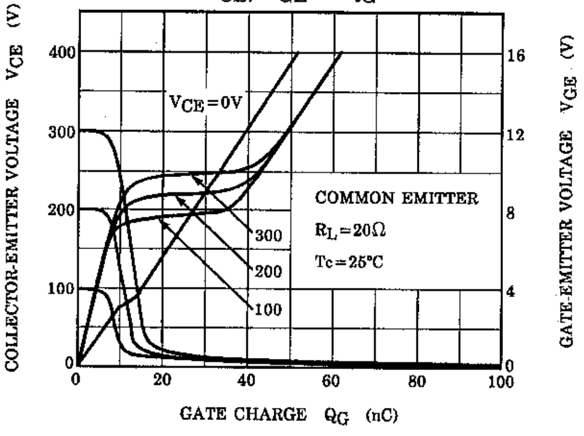
V_{CE} – V_{GE}



V_{CE} – V_{GE}

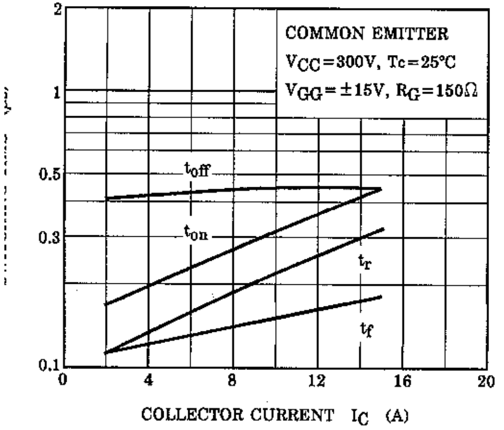


I_C – V_{GE}

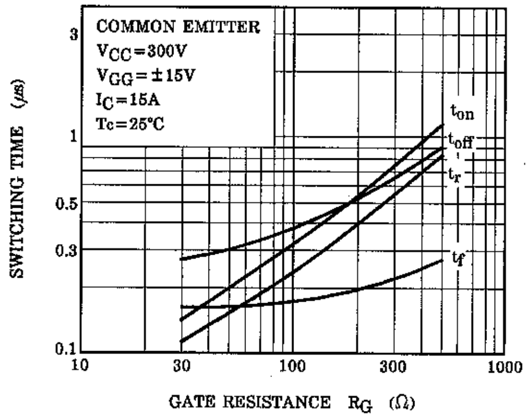


V_{CE}, V_{GE} – Q_G

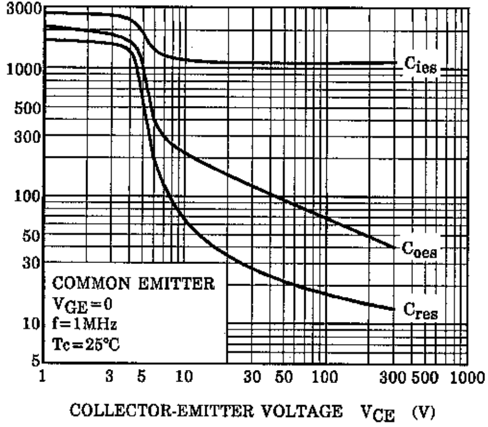
SWITCHING TIME – I_C



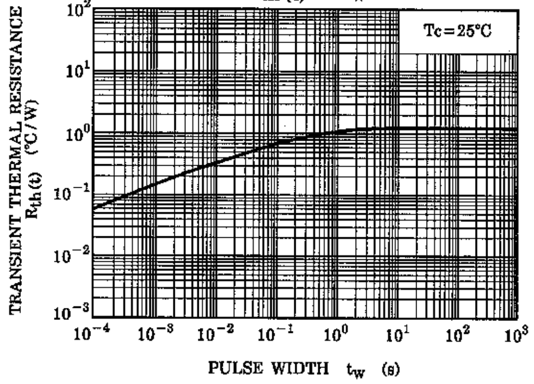
SWITCHING TIME – R_G



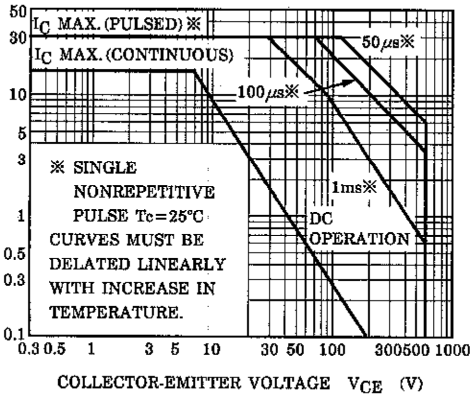
C – V_{CE}



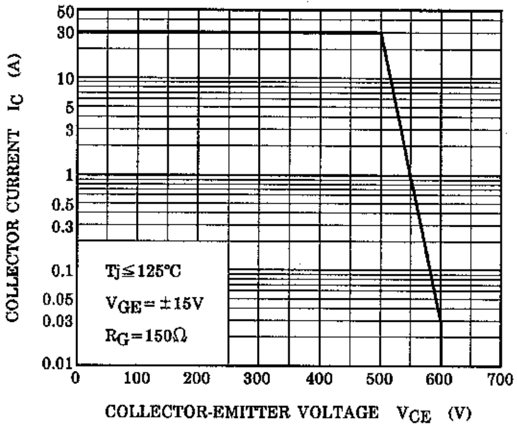
$R_{th}(t)$ – t_w



SAFE OPERATING AREA



REVERSE BIAS SOA



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APPENDIX 6

SWG TABLE