Attributes of Direct Measurement of Inductance in a Loop Detector for Traffic Control

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Abstract – Inductive loop detectors for traffic control conventionally operate by sensing a resonant frequency shift when a vehicle passes over a loop. Using a digital system to measure the inductance as a function of time, better sensitivity and additional capability is available. This includes the ability to use both amplitude and frequency domain information to separate signals produced by vehicles that introduce only small interactions with the loop from signals due to vehicles in adjacent lanes. The detection scheme also permits an alternative approach for detecting bicycles and the option of placing detectors farther from an intersection to better control high speed traffic.

Index Terms – Inductive loop detectors, detection sensitivity, lead length, bicycles

I. INTRODUCTION

The inductive loop detector is a system used worldwide for traffic control [1]. It consists of several turns of wire buried in the pavement and energized by a current, which is typically at a frequency between 1 kHz and 20 kHz. The current through the loop generates a magnetic field. When a vehicle passes over the loop, eddy currents induced in the vehicle counteract the magnetic field, yielding a net decrease in loop inductance. Automobiles induce an inductance perturbation of ~5 μH out of an approximately 100 μH unperturbed inductance for a square loop. In general, automobiles with relatively low clearance above the road surface induce large inductance shifts because the induced eddy currents are near the loop [2, 3].

In conventional operation, the loop is powered by a loop detector unit consisting of an oscillator in which resonant frequency depends on the parallel combination of loop inductance, L, and capacitance, C. The detector unit also has electronic circuitry to measure shifts in resonant frequency caused by vehicular-induced changes in inductance. The frequency shift is illustrated in Figure 1, where the decrease in the inductance yields an increase in the frequency.

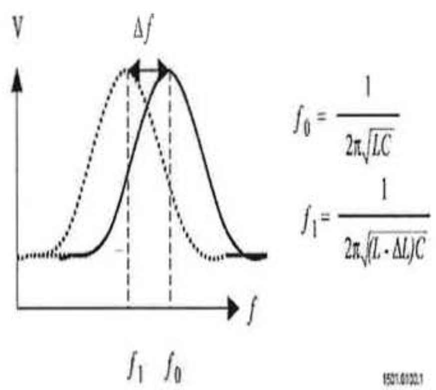


Figure 1. Loop detector unit measures increase in resonant frequency caused by a vehicle passing overhead

When the frequency shift, Δf, in Figure 1 is larger than a preset threshold, the detector unit is activated. Although these detectors are robust, a challenge has arisen in the detection of vehicles such as high bed trucks, motorcycles, and bicycles. These vehicles produce small signals due to the small amount of conducting material they introduce into the magnetic field. One cannot compensate for the small signal by increasing the sensitivity of detection as, for many loop configurations, the effect of some vehicles in adjacent lanes on the loop's magnetic field can be larger than the signal by a truck, motorcycle or bicycle in the monitored lane. It is frequently preferable to set the threshold level high enough to avoid false triggering due to this so called "splashover" effect. This work examines some attributes of an alternative measurement approach in addressing some of the practical problems that have been observed with conventional systems. While it is unlikely alternative detection approaches will make significant inroads on the installed base of conventional systems, these results will likely be of interest to those trying to expand the capability of inductive loop sensors for particular applications, including accumulating data useful in intelligent transportation systems [4].

II. MEASUREMENT APPROACH

A block diagram of the experimental apparatus is shown in Figure 2. At 5 kHz, the loop impedance is in the range of 5 to 10 Ω. An excitation current of 0.5 A to 1 A is provided by a function generator and an audio amplifier. A wide-band current probe provides a 0.1 V/A voltage proportional to the current signal which is then boosted by an operational amplifier to a peak of 3 to 4 V. The voltage and current signals are sampled by a LabVIEW® data acquisition card [5] installed in a conventional desktop computer.

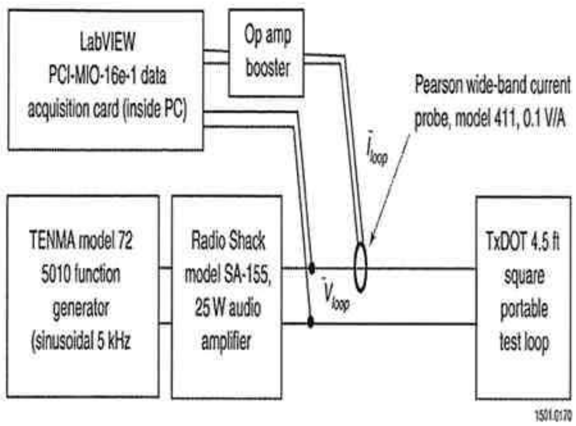


Figure 2. Block diagram of experimental apparatus

The measurement procedure used with this apparatus is:

- The loop is powered with a sinusoidal voltage.
- The loop current is measured.
- Loop impedance is determined by the relationship

$$Z_{loop} = (V_{loop}/I_{loop}), \qquad (1)$$

or

$$Z_{loop} = R_{loop} + j\omega L_{loop}, \qquad (2)$$

where R_{loop} is the resistance of the loop and any wire connecting the loop to the detector, $\omega = 2\pi f$, and $j = \sqrt{-1}$.

As long as the calculations are made quickly enough, the L_{loop} can be computed many times as a vehicle passes directly over or near the loop. The L_{loop} points for each vehicle passage are then graphed and saved.

The operational amplifier, with gain of ~50 and designated as "Op amp booster" in Fig.2, improves the signal/noise ratio, reducing sampling error.

Several constraints must be addressed to use this approach. These include

- Noise and distortion in the excitation voltage and current must be dealt with so as not to introduce unacceptably large errors.
- Fundamental frequency of V_{loop} and I_{loop} must be determined using sampled points.
- The analysis assumes the problem to be in steady-state, or near steady-state, meaning that the vehicle must not move far during each measurement of V_{loop} and I_{loop}.
- The frequency of the voltage and current must be constant.

The first three constraints are met using a sufficiently high sampling rate for the voltage and current. No effort was made to optimize the sampling rate as numerous sampling systems are commercially available that operate at speeds well above those required for traffic monitoring. So, the limitation is likely to be cost rather than availability of appropriate technology.

For the specific data reported here, it was found that vehicle motions of 20-25 cm during data acquisition introduced negligible error compared to assuming the vehicle was stationary during data acquisition. In the time allowed by that motion, sufficient cycles of the voltage and current waveforms were available so that a fast Fourier transform (FFT) of the accumulated data could be used to extract the fundamental-frequency components of voltage and current, thus rejecting sampling noise and any harmonic distortion. The FFT-produced fundamental components of voltage and current contain the magnitudes and phase angles needed to perform the loop impedance calculation.

Specifically, a sampling rate of 600 kHz per channel (one channel for voltage and one channel for current), and excitation frequency of 5 kHz yields about 30 points per cycle. An 8.3 ms sampling interval yields about 42 cycles, a sufficient number of cycles for the FFT to take advantage of averaging to reduce noise in the measurements. At the same time, the vehicle is approximately stationary during the sampling period because, for vehicle speeds less than about 100 km/hr the vehicle movement is about 25 cm or less during the sampling period.

The fourth problem is overcome by exciting the loop with a sinusoidal function generator and audio amplifier instead of with a conventional traffic detector variable-frequency oscillator.

Finally, the data acquisition system must be triggered so that events can be automatically recorded, plotted, and saved. Because the system computes R_{loop} and L_{loop} continually, sudden changes in L_{loop} can be used to indicate when a vehicle passes over or beside the loop. A smoothing constant α is used to minimize false triggers on noise signals. The smoothing equation used is

$$L_{base}^{new} = \alpha L_{loop}^{new} + (1-\alpha) L_{base}^{old} \qquad (3)$$

Typically, α is in the 0.5 to 0.9 range, depending on the noise level. If the change in L_{base} from one sample set to another is greater than a trigger level β, i.e.,

$$L_{base}^{old} - L_{base}^{new} > \beta \ , \qquad (4)$$

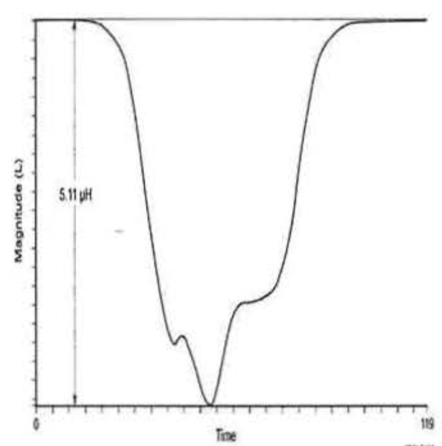
it is likely that an event has occurred. A typical value for β is 0.1 to 1.0 μH for standard detection, and 0.01 μH for maximum sensitivity. Pre-event data are included in the graph and the file of saved information because the system continually computes L_{loop} and remembers a few seconds of pre-event values.

The measurement approach provides improved sensitivity over systems that measure the shift in resonant frequency. In this work, the temporal dependence of the inductance is measured. The frequency change is not proportional to the inductance, however. It is proportional to the reciprocal of the square root of the inductance.

III. Splashover Identification

With conventional detectors, it is often necessary to set a low triggering threshold to detect a wider range of vehicles. For example, high-bed vehicles and motorcycles create from one-third to one-tenth the reaction of an average compact car. As the trigger threshold of a detector system is lowered, the probability of a car in an adjacent lane triggering the detector increases. These splashover triggers are generally misleading and undesirable.

Examining typical experimental data, however, showed there is not only an amplitude difference between a vehicle passing over a loop and a splashover signal. There is also a discernable difference in the shape of the detected inductance signal as a function of time. A typical comparison is shown in Fig. 3. Cars or trucks passing directly over the loop produce low-frequency irregularities in the inductance waveform. The splashover waveforms tend to show a smoother dip (ignoring measurement noise). The full scale of the upper drawing of Figure 3 is greater than 5 μH in the lower drawing is about 0.25 μH, small enough that the measurement noise of magnitude 0.01 μH peak-to-peak can be observed.



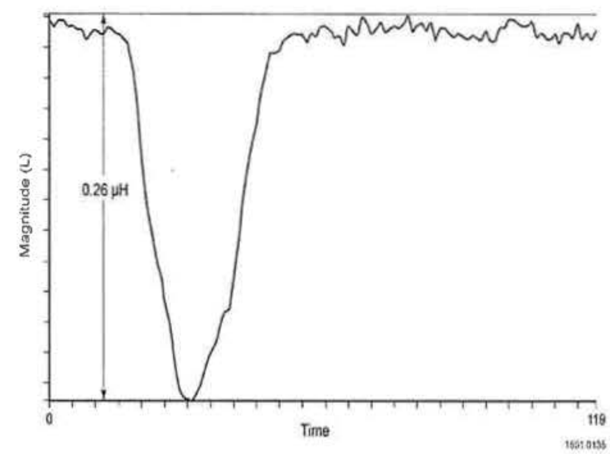


Figure 3. The upper trace shows the change in inductance as a sport utility vehicle passes directly over a loop detector and the lower figure shows the inductance change for splashover

This difference is consistent with the interaction between a vehicle and a loop. The loop is composed of lines of current in a specific shape, square, rectangle, diamond, etc., with a magnetic field encircling them. A vehicle passing beside the loop primarily impacts the magnetic field of the side of the loop nearest it. Because the loop and the vehicle are of comparable sizes, the resulting change in inductance is smooth at the frequencies of interest.

A vehicle passing directly over the loop, however, cuts the magnetic fields of all sides of the loop. When different parts of the vehicle are directly over different components of the loop, different reactions are produced. These effects cause the variations in the waveforms the vehicles induce. Variations in the undercarriage of the passing vehicle may also contribute to the effects observed. A simplified diagram of the spatial distribution of the magnetic field in the vicinity of a rectangular loop is shown in Figure 4.

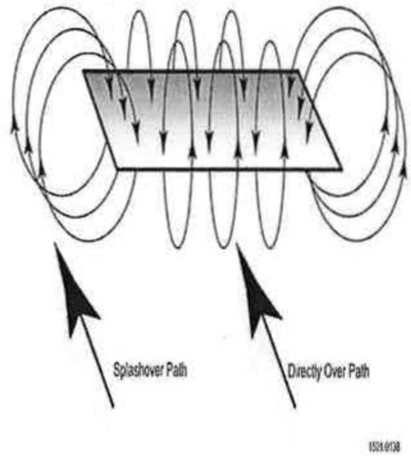


Figure 4. Vehicle passing directly over loop cuts more of the magnetic field

Because there is a discernable difference in the patterns in the two cases to be distinguished, more sophisticated pattern recognition beyond simple amplitude discrimination is attractive. Different vehicles produce differently shaped waveforms, a fact that has been used to track an individual vehicle across a series of loop sensors (4). There are far too many patterns to test for each type individually, however. This situation suggested the approach of determining differences in frequency content in various signals using a fast Fourier transform.

The FFT transforms a time domain signal into a frequency domain waveform giving the amplitudes of individual frequency components directly. In our case, the inductance of the loop, $L(t)$, becomes $L(\omega)$, allowing us to determine the frequency distribution in the waveform.

Graphs of the measured frequency content for an automobile passing directly over and next to the loop are shown in Figure 5. As expected, the frequency responses for vehicles passing directly over the loop are much greater in the 1 to 10 Hz range. These results are for an automobile. Similar results were obtained for sports utility vehicles and trucks.

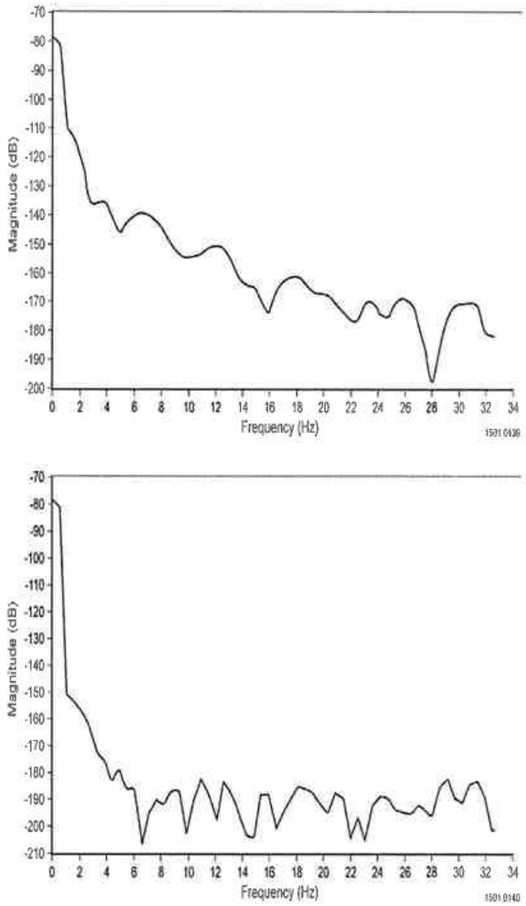


Figure 5. The upper trace shows the frequency content of the induced signal for an automobile passing directly over the loop while the lower trace is the automobile's splashover signal.

Based on the above observations, we developed a two-stage algorithm for the rejection of most splashover effects. The computational approach is summarized in Figure 6. The first stage is a magnitude test. This test is already implemented in the detector station in the form of a triggering threshold. The second stage uses the frequency content of the inductance waveform. The average value of the FFT for the range 1 to 10 Hz (or any other user-specified region) will be compared with a user-determined constant.

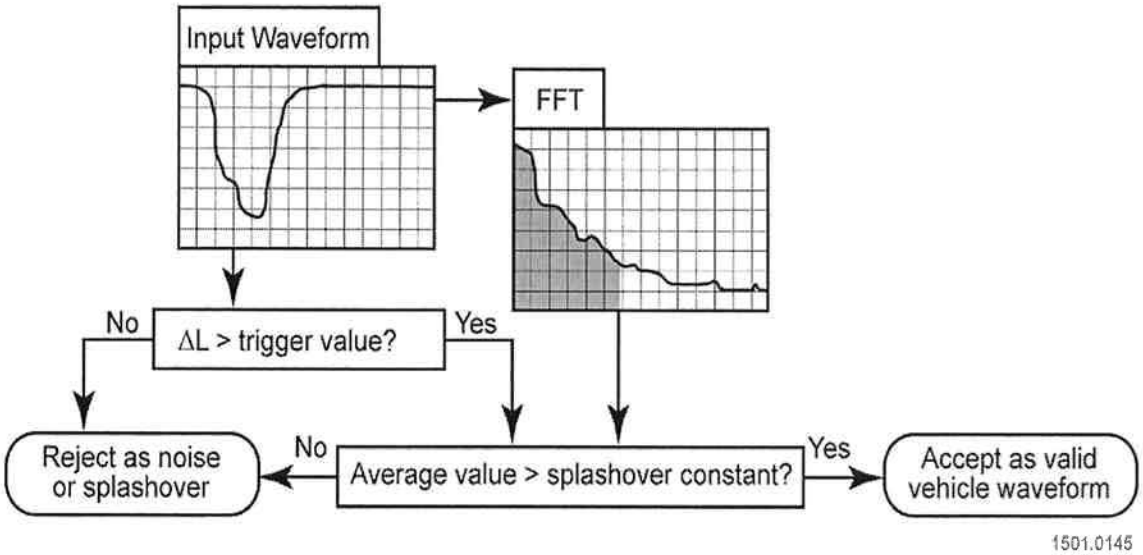


Figure 6. Process chart for proposed algorithm

The numerical values of frequency are set by the time required for the vehicle to pass over the loop, i.e., the speed of the vehicle. For this analysis, all vehicle responses are normalized to a speed of ~16 km/h. This normalization does not introduce any loss of generality. Because the low frequency oscillations are due to geometric attributes of the loop and the vehicle, they are low frequency compared to the inverse of the transit time of the vehicle over the loop. Normalizing to a constant transit time, or speed, provides for consistent waveform comparisons over the speed range.

It was determined experimentally that -137 dB was an appropriate discrimination constant to distinguish against splashover for the loop used in these tests. When the average signal strength for the frequency interval below 10 Hz was greater than this value, the signal was classified as not being due to splashover. This signal level corresponds to an inductance change of about 0.1 μH. Other loops and systems will use slightly different constants.

To test the effectiveness of the frequency-based splashover test, we recorded 108 inductance waveforms for passing vehicles; 59 of these were splashover, and the remaining 49 were for vehicles passing directly over the loop. The vehicles observed included 26 cars, 17 pickup trucks, 19 SUVs and minivans, and 16 other larger vehicles, including mid-sized freight trucks. The frequency test was applied to all of these waveforms and correctly identified splashover with 100% effectiveness. These results confirm that frequency analysis of an inductance waveform can be used to distinguish between vehicles passing directly over the loop and splashover effects caused by vehicles traveling in adjacent lanes.

Extension of this approach was also examined for motorcycle detection. Motorcycles consistently produce reactions with magnitudes comparable with those of splashover signals. Unfortunately, the small reactions of motorcycles also decrease the average FFT value described above. In order to prevent rejection of motorcycle waveforms, we decreased the threshold constant from –137 Hz in dB to –144 Hz in dB. However, this new value is lower than the average value calculated for some of the splashover waveforms. When –144Hz in dB is used all motorcycles are detected, but about 1 in 9 of the splashover reactions results in a false trigger. Further refinement of the combined magnitude and frequency tests is needed to produce a lower false-positive error rate.

IV. BICYCLE DETECTION

Bicycle detection poses a problem for inductive loops [6] because most modern bicycles do not contain sufficient metallic parts to induce appreciable eddy currents. The conventional concept is both the wheels and the frame induce eddy currents and the size of these currents is proportional to the cosine of the angle between the bicycle's direction of travel and the direction of current flow [1]. This implies that a bicycle driving on the loop perimeter would have the greatest likelihood of being sensed.

The measurements of bicycle response, supported by finite element computations [7], show the response can be somewhat different from this straightforward model. Specifically, bicycles induce two very different effects depending on the composition of their wheel rims:

- *Steel rims*: Ferromagnetic steel rims cause a noticeable increase in flux and inductance due to their close proximity to the loop, which is greater than the inductance drop caused by induced currents. The net effect is an inductance rise.

- *Aluminum (or other non-ferromagnetic) rims*: The ferromagnetic effect is absent in this case. The surface offered by these rims for eddy-current induction is not significant enough to cause any appreciable inductance change.

These results are summarized in Figures 7 and 8. Figure 7 shows data for a steel rimmed bicycle that induces an increase of inductance of about 0.05 μH as it passes over the test loop. For comparison, Figure 8 shows the calculated response of a bicycle with aluminum wheels producing a reduction of inductance of 0.015 μH, a value too small to be measured reliably with the detection system.

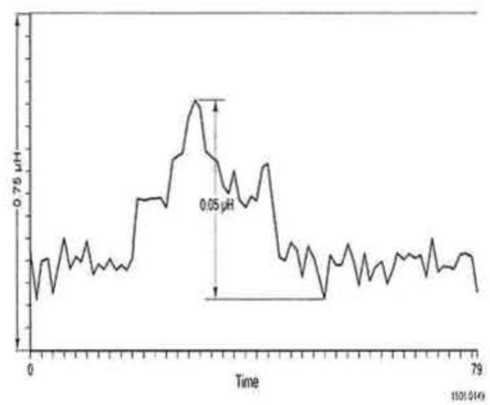


Figure 7. Experimentally observed increase in inductance due to steel-rimmed bicycles

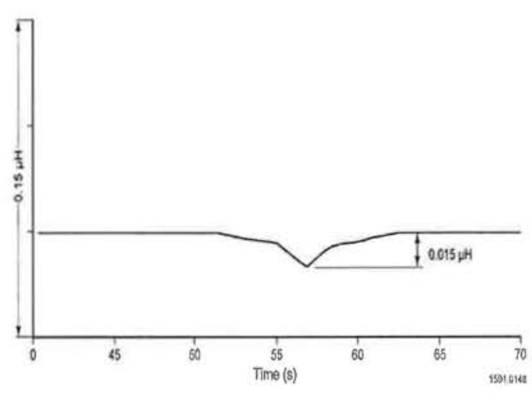


Figure 8. Simulated inductance reaction of a bicycle

In an environment in which steel-rimmed bicycles are expected to predominate, the increase in inductance could provide a key to distinguishing bicycles from small signal produced from nearby automobiles. One appropriate loop configuration is shown in Figure 9. This proposed loop is ~0.3 m long and a little wider than the lane in which it is to be installed. By shortening the length of the loop to approximately 0.3 m., we expect a rise in inductance from a steel-rimmed bicycle, with no appreciable effect from eddy currents. Ordinary vehicular traffic will still cause a decrease in inductance because of the significant chassis area that cuts the flux, but this reaction will be minimized by the length of the loop.

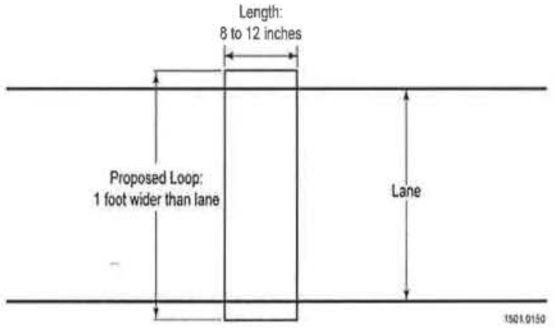


Figure 9. Possible bicycle detection loop

Bicycles outside the loop, but very close to the outer edge of the loop, may cause a slight decrease in inductance because of the relative decrease in the ferromagnetic effect compared with the induced-current effect. By designing the loop a little wider than the lane, any splashover effect from a bicycle can be eliminated. All bicycles traveling within the lane will cause an increase in inductance. A decrease will be caused only by a larger vehicle or a bicycle in an adjacent lane.

Experiments conducted by riding bicycles over the loop showed aluminum-rimmed bicycles induce a small decrease in inductance, as expected. Steel-rimmed bicycles cause an increase in inductance averaging around 0.06 μH. Bicycles running very close to the outer edge of the shorter side cause a drop of about 0.06 μH. The experimental results were verified by doing a finite element calculation of the interaction between a bicycle and the loop.

VI. LEAD LENGTH EXTENSION

At high-speed intersections, it is often desirable to place detector loops 300 m or more from the intersection. This placement allows time for the traffic light to change without slowing vehicles. Conventional systems become unreliable at large distances due to the increase in the intrinsic resistance and inductance of the circuit due to the lead-in cable, making the vehicle reaction smaller (in percent) and harder to detect. The approach described here allows for longer lead length because:

- it measures inductance directly (as opposed to frequency), and
- inductance and resistance measurements are decoupled.

To simulate the increases in lead-in length, appropriate amounts of inductance and resistance were introduced between the loop and the detector. Appropriate values were obtained from handbook data [1], which indicate the resistance increases at an approximate rate of 0.02 Ω/m, the capacitance changes at a rate of 33 pF/m, and the inductance changes at the rate of 0.7 μH/m. For conventional systems, the increases in these parameters typically limit lead length to about 600 meters for all vehicle types [1].

The experimental approach used to demonstrate the benefits of direct measurement of inductance was to induce a low level event, i.e. a reaction of 0.5 μH, which would be a large signal produced by a motorcycle but several times smaller than the signal produced by an automobile. Figure 10 shows the peak-to-peak noise levels in the detected signals as a function of simulated distance between the loop and the detector. This graph shows that the noise level becomes equal to that of the minimum motorcycle signal at 0.6 – 0.7 km. Even at 1.25 km, however, the noise level is far below the specified minimum detection level for an automobile [1]. These results suggest a two loop system, a remote loop for accurate control for the majority of the high speed traffic and a nearer loop for difficult to detect vehicles. Alternatively, additional signal processing could probably reduce the effective noise levels so even difficult to detect vehicles could be sensed at a significant distance.

VII. CONCLUSIONS

Alternative data acquisition technology provides the opportunity to extract additional information from inductive loops embedded in pavement for traffic control. The vehicles whose passage is to be sensed produce an inductance change in the loop. Sensitivity can be enhanced because the conventional detectors react to the change of inductance by sensing a change in frequency. The frequency change is related to the square root of the loop inductance. Direct measurement of the change of inductance with time provides the inherently greater sensitivity. Some benefits that accrued form the enhanced sensitivity have been identified for three different applications: 1) minimizing false responses due to splashover, i.e. the detection of signals from vehicles in lanes adjacent to the traffic lane being sensed; 2) the detection of bicycles; and 3) increasing the lead length between the loop and the traffic signal control box to enhance control in high speed situations. A frequency domain approach was developed, implemented, and tested to augment the conventional approach of discriminating against splashover through amplitude measurements. This approach demonstrated that the different patterns produced when a vehicle passed over a loop and when it passed the loop in an adjacent lane could be distinguished reliably by a straightforward characterization of the frequency spectrum of the induced signal.

A new approach to bicycle detection was proposed for those situations in which the bicycle wheel is made of steel. The approach exploits the magnetic field enhancement produced by the wheel while minimizing the reduction of the field due to induced currents in the bicycle frame.

Finally, it was shown the measurement approach, because it separates the inductive from the resistive components of the wire connecting the loop to the control box, provides the opportunity to locate a loop farther from an intersection than possible suing today's systems. This capability may be important in high speed applications as it can provide a better match between signaling times and a driver's reaction time.

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