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

Steven G. Goodridge, Ph.D.
Member, IEEE

## 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.

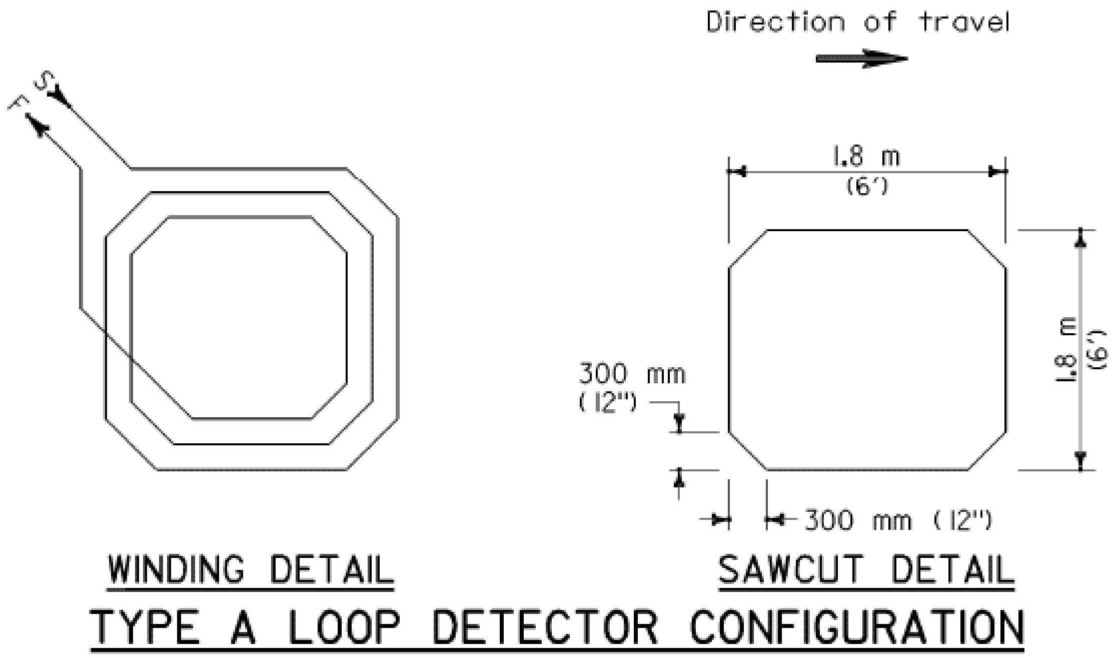


Figure 1: Basic dipole inductive loop sensor. (Source: California DOT)

A number of variables affect the degree to which the introduction of a conductive object will change the effective 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 nominal operating frequency of the circuit

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 belief 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. The iron cores used in typical power inductor applications provide an inductance boost for low frequencies such as 60 Hz. But at higher frequencies, the inductive coupling of eddy currents into the iron core often defeats the inductance boost of the iron. Ferrous inductor components manufactured for high-frequency circuits require a special form of powdered iron called "ferrite" which is designed to minimize its conductivity (especially large-loop conductivity) and thus minimize eddy currents. The steel in cars, by contrast, is highly conductive. 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-belted radial with poor loop conductivity positioned in the center of a traffic signal 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. In short, it is purely 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.

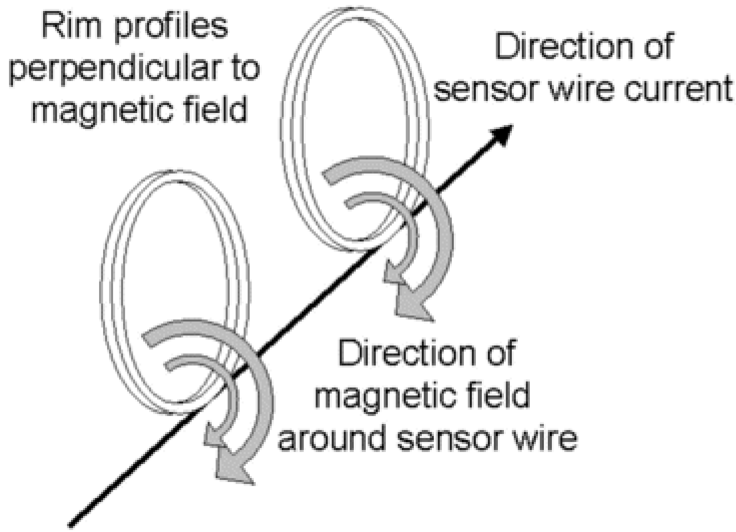


Figure 2: Magnetic field reception by bicycle rims

## 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). Quadrupole loops have a sweet spot about four times larger. Even this is smaller than desirable. The quadrupole 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).

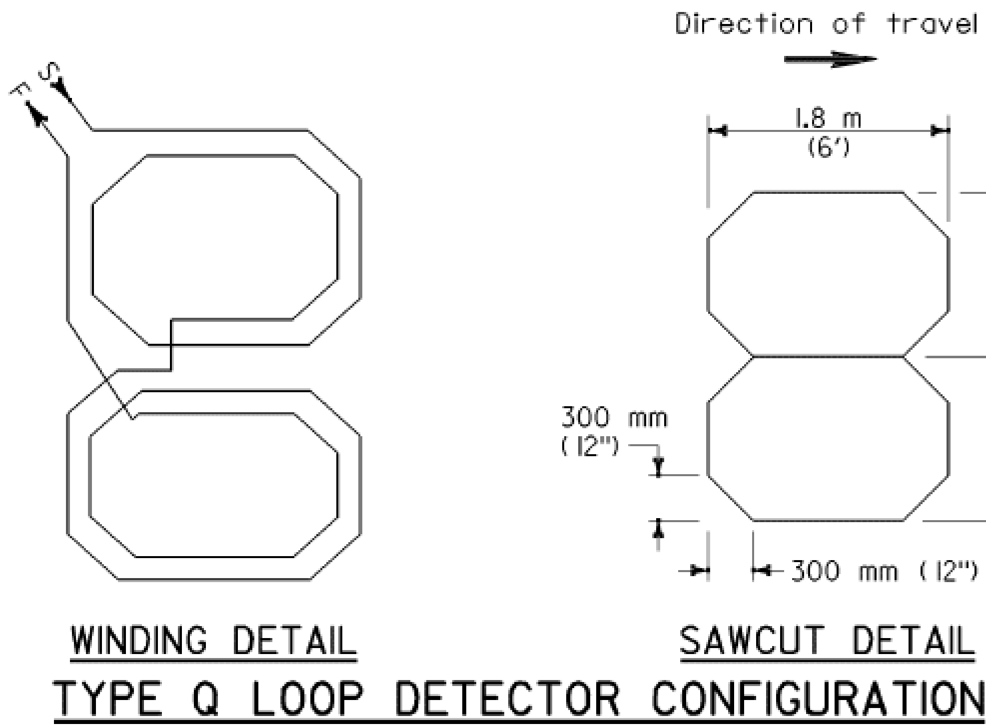


Figure 3: Small quadrupole loop sensor. (Source: California DOT)

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. ***(Note that as of summer 2004, this signal no longer detects bicycles. Apparent changes in the pavement surface around the loop wire installation suggest that the sensor wire has been replaced and the circuit consequently adjusted to lower sensitivity by the DOT. Ironically, this intersection is on a signed recreational bike route. But another Cary intersection, at the left turn lane from Weston Parkway to Norwell Boulevard, has recently been adjusted sensitive enough to detect bicycles reliably when before it was not.)***

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.

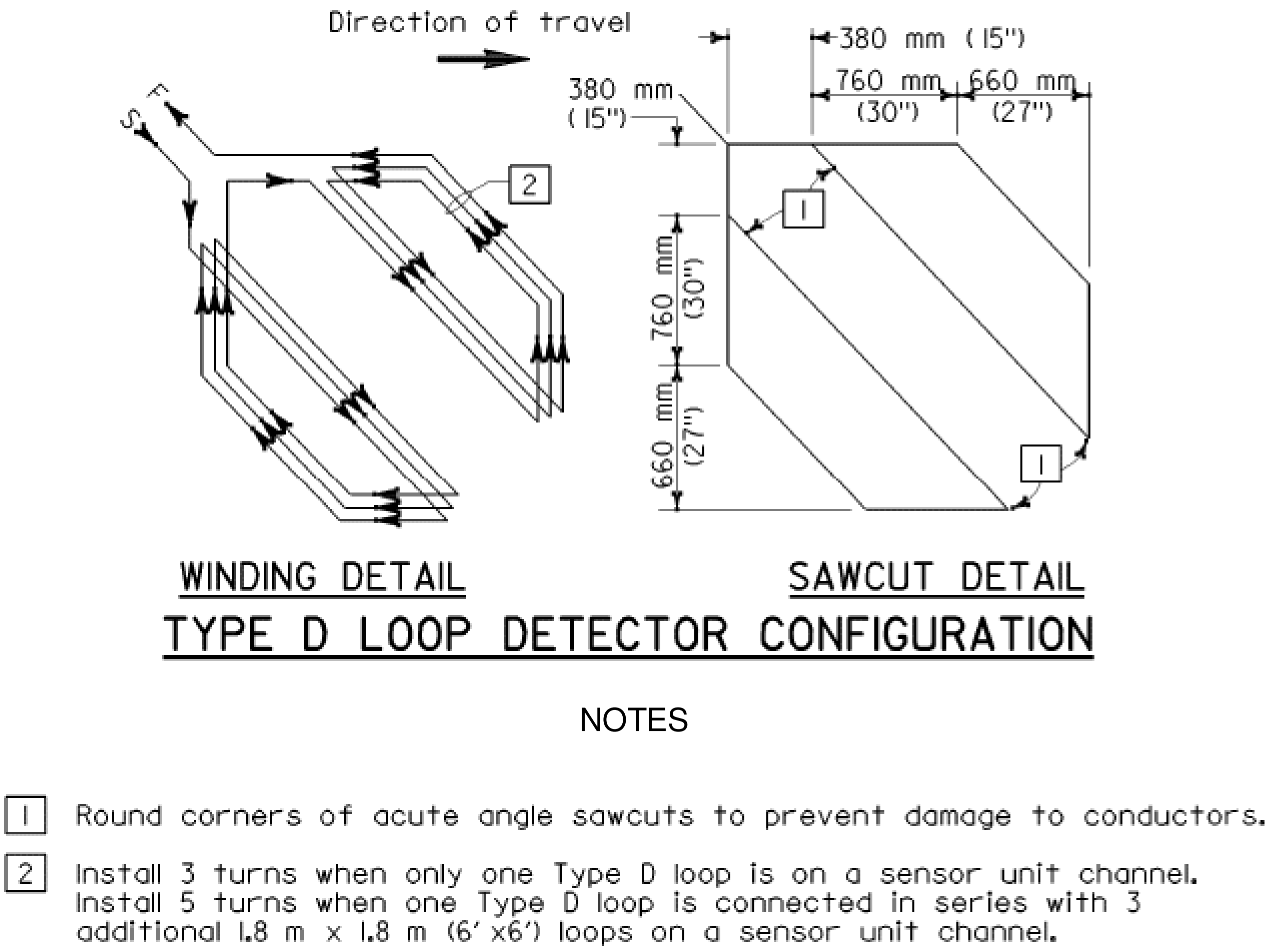


Figure 4: Diagonal quadrupole pattern (Source: California DOT)

## 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.

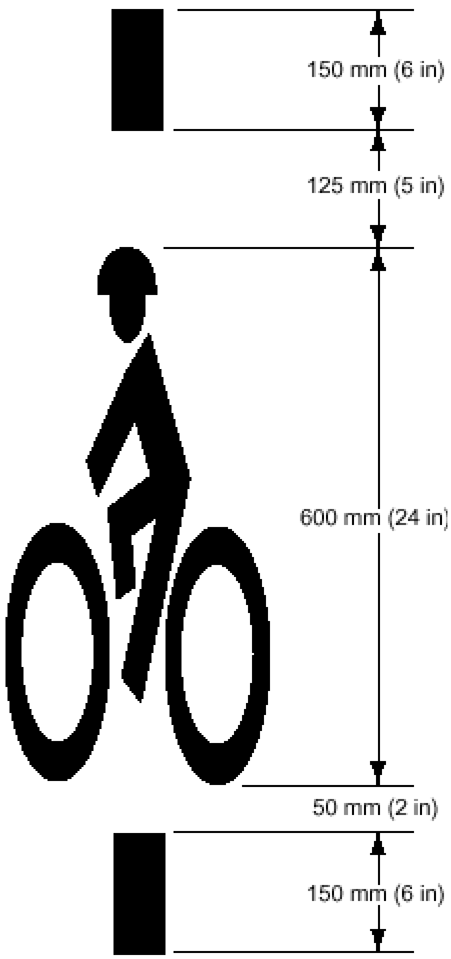


Figure 5: Stencil for marking location of most sensitive portion of traffic sensor (Source: 2000 MUTCD, Rev. 2)

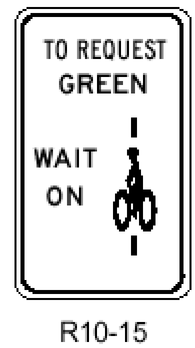


Figure 6: Informational sign describing optimum use of traffic sensor (Source: 2000 MUTCD, Rev. 2)

## 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?"