Traffic Detection by Inductive Loops

Abstract
Inductive loop traffic detectors are a very commonplace technology, however the physics behind their operation is quite complex – involving the ferromagnetic effect, magnetic induction and eddy currents. Despite their widespread use, cost and time constraints may see the end of inductive loops in favour of newer technologies.

Introduction
Inductive loop detectors have become the most commonly used method of traffic detection since their introduction over 50 years ago. In most cities, they are utilised to reduce traffic congestion. But how exactly do inductive loops work? Some sources, such as HowStuffWorks.com (2000) – which suggests that detection is based solely on the ferromagnetic effect – tend to oversimplify the physics involved. This report outlines the basics of inductive loops and explores how vehicles are really detected by these ubiquitous devices.

Discussion
Basic Setup
An inductive loop detector generally consists of three main components: (i) two to three turns of wire underneath the road surface, (ii) a lead-in cable connecting the loop to the detector, and (iii) an electronics unit that detects the presence of vehicles above the loop (Federal Highway Administration [FHWA] 2006). A typical setup is shown in Figure 1.

Magnetic Field around the Loop
The “active” part of the detector is the wire loop. The electronics unit transmits a current through the loop, causing a magnetic field to form around the wire, as stated by Oersted’s law. The direction of the magnetic field around the wire is given by the right-hand rule. Figure 2 shows the magnetic field around a single-turn loop (the white arrows).

The loop can be considered to act as a solenoid, and thus the magnetic field above the loop in
Figure 2 would be north, as given by the right-hand grip rule.

**Inductance**

Rather than using DC current, the electronics unit actually transmits AC current through the loop at a constant frequency somewhere between 10 and 200 kHz (FHWA 2006). The loop and lead-in coil act as a tuned circuit. The electronics unit monitors the resultant frequency of the loop, as the frequency of the loop decreases as its inductance decreases (FHWA 2006).

The alternating flow of current causes inductance – the ability to resist changes in current – in the loop. The formula for calculating the inductance of a coil is:

\[ L = \frac{NBA}{l} \]

where \( L \) = inductance (H), \( N \) = number of turns, \( B \) = magnetic flux density (webers/m\(^2\)), \( A \) = cross sectional area of coil (m\(^2\)) and \( I \) = current flowing through coil (A).

However, this equation does not allow for a change in the material forming the core of the coil, or for the non-uniform flux inside a coil whose length is longer than its diameter.

According to the FHWA (2006), the formula for the inductance produced by a roadway loop, which has a non-uniform flux, is:

\[ L = \frac{\mu_r\mu_0 N^2 A F'}{l} \]

where \( L \) = inductance (H), \( \mu_r \) = relative permeability of material (1 for air), \( \mu_0 = 4\pi * 10^{-7} \) henrys per metre, \( N \) = number of coils, \( A \) = cross sectional area of coil (m\(^2\)), \( l \) = length of coil (m), and \( F' \) = factor to account for non-uniform flux.

This formula shows that the amount of inductance is proportional to the relative permeability of the core material (\( \mu_r \)). The relative permeability of iron is approximately 5000 times greater than that of air (Wikipedia 2016b); therefore a coil with an iron core has a much higher inductance than a coil with an air core, as shown in Appendix 1.

When a vehicle (or any other large iron mass) is above the inductive loop detector, the vehicle acts as the core of the coil and increases its inductance (this is known as the “ferromagnetic effect”). Although the greatest increase in inductance occurs when a metal object passes through the loop, there is still a noticeable effect when the metal passes over the loop.

Despite this, the ferromagnetic effect does not cause the change sensed by the detector. Eddy currents induced in the vehicle decrease the inductance of the loop even more than the ferromagnetic effect raises it; therefore the net effect is a decrease in inductance. Eddy currents are explored in the following section.

**Eddy Currents**

An electrically conductive object (e.g. a metal) consists of many minute charges which are free to move (electrons). In the case of a stationary car above an inductive loop, the magnetic field of the loop is constantly changing (reversing), due to the alternating current. This means that a magnetic force is imposed on each charge in the conductor, and the
charges subsequently move through the conductor. This creates a current (an eddy current) in the conductive object, as predicted by Faraday’s law of induction (Wikipedia 2016b). An example of eddy currents caused by an inductive loop is shown in Figure 3. The blue lines show the magnetic field around the loop, and the red lines show the induced current in the metal surface.

The eddy currents create another magnetic field in the metal object (as stated by Oersted’s law). According to Lenz’s law, this induced magnetic field opposes the magnetic field that created it (that of the inductive loop), and therefore acts in the opposite direction to the loop’s magnetic field. This decreases the magnetic flux density of the loop, which in turn reduces the inductance of the loop, as the inductance is proportional to the magnetic flux density \(L = \frac{NBA}{I}\) for a coil.

The decrease in inductance is sensed by the electronics unit, which triggers the traffic lights to change.

Figure 4 illustrates how eddy currents are induced in the wheels and frame of a bicycle above an inductive loop. The white arrows show the induced magnetic flux, and the black dashed arrows indicate the induced eddy currents opposing the magnetic field.

**System Layout**

As inductive loop detectors rely on a number of complex phenomena to operate, proper system layout is very important in order to prevent false triggers or reduced accuracy. The loop must be placed less than 5 cm below the surface of the road, otherwise sensitivity will be lost (Marsh Products 2000). Other precautions taken include: soldering all connections, twisting the lead-in wires to prevent unwanted induction, removing any metal reinforcement around the area, and ensuring that no air pockets remain once the wire loops are sealed into the road (Marsh...
A typical layout is illustrated in Figure 1, which shows a loop under the road surface, lead-in wires, and an electronics unit that senses any change in frequency. Two or three turns are typically used in the loop (FHWA 2006), as increasing the number of turns does not increase the sensitivity of the loop, but the stability (Marsh Products 2000). Therefore increasing the number of turns results in decreased sensitivity, as the loop is more stable.

A number of loops can be used to monitor multiple lanes, as shown in Figure 5. Each loop can be connected to a separate channel on the detector, so that it is possible to determine which lane a vehicle is in. Alternatively, the loops can be joined together, and will only be able to detect that a vehicle is present in one of the lanes. If the loops are connected in series, then the total inductance is the sum of each loop’s inductance, i.e. \( L_{total} = L_1 + L_2 + L_3 \ldots \)

If the loops are connected in parallel, the total inductance will be: \( \frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \ldots \)

The total inductance of the loop system needs to be kept within the operating range of the electronics unit, typically between 50 and 700 µH.

History

Inductive loop detectors were first used in the early 1960s (FHWA 2006). The original systems were quite simple and used small loops to count vehicle numbers, and large loops to detect the presence of vehicles in a lane (Potter n.d.). In 1975, digital loop detectors came into use. They were much more reliable, and were also able to detect smaller vehicles like motorcycles due to the ability to tune their sensitivity (Potter n.d.). Programmable software based detectors were introduced in the mid 1990s. They have allowed greater flexibility in detection systems, better diagnostics, and the ability to use inductance ‘signatures’ to detect the vehicle type (Potter n.d.). This adaptability has led to a wide range of uses for inductive loops.

Uses of Inductive Loop Detectors

There are many different applications for inductive loops, including detecting vehicles at intersections, counting traffic, monitoring the speed of vehicles, and sensing the presence of trains at railroad crossings (Marsh Products 2000; FHWA 2006). Inductive loops are currently utilized to provide information on the density and speed of traffic, which is then used to reduce traffic congestion (McKeena, 2011).

Alternative Technologies

Although inductive loop detection systems are currently the most common method of monitoring traffic conditions, installing them can be disruptive and expensive (Graham-Rowe 2009). Moreover, a single loop cannot monitor multiple lanes or provide multiple vehicle detection (FHWA 2006). Other options are currently being explored, including wireless infrared sensors installed on lamp posts, and traffic monitoring using GPS-enabled smart phones (Graham-Rowe 2009). These options are likely to be much cheaper and easier to install than inductive loops.

Due to these factors, inductive loop traffic detection is likely to become obsolete in the future, although loops that are already installed may continue to be used. However, it will
take many years to fully develop other sensor technologies, so the inductive loop will continue to be the most commonly used traffic detection system for quite some time.

Health and Safety
There are few safety issues associated with inductive loop detection. One of the main problems is that motorbikes may fail to be detected by inductive loops, as they have few metal surfaces parallel to the loop. In a situation where the traffic light remains red unless triggered, drivers of motorbikes that fail to trigger the loop could be tempted to drive through the red light, increasing their risk of a crash. Increased sensitivity of inductive loops, due to improved signal processing, should help solve this problem.

Conclusion
Inductive loop traffic detectors are quite complex devices, using magnetic fields, induced magnetism and eddy currents to function. Since their introduction in the 1960s, they have become the most utilised traffic sensor, but that may change in the future as other technologies emerge.

Bibliography


Appendix 1 – The Ferromagnetic Effect

According to Wikipedia (2016b), the relative permeability of 99.8% pure steel (in comparison to a vacuum), is 5000. The relative permeability of carbon steel is only 100, and that of aluminium is barely above 1 (actual value is 1.000022).

The formula for the inductance of a roadway inductive loop is:

\[ L = \frac{\mu_r \mu_0 N^2 AF_t}{l} \]

where \( L \) = inductance (H), \( \mu_r \) = relative permeability of material (1 for air), \( \mu_0 = 4\pi \times 10^{-7} \) henrys per metre, \( N \) = number of coils, \( A \) = cross sectional area of coil (m\(^2\)), \( l \) = length of coil (m), and \( F_t \) = factor to account for non-uniform flux (FHWA 2006).

This formula shows that the inductance of the coil will be proportional to the relative permeability of the core material.

Assuming a coil with 3 turns, an area of 3.24 m\(^2\) (dimensions of 1.8 by 1.8m), 1.8 metres long, and a non-uniform flux factor of 0.5, the inductance with an air core will be:

\[ L = \frac{\mu_r \mu_0 N^2 AF_t}{l} \]
\[ L = \frac{1 \times (4\pi \times 10^{-7}) \times (3)^2 \times 3.24 \times 0.5}{1.8 \text{ m}} \]
\[ L = 0.000 \: 0102 \: H = 10.2 \: \mu H \]

If a 99.8% pure steel core was used (\( \mu_r = 5000 \)), then the inductance would be:

\[ L = \frac{\mu_r \mu_0 N^2 AF_t}{l} \]
\[ L = \frac{5000 \times (4\pi \times 10^{-7}) \times (3)^2 \times 3.24 \times 0.5}{1.8 \text{ m}} \]
\[ L = 0.050894 \: H = 50.894 \: \mu H \]

However, if carbon steel (\( \mu_r = 100 \)) was used, the inductance would only be:

\[ L = \frac{\mu_r \mu_0 N^2 AF_t}{l} \]
\[ L = \frac{100 \times (4\pi \times 10^{-7}) \times (3)^2 \times 3.24 \times 0.5}{1.8 \text{ m}} \]
\[ L = 0.0010179 \: H = 1,018 \: \mu H \]
As a vehicle would probably not be made of very pure steel, the increase in inductance would not be as high as indicated by the calculation for 99.8% pure steel. Moreover, the change in inductance is not as significant when the metal mass passes above the loop, rather than through it. However, these calculations do show how the core material can affect the inductance of a loop.