Bicycle Detection Using Caltrans Type D Loops:
More Options for Practitioners

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Abstract: A major component of sustainability is encouraging bicycling by designing roads and traffic signals to accommodate bikes as equal users, including reliable detection of their presence. To further this goal, the State of California recently implemented legislation to require detection and/or timing of traffic signals to fully accommodate bicycles and motorcycles at all newly signalized and updated signalized intersections.

One option for reliable detection of bicycles is the use of the Caltrans Type D inductive loop detector (ILD). Caltrans has released recommendations on deploying the Type D loop in conjunction with standard vehicle detection at intersections. However, the Caltrans recommendations differ from typical ILD deployments in Moreno Valley and elsewhere.

The paper presents recommendations for deploying the Type D ILD with other loops in a manner that deviates little from previous common practice while retaining the expected functionality.

Introduction

In 2007, the State of California passed a law (AB1581) to mandate that bicyclists be fully accommodated at signalized intersections, pending implementation instructions from the California Department of Transportation (Caltrans). In 2010, Caltrans released said instructions (via a memorandum entitled "Traffic Operations Policy Directive 09-06 Implementation"). With release of the necessary guidance, AB1581 is the law of the land in California.

The City of Moreno Valley has explored options for complying with AB1581. Recognizing that product manufacturers are developing products to meet the new requirements, at the time of this writing the best means of complying is via the use of inductive-loop detection (heretofore referred to as ILD), through the use of a combination of standard and special loop configurations. This paper seeks to explore the best (functional at reasonable cost) means of configuring ILD to achieve reliable detection of both motorized vehicles and bicycles without false calls, for example, due to detection of vehicles in the adjacent lane (splashover) or interference between nearby detectors (crosstalk).

AB1581 and Implementation

AB1581 modified the California Vehicle Code to require that all traffic-actuated signals, when newly constructed or when detection is installed or replaced, "to the extent feasible and in conformance with professional traffic engineering practice, be installed and maintained so as to detect lawful bicycle or motorcycle traffic on the roadway." Compliance by local agencies was not required until Caltrans "established uniform standards, specifications, and guidelines for the detection of bicycles and motorcycles by traffic-actuated signals and related signal timing."

Although the statute exempts pre-timed traffic signals (i.e. signalized intersections with no vehicular detection), fully actuated signals are the norm for Moreno Valley and most nearby agencies.

The Caltrans guidance, issued in the form of a memorandum entitled "Traffic Operations Policy Directive 09-06 Implementation," dated August 19, 2010 (and subsequently incorporated into the current California MUTCD), establishes the following:

- The "reference bicycle-rider," that is, the lowest-profile object the system must be able to reliably detect, is defined as "a four-foot-tall person, weighing minimum 90 pounds, riding on an unmodified minimum 16-inch wheel bicycle with non-ferromagnetic frame, non-ferromagnetic fork and cranks, aluminum rims, stainless steel spokes, and headlight." (The rider is defined with detail over and above that necessary to establish ILD detection in order to allow the use of alternate detection technologies such as video.)

- Either the reference rider must be detectable, or the approach must be on recall. This allows provision of bicycle detection only on the side street if the intersection is semi-actuated. It also allows agencies with fully actuated traffic signals to comply by upgrading side-street and protected left-turn lane detection only, if applicable; coupled with placing the main street on recall—a common mode of operation.

- Bicycle pushbuttons are allowed as the sole form of detection only for "bike path approaches" which are presumably Class I (separated) facilities; however, they may supplement the otherwise-required detection.

- Bicycle-friendly timing is suggested, although not mandated. Such timing generally has the effect of increasing the minimum-green time. The bicycle timing is not the focus of this paper and is thus not further discussed (except see "Future Developments").

Although not specifically discussed in the text, the attachments to the policy memorandum make clear that detection would also need to be placed in any present on-street marked bike lane.

The Directive also includes installation notes, which provide three alternatives for installing ILD:

1. Wire the Type D loop (see the section entitled "Type D Loop Detector" for a definition) together with three Type A (square/octagonal, six feet on each side) or Type E (six-foot-diameter round) loops. (This paper will refer to Type A or E loops as "standard vehicular detection." For the purposes of this analysis, they are assumed to be interchangeable; although the calculations are performed assuming circular loops.) The Type D loop is connected in series with the other three loops, which are all in parallel. The Type D loop is wound with five turns of loop wire; the number of turns for the standard loops is not specified. The applicable Caltrans Standard Plan requires three turns for such loops unless otherwise specified. The recommendation to place three turns is consistent with recommendations in the *Traffic Detector Handbook* (as referenced below).

2. Wire the Type D loop together with two standard detectors. The Type D loop is connected in series with the two standard detectors, which are in parallel.

3. Place the Type D loop on its own channel.

The City desired additional flexibility for installation of loops, specifically:

- The standard non-left-turn-lane layout is two loops separated by 10 feet (or 16 feet, center to center).

- For two non-left-turn approach lanes (i.e. two through lanes or a through lane and right-turn lane), the total of four required detectors (two Type D and two standard detectors) are typically connected to the same channel.

The remainder of this paper explores the feasibility of adapting these layouts to the Type D loop installation.

Inductive Loop Detector Theory of Operation

This section, and much of the circuit analysis found in later sections of this paper, is written using information obtained from the Federal Highway Association's *Traffic Detector Handbook,* Third Edition (October 2006). This publication can be purchased in hardcopy, or downloaded at no cost in PDF format. This paper would not have been possible without the excellent materials available therein. Readers who desire additional information about theory or practice of traffic detection are highly encouraged to study this reference.

Definitions of certain electrical terms are included at the end of the paper, for the reader's convenience.

The inductive loop detector, when driven by a sine wave in a frequency range typically between 20 and 100 kilohertz, produces a magnetic field above (as well as below) the detector. The driven frequency depends in part on the inductance of the circuit being driven. When an electrically conductive material enters the magnetic field, it causes the inductance of the loop to decrease; the reduction is registered as a change in the observed frequency of the detection circuit.

As stated elsewhere, when this paper refers to "standard detectors," it is referring specifically to six-foot circular loops; however, octagonal loops are sufficiently similar electrically.

Type D Loop Detector

The Caltrans Type D loop, which has been available for use since at least 1988, is capable of detecting the design bike-rider anywhere across its surface; it also reliably detects motorized vehicles. Its essential characteristics are illustrated on **Figure 1** (next page). The Caltrans standard plans indicate it should have three turns of loop wire if installed by itself on a detector channel, or five turns if installed together with other loops.

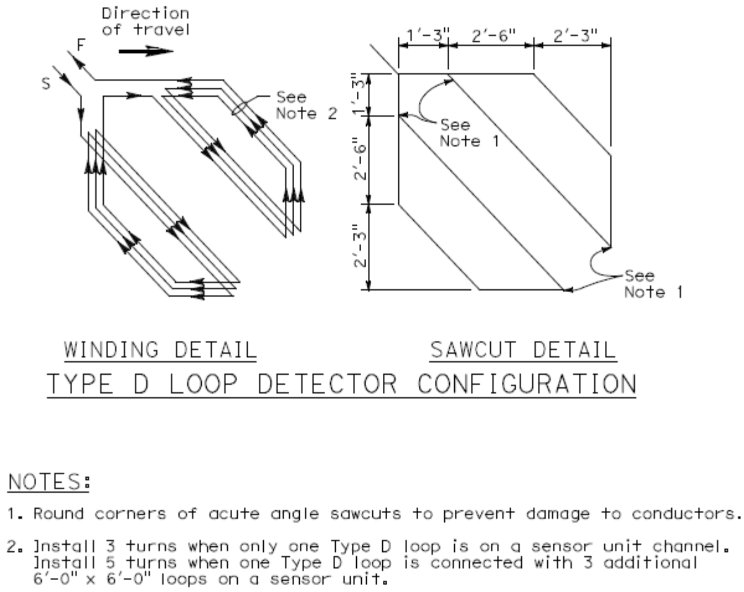

Figure 1. Type D Loop (Caltrans Standard Plan ES-5B)

The author has corresponded with the Caltrans staff that prepared the policy directive memorandum. They have indicated, and the author hereby relays, that the winding direction shown on the Standard Plans is crucial for proper operation of the detector. Specifically, the center windings (i.e. the two diagonal slashes through the center of the loop) must carry current in the same direction. It is possible to determine after the fact if the installation was performed properly, but doing so requires cutting the loop wire and then re-splicing, as well as a DC power source such as a car battery, and a compass placed at key points over the loop in the street (in traffic); so it is not convenient. It is thus important to carefully instruct the loop installation personnel prior to installation, and supervise the work if necessary; so that the detection may perform in the intended manner. It is Moreno Valley staff's impression that without instruction, the installer's tendency is to wind the loop incorrectly; as the correct winding method is apparently unnatural. This should improve over time as loop contractors become more experienced with the Type D loop, but only if agencies continue to enforce the proper technique.

Since the City uses round loops (having found they are less prone to failure), contractors are allowed to install Type D loops as round loops with two diagonal sawcuts trisecting the loops. The diagonal sawcuts are required to be the same distance apart as with standard Type D (i.e., those installed as previously shown in Figure 1) loops: 21 inches apart (measured perpendicular to the diagonal sawcuts). The loops that were field-measured for this study were installed in this manner.

Installation and Wiring Methods

As previously stated, the goal of the loop detector layout and configuration optimization documented herein is to reliably detect bicycles and motorized vehicles without false detection, e.g. crosstalk and adjacent-lane detection (splashover). Crosstalk is generally avoided through selection of frequency on the detection card and this paper does not further consider this phenomenon. Splashover is best avoided by setting the detector's sensitivity threshold to the minimum setting required to detect the design vehicle.

Typical ILD sensor units require the following characteristics of the ILD circuit:

- Inductance between 20 and 200 μH (microhenrys) (including detector lead-in cable)
- Quality factor[1] of at least five

Circuits outside of these ranges may function, but the system will not work optimally.

The following list summarizes, in general terms, how the circuit's electrical characteristics are modified if certain changes are made.

- For a given loop, increasing the number of turns of loop wire increases the amount of energy present in the magnetic field around the loop, which causes the loop to be more responsive to the presence of conductive material. Increasing the number of turns beyond five imposes physical constraints—more turns simply do not fit in the sawcut—and electrical constraints—capacitance, inductance, and resistance are all increased. These constraints place a practical upper limit on the quality factor that can be achieved. However, Q substantially greater than 5 (for the entire circuit) has no significant benefit; thus increasing the number of turns over and above published recommendations (generally, three, four, or five turns for the loops examined in this paper, depending on the application) has no benefit. Care should also be taken to not exceed the recommended limit of 200 μH for the circuit; a five-turn rectangular, six-foot-square loop has an inductance of approximately 185 μH.

- The inductance of the circuit can be controlled by changing the manner in which detectors are connected. The connection of two loops in series causes the inductance of the circuit to increase by approximately the sum of the inductance of the individual loops. The connection of two loops in parallel reduces the inductance of the circuit, more or less by this formula:

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$$

  For the case where the two loops are essentially identical so that $L_1 = L_2$, the inductance is approximately halved:

$$1 = L\left(\frac{1}{L_1} + \frac{1}{L_1}\right)$$

$$1 = L\left(\frac{2}{L_1}\right)$$

$$L = \frac{L_1}{2}$$

[1] The quality factor is a measure of how much energy is placed into the loop's magnetic field relative to energy lost elsewhere in the circuit. Higher values represent less dissipation relative to the induced magnetic field and thus reflect better performance.

It follows that connecting two loops in parallel, and then connecting those in series to another set of two loops connected in parallel (series/parallel), has approximately the inductance of a single loop. This happens to be the standard means of connecting four loops.

Field Measurements

The *Traffic Detector Handbook* contains both theoretically and empirically derived data for many detector types, but not for the Type D loop. Accordingly, key parameters were field-measured using a U.S. Traffic ILA-551 loop tester. This tester offers the following capabilities:

1. Frequency measurement
2. Loop locating
3. Loop measurement (inductance, resistance, and quality factor)
4. Measurement of inductance change
5. Measurement of loop insulation resistance to ground

A total of seven Type D loops were measured using mode 3. The measurements were taken at the homerun pullbox prior to splicing of loop wire to DLC. The measured inductance of each loop is as reported by the loop tester. The loop inductance varies by frequency. Unfortunately, the tester does not report the frequency at which the measurement is made, but fortunately the variation over the typical frequency range of such circuits (20 to 100 kilohertz) is small. For the purposes of this paper, loop inductance is assumed to be constant in the applicable frequency range.

Table 1 (next page) summarizes the observations.

Observations about Table 1:

- ❑ Any series connection of two or more loops will exceed the 200 μH limit for the circuit. Thus, some combination of parallel or parallel/series must be used.
- ❑ The inductances are either near 135 μH or between 200 and 250 μH. Further testing is required, and will be performed, to determine why this is the case. It is presumed that certain loops were incorrectly installed. The analysis will show that the Type D loop performs best if its inductance is high.

Table 1: Field Measurements of Type D Loop Characteristics

	Inductance (μH)	Resistance (Ω)	Quality Factor
	138	0.7	59.2
	135	0.6	58.6
	254	0.7	64.3
	237	0.6	77.5
	221	0.7	59.9
	203	0.6	71.7
	137	0.6	59.0
Average	*189*	*0.64*	*64*

μH—microhenrys

Ω—ohms

One loop, known to be wrapped correctly, was also used to determine inductance change (in percent) when a reference bicycle was passed over the edges and center of the loop several times. It was determined that the typical inductance change for the Type D loop together with the loop wire spanning the space between the loop and the homerun pullbox (where the measurements were conducted) is in the range of 0.05% to 0.1%. Although small compared to the change caused by vehicular traffic (which is roughly one percent), modern detector cards can register a call with a change in inductance of 0.01% (for the entire circuit) at the highest sensitivity setting.

The measured change in inductance is not further considered herein (instead a sensitivity reduction factor, defined later, will be used). Its relevance here is to indicate that the Type D loop's response to the reference bicycle requires a high detector card sensitivity setting to ensure detection.

Circuit Optimization

The goal of circuit optimization in this case is twofold:

- Preserve the sensitivity of the Type D loop to bicycles. Given that the Type D loop's response to the reference bicycle was as low as 0.05% and the threshold for detection is 0.01% at the highest sensitivity setting of the detector card, there is not much room for loss in the circuit.

- Limit the sensitivity of the loop system to vehicular actuations so that likelihood of detection of adjacent-lane vehicles (splashover) is minimized.

As the analysis below will show, the circuit's response to the bicycle input becomes paramount, so potential for splashover is only discussed qualitatively. Further analysis and testing is recommended to determine the potential for splashover.

One Plus One Layout

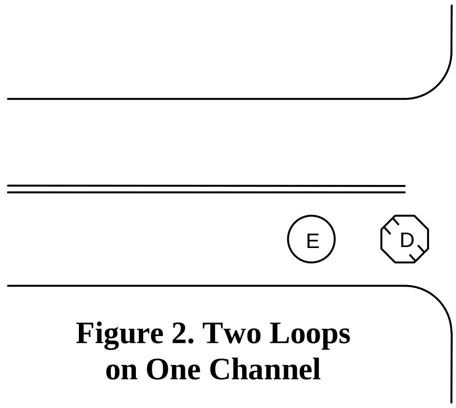

Figure 2. Two Loops on One Channel

The "one plus one" detector layout **(Figure 2)** consists of one Type D loop wired together with one Type E loop. This layout is commonly deployed at approaches with one through lane. We have already established that the wiring of this layout cannot be in series since the recommended circuit inductance limit of 200 μH is exceeded; thus, the parallel wiring method must be employed.

Equation 2-26 from the *Traffic Detector Handbook*, reproduced here as Equation 1, predicts the sensitivity (defined as previously used in this paper, which is the percent change in inductance) of this circuit, given the inductances of the two loops and the sensitivity of the loop in question to the presence of the design vehicle:

$$S_{TP} = S_L^A \frac{1}{1+\frac{L_A}{L_B}} \qquad (1)$$

Where S_{TP} is the sensitivity of the circuit, $S^A{}_L$ (apologies for the poor formatting) is the change in inductance of the loop when the design vehicle is present, L_A is the inductance of the loop in question, and L_B is the inductance of the other loop in the circuit. This equation does not consider the inductance of the detector lead-in cable (DLC), which is assumed to be negligible since DLC has little inductance per foot, and since Type D loops are near the controller cabinet because they are usually installed at the stop bar.

In considering the Type D loop's response to the bicycle input, the goal is to maximize S_{TP}. Inspection of Equation 1 reveals that S_{TP} is maximized if the ratio of L_A to L_B is minimized. S_{TP} is maximized if the inductance of the other loop in the circuit is maximized, since L_B should be more than L_A.

In considering either loop's response to a motorized vehicular input, the goal is to minimize S_{TP} (in order to cause the change in inductance to be more similar to a bicycle input). The Type D loop cannot be simultaneously made to be sensitive to bicycle inputs and insensitive to motorized vehicle inputs, so this goal is considered in the context of the Type E loop. Inspecting Equation 1 reveals that S_{TP} is minimized when the ratio of L_A to L_B is maximized. Thus the Type E loop's inductance should be as high as practically achievable. This goal is in harmony with the above goal for maximizing the response of the circuit to the bicycle input.

So, generally, in this layout, the inductance of the Type D loop should be minimized, and the inductance of the Type E loop should be maximized.

One potential means of doing so is immediately identifiable, which is to reduce the number of windings in the Type D loop in order to reduce the inductance of the loop. However, this has the undesirable side effect of reducing the loop's response to the presence of the reference bicycle and is thus not feasible.

Two other potential means of tuning the circuit exist:

- Maximize the number of windings in the Type E loop.
- Install a shunt in series with the Type E loop to increase its inductance. (Credit for this method goes to Caltrans electrical engineering staff.)

Either solution is acceptable, although the detector card's sensitivity will have to be set to a high setting to detect the reference bicycle.

Further testing is required in order to determine whether this wiring method results in splashover, which may be the result of setting the detector card to its maximum sensitivity so that the circuit would respond to the bicycle input. However, if the approach is truly single-lane, and/or any adjacent lane is on the same phase, splashover may not be a concern.

Two Plus Two Layout

The "two plus two" layout **(Figure 3)** consists of two Type D loops and two Type E loops. This is commonly provided for two adjacent through lanes. Unlike the prior case, this case is often installed adjacent to a protected left-turn phase, so splashover is a concern here.

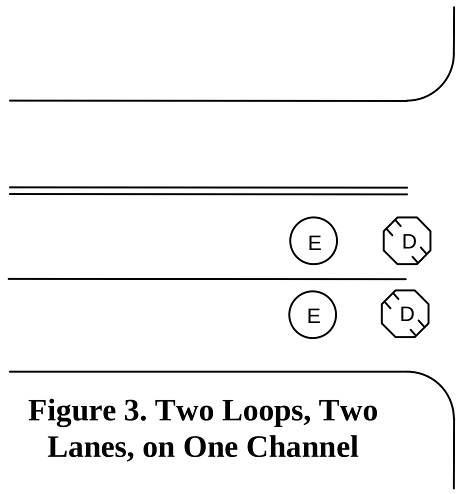

Figure 3. Two Loops, Two Lanes, on One Channel

Candidate wiring methods include:

- All loops in series. This is not recommended because total inductance of the circuit exceeds the recommended maximum threshold of 200 μH for the circuit.
- All loops in parallel. This is not recommended for two reasons. First, total inductance of the circuit is very near, and potentially less than, the recommended minimum threshold of 20 μH for the circuit. Second, Equation 1 predicts that the response of the circuit to the bicycle input would be poor: The inductance of the other three loops would be low, thus making the ratio of L_A to L_B high, resulting in a low S_{TP}.
- Two loops in parallel, combined in series with the other two loops in parallel. Several combinations exist.

To analyze series connections of loops, another equation from the *Traffic Detector Handbook* is presented (Equation 2-24), which predicts the sensitivity of a circuit with two loops in series:

$$S_{TS} = S_L^A \frac{1}{1+\dfrac{L_B}{L_A}} \qquad (2)$$

The definitions of the terms in Equation 2 are identical to those in Equation 1. Equation 2 is also identical to Equation 1 except that the ratio of inductances is reversed. In a series connection, the sensitivity of the circuit is maximized if the inductance of the other loop in the circuit is minimized.

The circuit is symmetric in that regardless of which Type D loop is being considered, there will always be one other Type D loop and two other Type E loops in the circuit. To assure consistent response to the bicycle input, the wiring should also be symmetric; that is, the configuration of one loop connected with three other loops in some manner (e.g. one D in series with the other three loops in parallel) is not desired.

Four wiring configurations are thus available for analysis. For convenience of representation, "| |" denotes a parallel connection, "—" denotes a serial connection, and "D" and "E" represent Type D loops and Type E loops, respectively. Circuit diagrams are provided as **Figure 4-1** through **Figure 4-4.**

1. D | | D — E | | E
2. D — D | | E — E
3. D — E | | D — E
4. D | | E — D | | E

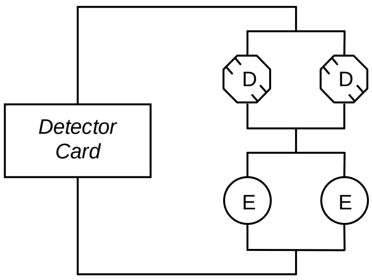

Figure 4-1: Wiring Configuration One *(Preferred)*

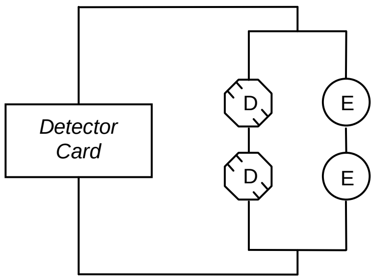

Figure 4-2: Wiring Configuration Two

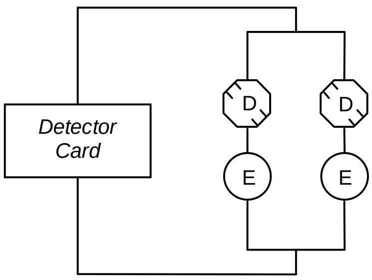

Figure 4-3: Wiring Configuration Three

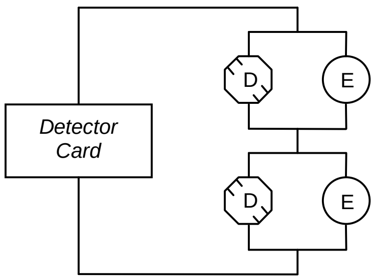

Figure 4-4: Wiring Configuration Four

<u>Wiring Configuration One</u>

Wiring configuration one consists of the two Type D detectors wired in parallel, and connected in series to the two Type E detectors also wired in parallel. In this wiring configuration, the response of the circuit to a bicycle input on one of the Type D loops can be best determined by constructing an equivalent circuit diagram using the principle of Kirchhoff's voltage law. The resulting figure, **Figure 5,** is equivalent to Figure 4-1 and is more easily analyzed. The equivalent inductance of the two parallel Type E loops, L_{EQ}, is calculated using a known relationship for parallel resistances (or in this case, inductances):

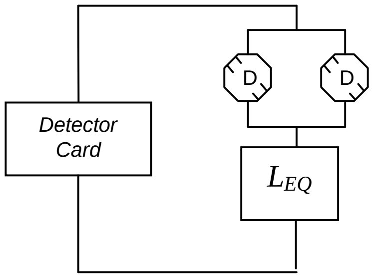

Figure 5: Simplification of Configuration One

$$L_{EQ} = \frac{L_1 L_2}{L_1 + L_2}$$

Since in this case the two inductances are equal, this reduces to:

$$L_{EQ} = \frac{L^2}{2L}$$

$$L_{EQ} = \frac{L}{2} \qquad (3)$$

The sensitivity of the entire circuit to a bicycle over either Type D loop in Figure 4 can be analyzed sequentially, first considering the effect of the other Type D loop in parallel using Equation 1, and then the effect of L_{EQ} using Equation 2. The intermediate sensitivity, S_{DP}, represents the sensitivity of one Type D loop in parallel with another Type D loop. S_D represents the sensitivity of one Type D loop, and L_D represents the inductance of one Type D loop.

$$S_{DP} = S_D \frac{1}{1 + \frac{L_D}{L_D}}$$

$$S_{DP} = S_D \frac{1}{1+1}$$

$$S_{DP} = \frac{S_D}{2} \qquad (4)$$

So the sensitivity of two identical loops in parallel is half the sensitivity of the loop itself, mirroring the inductance of the circuit, relative to the detectors' inductance, when two identical detectors are wired in parallel.

Next the sensitivity of the entire circuit is calculated using Equation 2, using S_{DP} and L_{EQ}.

$$S_C = S_{DP} \frac{1}{1 + \frac{L_{EQ}}{L_{ED}}}$$

Here, L_{ED} is the inductance of the portion of the circuit for which we just calculated sensitivity (i.e. the two Type D loops in parallel). Equation 3 tells us L_{ED} is half the inductance of a single Type D loop.

$$S_{TP} = S_{DP} \frac{1}{1 + \frac{\frac{L_E}{2}}{\frac{L_D}{2}}}$$

Using an inductance of 100 µH for the Type E loop and 190 µH for the Type D loop:

$$S_{TP} = S_{DP} \frac{1}{1 + \frac{\frac{100}{2}}{\frac{190}{2}}}$$

$$S_{TP} = S_{DP} \frac{1}{1 + \frac{50}{95}}$$

$$S_{TP} = S_{DP} \frac{1}{1 + 0.52}$$

$$S_{TP} = \frac{S_{DP}}{1.52}$$

Substituting using Equation 4:

$$S_{TP} = \frac{\frac{S_D}{2}}{1.52}$$

$$S_{TP} = \frac{S_D}{3.05}$$

So in wiring configuration one, the sensitivity of the entire circuit to a bicycle is approximately three times less than the sensitivity of the Type D loop alone. This factor is termed herein the “sensitivity reduction factor” and describes the impact to sensitivity of placing the Type D loop in a circuit with other detectors.

Wiring Configuration Two

Wiring configuration two consists of the Type D loops wired in series, and connected in parallel to the Type E loops wired in series.

The circuit analysis is performed similarly to that which is presented for configuration one. For this configuration, the sensitivity reduction factor is 5.8.

Wiring Configuration Three

Wiring configuration three consists of the detectors in each lane (i.e. one Type D and one Type E) wired together in series, and connected in parallel to the detectors in the adjacent lane wired in series. For this configuration, the sensitivity reduction factor is 3.8.

Wiring Configuration Four

Wiring configuration four consists of the detectors in each lane wired together in parallel, and connected in series to the detectors in the adjacent lane wired in parallel. For this configuration, the sensitivity reduction factor is 5.8.

Preferred Wiring Configuration for Two Plus Two Layout

The preferred configuration is configuration one, as it results in the least reduction of Type D loop sensitivity. This is accomplished by taking advantage of equations 1 and 2: Minimizing the inductance placed in series with the Type D loops (by placing the Type E loops in parallel), and maximizing the inductance placed in parallel with the Type D loops. This qualitative interpretation confirms the validity of the mathematical model.

The preferred configuration works best if the inductance of the Type D loop is maximized and the inductance of the Type E loop is minimized. Accordingly, the Type D loop should be installed with five turns of wire as per Caltrans recommendations, and the Type E loop should be installed with the minimum recommended turns of wire, which is three. Since the calculations were performed assuming four turns (as is standard practice in Moreno Valley), the calculations were re-run for a Type E loop with three turns, which is predicted to have an inductance of 60 μH. The sensitivity reduction factor becomes 2.6, which is an improvement of approximately 10%.

Splashover may be a concern, as this layout often has an adjacent left-turn lane on a different phase. Further testing and analysis is necessary to determine if splashover would occur.

One Plus Three Scenario

The "one plus three" layout consists of one Type D loop and three Type E loops **(Figure 6).** This is the standard layout for left-turn lanes. (The rationale for installing four loops in the left-turn lane is to allow use of short extension times while preventing premature gap-out if the left-turn queue has not been cleared.)

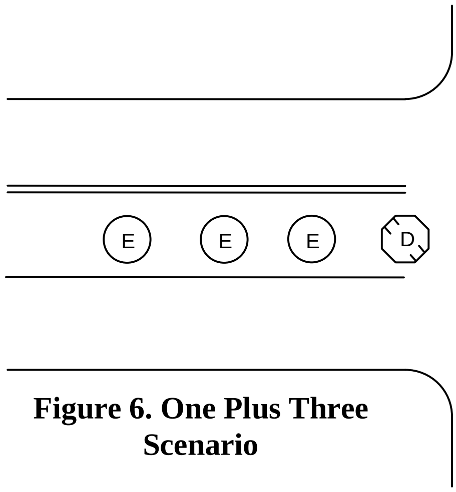

Figure 6. One Plus Three Scenario

The best wiring methods for this case can be inferred from Equations 1 and 2. Either of the following two options is reasonable:

- Wire the three Type E loops in series, and connect in parallel with the Type D loop. The circuit's response to the reference bicycle is maximized through maximization of L_B in Equation 1. Total circuit inductance is expected to be within the recommended range of 20 to 200 μH.

- Wire the three Type E loops in parallel, and connect in series with the Type D loop. The circuit's response to the reference bicycle is maximized through minimization of L_B in Equation 2. Total circuit inductance is expected to be within the recommended range of 20 to 200 μH.

Splashover may also be of concern with this installation. Further testing and analysis is necessary.

Future Developments

Although the Type D loop can reliably detect both bicycles and vehicles, it cannot discriminate between them. Discriminating bicycles from motorized vehicles would be helpful in complying with the bicycle minimum green time recommendations discussed earlier, because without discrimination, practitioners must either set minimum green times substantially higher than would otherwise be necessary, or run the risk of trapping bicyclists in the middle of the intersection when conflicting traffic is released. With discrimination, the bike minimum green time can be timed only when necessary.

Vendors are working hard to bring new technologies to the market. The author is aware of the following potential solutions either currently available or announced:

- The Orange County (California) Traffic Engineering Council (OCTEC), in conjunction with Reno A&E (a detector manufacturer), have developed and are currently testing a detector card that can be wired to a circuit which interleaves a bicycle detector with standard detection. Since in this layout the bike detector is not at the stop bar, bicycle calls are locked (that is, held until the associated phase is green). The model numbers of the cards are C-1100-B and C-1200-B.

- Microwave detectors, which have been developed and marketed off and on for a number of years, have recently found favor with a new generation of product. At least two lines are currently being produced and sold. One line (the MS Sedco Intersector) is claimed to be able to perform bicycle/vehicular discrimination. It is understood that the other known product line (Wavetronix) is being augmented to provide same.

- Video detection systems, which have been continuously available for use for about 20 years, are theoretically suited to discriminate bicyclists and motorized vehicles in the sense that a person viewing video signals can perform such discrimination, thus doing so automatically is a matter of developing the appropriate computer algorithm. It is understood that VDS manufacturers are working on providing this function.

Regardless of the technology used, additional controller inputs are required compared with standard detection, so availability of sufficient inputs for controllers installed at large intersections should be confirmed. Additionally, the controller must be able to time a different minimum green time when presented with the appropriate call.

Further Research

Further research is necessary in at least the following areas:

- The work would benefit from a derivation of the theoretical electrical characteristics of the Type D loop in a manner similar to that which is performed in the *Traffic Detector Handbook,* Appendix A *et al.* as well as the theoretical response of the Type D loop to the reference bicycle.

- Likewise, further field investigation of Type D loop characteristics, both absolute values and changes in response to the reference bicycle, would be beneficial.

- The wiring configurations recommended herein should be field-tested to determine their propensity for splashover.

The author intends to perform the field research as time allows.

Definitions

Frequency: The rate of change of a signal, in cycles per second.

Inductance: A circuit component that stores energy in a magnetic field. The amount of energy stored is measured in henrys (H), or in this paper, microhenrys (μH).

Resistance: A circuit component that expends energy, generally through heat dissipation. Resistance is measured in ohms (Ω).

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