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Using Inductive Loops to Count Bicycles in Mixed Traffic

By Krista Nordback, P.E., Daniel Piatkowski, Bruce N. Janson, Ph.D., Wesley E. Marshall, Ph.D., P.E., Kevin J. Krizek, Ph.D., and Deborah S. Main, Ph.D.

Inductive loops are commonly used for bicycle detection both on- and off-street, but until recently, few such detectors were able to differentiate between bicycles and motor vehicles. For this reason, automated bicycle counting is usually confined to off-street locations. With bicycle use increasing around the world, particularly on shared roadway facilities such as bicycle boulevards, there is a growing need to detect bicycles in on-street traffic conditions. This study tests the accuracy of an off-the-shelf inductive-loop technology designed to count bicycles in mixed traffic conditions and compares this accuracy to similar inductive loop technology used for detection on separated bicycle facilities. The results show that the inductive loop technology is capable of differentiating bicycles from motor vehicles and counting bicycles in traffic with reasonable accuracy, but an individual bicycle may be undetected or counted more than once. Overall, there was a 3 percent undercount for the counter on the separated path and a 4 percent overcount for the counter on the shared roadway. The results show that refinements in inductive loop detector/counter software and setup have made it possible to distinguish bicycles from motor vehicles; however, care must be taken in installation, calibration, and maintenance to ensure that the counters are accurate.
Introduction

Policymakers are increasingly looking to bicycling as a sustainable mode of transportation that can reduce vehicle emissions and fuel use. Accurately quantifying bicycling levels is necessary to better understand the degree to which public policies and changes in the built environment are affecting bicycle use.

Automated detection of motor vehicles is the standard for estimating average annual daily traffic (AADT) on roadways as well as quantifying vehicle miles traveled (VMT) locally and nationally. Automated detection, usually using inductive loop detectors, has proven to be a relatively accurate and necessary part of monitoring vehicle use, as allocation of federal transportation funds is linked to VMT estimates. If bicycle use is to be similarly quantified, automated detectors using inductive loops may provide the basis for such estimates, which can also be used to evaluate current and future bicycle infrastructure investments. For these reasons, this study focuses on testing the accuracy of automated bicycle detection.

Bicycles travel on three main types of bicycle facilities: separated paths, bicycle lanes, and shared roadways. For the purposes of this study, the term “separated path” includes any bicycle facility physically separated from motor vehicle traffic; the term “bicycle lanes” includes on-street facilities separated from motor vehicle lanes by a solid line and on which bicycles are either designated or allowed to ride; the term “shared roadway” includes on-street facilities where bicycles share the motor vehicle lane whether specific signs and markings are present or not. Though it is desirable to count bicycles on all three facility types, this paper focuses primarily on methods for counting bicycles on shared roadways.

For decades, inductive loops have been used to detect bicycles at signals and to count bicycles on separated bicycle facilities such as paths. Inductive loop detectors are relatively low cost, well understood by transportation technicians, and easy to maintain. Although accurately counting bicycles on separated paths using inductive loops has proven feasible with proper setup and maintenance, bicycles on shared roadways cannot be accurately counted with conventional inductive loop technology because these detectors fail to differentiate between bicycles and motor vehicles. Even when loops are placed in bicycle lanes, motor vehicles traveling in adjacent lanes can be erroneously counted as well. In order to count bicycles on increasingly popular, mixed-traffic facilities such as bicycle boulevards, new automated methods and technologies are now emerging.

A few systems for classifying bicycles in mixed-traffic conditions have been developed. Among them only two were found to be off-the-shelf products for permanent installation in mixed traffic: the MS Sedco Intersector, which uses microwave radar to identify bicycles by speed, shape, and microwave reflectivity and the Eco-Counter Zelt, which uses inductive loop technology. Since these technologies are relatively new, little field testing has been done. Several studies of the accuracy of the Zelt are available however, no third-party studies of the MS Sedco Intersector were found, though the manufacturer cites internal tests. The bicycle detectors (hardware only) discussed above generally range in price from roughly $2,000 to $5,000 depending on the type of location, with the loop detectors on the lower end of the range. (Installation costs can vary substantially by location. Prescribed maintenance of the Zelt is limited to annual battery replacement.)

Other permanent bicycle counting technologies for shared roadways are under development. A FHWA study found that eight of eight bicycles were correctly classified and counted using a Migma, Inc. detector, which combines stereo camera, infrared thermal camera, and acoustic sensor technologies. Piezoelectric and video-detection technologies might also be incorporated into future permanent shared-roadway bicycle detection products by other manufacturers. For temporary applications, pneumatic tube counters might also be used.
The purpose of the study was to evaluate the effectiveness of the Eco Counter Zelt inductive loop counter by comparing the accuracy of its automated bike counts on separated paths and shared roadways and to third-party studies. This study will address two key questions: Can an inductive loop detector fill the need for automated bicycle counts on shared roadways, and if so, what are its limitations? (The inductive-loop counters were installed and tested on bicycle lanes as well, but due to electrical interference at these locations, these loops are not performing properly and will be moved. For this reason, the bicycle lane locations will only be discussed tangentially herein.)

**Inductive Loop Detectors**

Inductive loop detectors are commonly used to detect motor vehicles at traffic signals and are the most common vehicle-sensor type in traffic management. An inductive loop circuit is composed of loops of wire embedded in the pavement and the associated lead-in cables. The detector constantly senses the inductance in the circuit by measuring the resonant frequency. When a metal object passes above the loops, it induces eddy currents in the circuit, which changes the circuit’s inductance. Bicycle detection by inductive loops was studied in detail, by modeling the extent of bicycle detection zones for typical traffic signal loop detector configurations.\(^2\)

A field study of 100 steel-frame bicycles and 51 aluminum-frame bicycles performed by SRF Consulting compared various automatic bicycle and pedestrian counting technologies and found no discrepancies between manual and inductive loop detector counts, while other counting technologies showed discrepancies of up to 4 percent.\(^1^2\) However, a previous study showed that after years of use in field conditions with little maintenance, conventional inductive loop detector accuracy varied substantially from 67 percent undercounts to 114 percent overcounts with average absolute percent accuracy of 81 percent and only 68 percent of the detectors considered accurate.\(^3\) However, the previously tested technologies are not able to differentiate between bicycles and motor vehicles and thus are limited to separated paths or perhaps bicycle lanes.

The Eco-Counter Zelt is a relatively new inductive loop technology, which claims to be able to differentiate bicycles from motor vehicles by analyzing the signals from the inductive loop or loops. Using a proprietary algorithm that takes into account variables including signal strength, vehicle speed, and wheel spacing, the manufacturer claims that the technology can determine whether a detected object should be classified as a bicycle or not.

Zelt has been evaluated in a few international studies with accuracies ranging from 74 percent to 99 percent.\(^7^–^1^0\) A detailed comparison of these studies is provided in the discussion section of this paper. While these studies are useful individually, this paper offers a comparison of these studies to better inform potential users.

While inductive loops are a proven technology for vehicle detection, some issues may confound their use for bicycle detection: carbon fiber bicycles, long-wheel base bicycles (such as tandems), bicycles with trailers, bicycles riding side by side, bicycles riding closely one behind the other, and bicyclists riding slowly. Each of these special cases is tested in this study.

**Data Collection Method**

The testing protocol was consistent across test locations in order to determine whether bicycles were counted accurately. There were two test parts: common bicycles and special cases. The common bicycle test was conducted twice for each location, each of which consisted of volunteer cyclists riding for at least 30 minutes on standard bicycles again and again over the loop detectors. Standard bicycles included aluminum, steel, and titanium bicycles. Volunteers rode over the loops as frequently as feasible during this time period (typically at least twice per minute per rider).
Volunteers were also stationed to count vehicles and bicycles crossing each loop and record any special circumstances that may affect the loop detector counts. Other bicyclists and vehicles (where allowed) also crossed the loops during testing, since test locations were open to the public. Because of these frequent crossings, it was not practical for the volunteer manual counter to verify whether each vehicle or bicycle was properly detected during the common bicycle test. Thus, counting was divided into one-minute bins synchronized with the loop detector’s clock.

Each detector has its own battery-powered data logger with a digital display indicating the total number of counts recorded since the counter was installed or reset. The digital display allows the volunteer manual counters to observe, in real time, whether a bicycle or other vehicle is counted or not. However, when bicycle traffic is high, it can become difficult to maintain an accurate manual count. For this reason, volunteer manual counters were asked to record the total bicyclists observed each minute and the count displayed on the data logger at the end of each minute. After the data were downloaded, these manually recorded readings were compared to the 15-minute bin outputs from the data file.

Special case testing was conducted using the same one-minute binning method described, except that volunteer riders rode specific bicycle types, or in specific ways, for three or more minutes of each case. Unless otherwise specified, the frame types of the special case bicycles below were either aluminum or steel.

Special cases that were tested include the following:

- A carbon fiber bicycle with aluminum wheels;
- A steel bicycle with a trailer;
- A tandem bicycle;
- Two bicyclists riding side by side;
- Two bicyclists riding closely, one behind the other; and
- Bicyclists walking or riding at walking speed.

**Description Of Equipment**

The inductive-loop detector was tested in two different configurations: a single loop configuration and a three-loop configuration. Two bicycle facility types were tested: a separated bicycle facility and a shared roadway. Installation locations are listed in Table 1.

**Table 1: Locations and loop configurations studied.**

<table>
<thead>
<tr>
<th>Bicycle Facility Type</th>
<th>Location</th>
<th>Model</th>
<th>Number of Loops</th>
<th>Number of Detector Channels Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared Roadway</td>
<td>13th Street northbound</td>
<td>Eco-Twin</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Separated Path</td>
<td>13th Street southbound</td>
<td>Eco-Pilot</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bicycle Lane</td>
<td>Folsom Street*</td>
<td>Eco-Pilot</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bicycle Lane</td>
<td>Folsom Street*</td>
<td>Eco-Pilot</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

* Not tested due to electrical interference causing variable accuracy (loops to be moved).
The detectors tested in this study use diamond-shaped induction loops as described by Eco-Counter. These were installed in conjunction with Eco-Counter and the city of Boulder, Colorado, USA in late June 2010 at four locations: in north and southbound bicycle lanes of Folsom Street, on a 12.5-foot-wide shared roadway segment with one-way motor-vehicle traffic on 13th Street, and on an 8-foot-wide bicycle contraflow lane with one-way bicycle traffic on 13th Street. For the purposes of this paper, the contraflow lane is categorized as a “separated path,” since motor vehicles are separated from this section of the roadway by concrete planters and is thus too narrow for most cars and trucks. The inductive loops for the bicycle lane and separated path locations consisted of single diamond-shaped inductive loops. For the shared roadway location, three diamond-shaped inductive loops were installed. Figure 1 shows the configuration of the loops and detectors at each location.

A separate, waterproof, battery-powered detector and data logger was provided for each location. This paper focuses on results of the separated path and shared roadway locations, but results from the bicycle lane testing will also be discussed briefly.

Testing
Tests were performed on the mornings of Thursday, July 1 and Monday, July 19, 2010 between the hours of 8:00 a.m. and 11:00 a.m. with favorable weather conditions. Since the two detectors on 13th Street are

Figure 1: 13th Street loop locations (inductive loops are highlighted in the graphic).
located within 100 feet of each other, the same group of volunteer bicyclists was able to test both detectors during one testing period, though each automated detector required its own volunteer manual counter. A completely different set of riders and counters participated in the testing on each day.

After all tests were completed, the data from the data loggers were downloaded. Manual counts were compared to automated detector counts under the assumption that the manual counts were accurate. The team compared the counts for the special cases and examined the notes from the manual counters.

**Analysis**

As described above, the counts were aggregated into one-minute bins. Bins contained one to 10 counts each and averaged four counts per bin. The number of bins and number of counts for each location are shown in Table 2.

For each bin the percent difference, $d_i$, between the automated detector counts and the manual counts was computed.

$$d_i = c_i - m_i$$

where:

$d_i$ = difference per bin

$i$ = one-minute bin

$c_i$ = automated detector count per bin

$m_i$ = manual count per bin

The automated detector counts were compared to the manual counter counts, using the manual counter as the baseline and assuming the manual count is completely accurate. To understand the overall errors, the average of the percent differences, $a$, was computed. To better understand the accuracy of the counters, the average of the absolute values of the percent differences, $a_{AAPD}$, also called the average absolute percent difference (AAPD), was computed as shown in the following equations.

<table>
<thead>
<tr>
<th>Bicycle Facility Type</th>
<th>Number of Bins</th>
<th>Total Manual Bicycle Counts</th>
<th>Total Automated Detector Counts</th>
<th>Total Manual Motor Vehicle Counts</th>
<th>Total Difference $c - m = d$</th>
<th>Average Total Percent Difference $a$</th>
<th>Average Absolute Percent Difference (AAPD) $a_{AAPD}$</th>
<th>Average Absolute Percent Accuracy $1 - a$</th>
<th>95 percent Confidence Interval (+ or -)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separated Path</td>
<td>106</td>
<td>316</td>
<td>306</td>
<td>0</td>
<td>24</td>
<td>-3.2 percent</td>
<td>7.6 percent</td>
<td>92 percent</td>
<td>3 percent</td>
</tr>
<tr>
<td>Shared Roadway</td>
<td>122</td>
<td>500</td>
<td>520</td>
<td>182</td>
<td>20</td>
<td>4 percent</td>
<td>23 percent</td>
<td>77 percent</td>
<td>4 percent</td>
</tr>
</tbody>
</table>
where:

\[ n = \text{number of one-minute bins} \]

\[ m_t = \text{total manual counts} \]

\[ a = \text{average percent difference} \]

\[ a_a = \text{average of the absolute value of the percent differences} = \text{AAPD} \]

For these detectors, there are three types of errors: (1) counting something when a bicycle is not present (overcounting), (2) counting a bicycle more than once (overcounting), and (3) not counting a bicycle when one is present (undercounting). If traffic on the roadway could have been controlled, then the experiment would have been designed to know whether each bicycle or vehicle was counted properly. However, due to the volume of both bicycle and motor vehicle traffic on the public roadway, and the limits of human ability to both count bicycles and motor vehicles, the test was instead designed to count bicycles and motor vehicles in one-minute bins. This method allows for comparison of manual counts with detector counts, but it hides, to some extent, the different types of errors present in the bin. For example, if a bicycle is counted twice and another is not counted at all in the same bin, it will appear that there is no discrepancy when in reality the detector has a low accuracy. For this reason, the average absolute percent difference (AAPD), which reveals more of the detector inaccuracies, is used to compare the detectors. The average percent difference is also included in Table 2, since users of automated detectors may want an indication of how much to adjust the counts to better reflect actual bicycle counts.

Given that counts are discrete data, they were modeled using a binomial distribution where each manual count was considered a trial for whether the result is either zero or one. If the result of the trial is zero, this indicates that there was no difference between the automated detector count and the manual count—that is, no errors occurred. If the result of the trial is one, this indicates that one error occurred and the bicycle was either not counted or was double counted. The probability of a trial being in error is computed by dividing the total number of errors by the total manual bicycle counts. Since the total number of errors is estimated by summing the absolute values of the differences between detector and manual counts for each bin, the probability of a trial being in error is approximated by the AAPD.

Modeling the test using the binomial distribution as described above involves the following assumptions:

- One trial occurs for each manual bicycle count. This is not completely accurate, since an overcount sometimes occurs when a motor vehicle or some other non-bicycle passes over the detector. Fortunately, this type of event is rare. Only once during testing did a volunteer notice the multi-loop system on the shared roadway record a count when a motor vehicle passed. Testing by others reported that only 0.4 percent to 0.8 percent of motor vehicles passing a loop on a shared roadway were counted as bicycles.\(^8\)
Double counts cancelled out by undercounts within a bin are ignored. This assumption means that the AAPD will tend to underestimate the probability of a bicycle being under- or overcounted; and

If an automated detector counts a given bicycle as three or more bicycles, the AAPD will tend to overestimate the probability of a bicycle being under or overcounted. However, there were no instances when an automated detector counted a given bicycle more than twice.

Confidence intervals were calculated assuming the binomial distribution with 95 percent confidence interval estimated using the standard normal z-statistic.

Since the results from the two days of testing were similar, the data were combined for each location, with the results presented in Table 2. Generally, the automated detector on the separated path was more likely to undercount than overcount, while the automated detector on the shared roadway was more likely to overcount than undercount. The results for each case are discussed separately below.

**Separated Path**
The system in the separated bicycle path generally undercounted bicyclists with average percent difference of 3 percent undercounting but was relatively accurate with an AAPD of 8 percent.

**Shared Roadway**
The average percent difference for the system on the shared roadway was low, with 4 percent overcount overall, but the AAPD of 23 percent reveals the inaccuracies of detecting individual bicycles in an environment where motor vehicles are present.

During testing, one volunteer manual counter noticed that some bicycles were not counted while others were counted more than once. Speed and lane location are likely factors that will be discussed later. However, motor vehicles were generally not detected by the loops, confirming that the detectors can differentiate between motor vehicles and bicycles.

**Bicycle Lanes**
The loops installed on the Folsom Street bicycle lanes frequently undercounted bicycles; the manufacturer attributes this to electrical interference, and the counters will be moved to another location. The average percent difference, 27 percent undercount, and the AAPD of 29 percent measured for the southbound loop show that the loop studied is consistently undercounting. Increasing the sensitivity of the loop resulted in substantial overcounting. The loop installed on the other side of the bicycle lane, in the opposite side of the road, was so inaccurate due to interference that it was not tested. The manufacturer has offered to help the city of Boulder move the loops to a more suitable location, but this was not completed as of writing and the results from this test are not included in Table 2.

**Path Versus Roadway Comparison**
As shown in Table 2, the AAPD is lower for the path than for the shared roadway, indicating that the technology may be more accurate when bicycles are separated from motor vehicle traffic, as illustrated in Figure 2. This makes sense, since it is an easier task to detect bicycles when motor vehicles are not present.

Statistically, the AAPD for the two automated detectors were compared using a pooled estimate of a common proportion (also known as a test of proportions) to test the hypothesis that the AAPDs are the same. The p-value is less than 0.001, indicating that the AAPD for the two automated detectors are significantly different.
Potential Error Sources

Unfortunately, neither the inductive loop detectors nor the manual counts are perfect, and any test has sources of error. Human error has been identified in a previous study as one possible source of miscounting. In a previous study, volunteer manual counters slightly undercounted by 1 percent (+/- 4 percent) average percent difference and had a 6 percent average absolute percent difference (94 percent accuracy). It was also possible for manual counters to become overwhelmed by high levels of bicycle traffic, and in such cases, percent differences between manual counters were as high as 45 percent.

Another source of error is bicycles crossing loops at or near the time of the end of the one-minute bin, which may be recorded in either bin. There is a short, approximately 2-second, delay for detectors to recognize and count the bicycle, which may result in the detector putting the bicycle in a later bin than the manual counter. Analysis focusing on the average absolute percent differences is revealing but is also somewhat arbitrary in that the size of the aggregated bin influences the results.

Special Case Testing

The comparison of automated detector counts with manual counts provides overall information on accuracy, but a discussion of special cases and other observations encountered in the field may provide further insight into accuracy issues associated with the automated detectors. In order to get a sense of what special cases may confound the detectors, a few situations were specifically studied. Table 3 reports the results. The detector is designed to count bicycle wheels, not frames, so it is no surprise that the automated detectors were able to count the carbon fiber bicycle with aluminum wheels consistently. While tandem bicycles and bicycle trailers are relatively rare (generally less than 1 percent of bicycles), carbon fiber bicycles make up roughly 5 percent of bicycles observed on paths in Boulder, which is likely to be a higher percentage than in most cities.

Additionally, a steel bicycle with an aluminum two-wheel child trailer was ridden over the detectors. The automated detector consistently missed the bicycle with trailer, except in one case when it was double counted. The manufacturer does not claim to detect bicycles with trailers under standard settings, so this result is not surprising. Similar to the bicycle with trailer, the tandem bicycle with a long-wheel base (Bike-Friday brand with a steel frame) was only counted three of the 21 times it crossed the loops on the shared roadway. The manufacturer does not claim to be able to detect tandems, so the low detection of such long wheel-base bicycles is also not surprising.
One of the tradeoffs of identifying bicycles when motor vehicles are present, by filtering out some signals from the inductive loops, is that some bicycle types, such as those with long wheel bases or more than two wheels, are rejected because they are not similar enough to the standard bicycle. While the manufacturer states that settings could be changed to include longer wheel base vehicles, this may result in some motor vehicles being detected that would have otherwise been rejected. Perhaps as signal interpretation algorithms become more sophisticated, this may be remedied; currently, the uncounted long wheel-base bicycles and bicycles with trailers is minimal because such bicycles are relatively rare. The more traditional loop detectors (Canoga C800) studied previously were able to correctly count these bicycle types but cannot differentiate bicycles from motor vehicles.

Bicycles riding side by side were consistently counted as two bicycles by the multiloop system but as only one bicycle by the single-loop detector. This is probably because they crossed more than one loop when crossing the multiloop configuration but only one loop when crossing the single-loop configuration. The more traditional loop detectors studied previously counted side-by-side riders as one bicycle.

Bicycles riding in opposite directions crossing the loops simultaneously were not tested, since such movements are illegal on this stretch of roadway. Each lane is one way only, and though wrong-way bicyclists have been observed occasionally in the southbound contraflow lane, none was observed during testing.

When two bicyclists rode closely one behind the other (less than one bicycle length), only one bicycle was counted by the multiloop system on the shared roadway, while both bicycles were counted by the single-loop system on the separated path. One possibility is that the multiloop detector was set to be more selective, since it is designed to reject any vehicle similar to a motor vehicle. A previous test of the more traditional inductive loop detectors indicated that these detectors also count two bicycles following each other closely as one bicycle. Thus, it is surprising that the single-loop detector on the separated path was able to count the bicycles following each other closely as separate bicycles most of the time.

### Table 3: Special cases studied.

<table>
<thead>
<tr>
<th>Bicycle Facility Type</th>
<th>Separated Path</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>Observed number of bicycles counted by detector vs. by manual counter</td>
<td>Percent accurate</td>
<td>Percent accurate</td>
</tr>
<tr>
<td>Carbon fiber bicycle with aluminum wheels</td>
<td>8 of 8 bicycles counted</td>
<td>100 percent</td>
<td></td>
</tr>
<tr>
<td>Bicycle with trailer</td>
<td>2 of 11 bicycles counted</td>
<td>18 percent</td>
<td>0 of 18 bicycles counted</td>
</tr>
<tr>
<td>Tandem</td>
<td>3 of 21 bicycles counted</td>
<td>14 percent</td>
<td></td>
</tr>
<tr>
<td>Side-by-side bicyclists</td>
<td>7 of 14 bicycles counted</td>
<td>50 percent</td>
<td>8 of 8 bicycles counted</td>
</tr>
<tr>
<td>Bicyclists, one behind the other</td>
<td>16 of 18 bicycles counted</td>
<td>89 percent</td>
<td>5 of 10 bicycles counted</td>
</tr>
<tr>
<td>Bicycle at walking speed</td>
<td>16 of 16 bicycles counted</td>
<td>100 percent</td>
<td>11 of 11 bicycles counted</td>
</tr>
</tbody>
</table>

Bicycles riding side by side were consistently counted as two bicycles by the multiloop system but as only one bicycle by the single-loop detector. This is probably because they crossed more than one loop when crossing the multiloop configuration but only one loop when crossing the single-loop configuration. The more traditional loop detectors studied previously counted side-by-side riders as one bicycle.
When the bicyclists walked their bicycles or rode at walking speed over the detectors, both automated detectors had no trouble counting the bicycles. This is different from the behavior observed for more traditional loop detectors studied previously, whose time settings prevented them from detecting bicycles moving at walking speed, but these could have been adjusted to improve performance.

Other Observations
During the course of testing, other situations were observed that, although not necessarily repeated, may offer additional insights about what may cause counting inaccuracies.

Children
Child-sized bicycles with 20-inch wheels and smaller were not counted by the single-loop detector, but child-sized bicycles with 24-inch wheels and larger were counted. Bicycles with child bicycle attachments, also known as tagalongs, were only encountered once for each configuration, since this case was not specifically tested. Similar to the tandem bicycle, the tagalong bicycle was not counted for the multiloop system but was counted twice by the single-loop detector.

Double Counting
Occasionally, cyclists on the shared roadway were double counted. A volunteer riding through specific locations on the loops revealed that double counting can be triggered by a bicycle crossing the detector exactly between the two northern loops as shown by the arrow in Figure 1(c). A volunteer rider on an aluminum bicycle rode over this specific point six times and was double counted four of those six times.

Nondetection
It was observed three times that a cyclist was undetected when he or she rode through the exact center of the leftmost loop of the multiloop system. Although this is not a likely location for most cyclists who tend to ride in the center or right side of the lane, it may account for some observed cases of a bicycle not being counted during the testing.

Motor Vehicles
At the shared roadway location, motor vehicles were almost always excluded from the automated detector counts, except in one case when a spurious count was observed as a semi-truck with trailer crossed the loops. Motorcycles and scooters were also not counted, probably because these vehicles have more metal than a bicycle and thus give a stronger signal to the detector, which is then able to exclude such signals as not bicycles. While no standard-sized vehicles are able to use the separated path, a small, motorized utility vehicle used for city maintenance does occasionally cross the detector; when it was observed prior to testing, it was not counted by the single-loop detector technology.

To identify whether the multiloop detectors accurately differentiated motor vehicles from bicycles, Figure 3 was plotted to show that the number of motor vehicles passing over the detector does not affect the number of over or undercounts. The regression line is so close to horizontal that it is difficult to observe in this graph. If success in differentiating motor vehicles from bicycles were to be included in the estimate of accuracy, the multiloop detector on the shared roadway has 83 percent accuracy.
Discussion

While the multiloop detector on a shared-roadway does not seem to be as accurate as the single-loop detector on the separated bicycle path, it was able to consistently distinguish between bicycles and motor vehicles, a task that few other technologies can accomplish. The multiloop detector, however, may be prone to over or undercounting due to the configuration of multiple diamond loops, which seems to miscount depending upon where a bicycle crosses the loop.

The discrepancies of 23 percent absolute average difference for the loops on a shared roadway and 8 percent for the loop detector on a separated path are comparable to the 19 percent average absolute difference computed for the more traditional loop detectors studied previously (which had been in operation with little maintenance for approximately 10 years) on separated bicycle paths in Boulder. The multiloop configuration tends to undercount bicyclists traveling closely one behind the other, but other inductive loop technologies, such as those previously tested, also tend to undercount in such situations. The multiloop system can accurately count bicycles traveling side by side, which the more traditional inductive loop detector tested previously was also not able to do.

The single-loop counter in the separated path was significantly more accurate and able to distinguish metal vehicles (hand cart and four-wheel motorized utility vehicle) from bicycles and not count them. This accuracy makes sense, considering the single-loop detector’s task was much simpler: Only one loop was required, and motor vehicles were few. The accuracy of this counter exceeds that of the more traditional loop detectors studied previously (though these were installed many years prior to testing while the loop detectors studied here were installed days prior to testing), and the single-loop detector studied has the added capability of being able to differentiate between motor vehicles and bicycles.

As shown in Figure 4, accuracy as calculated by AAPD for both loop configurations is a function of the number of counts per bin, represented as bin size in minutes in the graph. The more cyclists counted per bin, the more the over and undercounts of individual cyclists cancel each other out and converge to the overall inaccuracy of 3 percent to 4 percent. The point at which the inaccuracy
converges to 5 percent or less AAPD roughly equates to counts per bin of 60 cyclists or more, which is a common bicycle hourly count for frequently used bicycle routes during peak hours. Thus, the accuracy of the inductive loop counters for hourly counts on high-frequency bicycle routes is likely to be more than 95 percent.

**Comparison to International Studies**

Zelt inductive-loop technology has been studied internationally. As summarized in Table 4, four studies were found that tested the accuracy of these inductive loop counters for counting bicycles on separated paths, bicycle lanes, and shared roadways. When sufficient data were provided in the published reports, the AAPD was calculated using the method presented above and reported in Table 4, which allows some comparison of the studies. The studies performed in New Zealand and Norway did not always aggregate counts into bins but may have instead been able to check count detection per trial for trials of bicycles passing over the detector, and in the New Zealand report, also for motor vehicles passing over the detector. For this reason, bin sizes for those studies are listed as “unknown” in Table 4.
The study from New Zealand reported an error adjusted index (EAI), which was computed by subtracting the automated detector’s under and overcounts from the manual counts for a particular test, summing these for all tests and dividing by the total manual counts for all tests of that equipment type (EAI = 1 - AAPD).

The Swedish study reported results as the mean absolute percent error (MAPE), which is computed in the same way that AAPD is computed. However, because the bicycles per bin was so large (30 to 220 bicycles per 15-minute bin) the under and overcounts in each bin would have cancelled each other out, and the resulting reported statistic may substantially overestimate the accuracy of the detectors.\textsuperscript{10}

<table>
<thead>
<tr>
<th>Bicycle Facility Type</th>
<th>Report</th>
<th>Number of Bins</th>
<th>Number of Reference Counts</th>
<th>Results Reported</th>
<th>AAPD*</th>
<th>95 percent Confidence Interval (+ or -)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separate Path</td>
<td>New Zealand (8)</td>
<td>26</td>
<td>269</td>
<td>88 percent EAI</td>
<td>12 percent</td>
<td>4 percent</td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>26</td>
<td>178</td>
<td>74 percent EAI</td>
<td>26 percent</td>
<td>6 percent</td>
</tr>
<tr>
<td></td>
<td>Sweden (10)</td>
<td>12</td>
<td>1503</td>
<td>1.1 percent MAPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sweden (10)</td>
<td>12</td>
<td>1443</td>
<td>1.6 percent MAPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>106</td>
<td>316</td>
<td>7.6 percent AAPD</td>
<td>8 percent</td>
<td>3 percent</td>
</tr>
<tr>
<td>Bike Lane</td>
<td>France (7)</td>
<td>102</td>
<td>201</td>
<td>1.5 percent undercount</td>
<td>6 percent</td>
<td>3 percent</td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>80</td>
<td>88.8 percent EAI</td>
<td>10 percent</td>
<td>7 percent</td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>96</td>
<td>72 percent EAI</td>
<td>28 percent</td>
<td>9 percent</td>
</tr>
<tr>
<td></td>
<td>Norway (15)</td>
<td>Unknown</td>
<td>557</td>
<td>97.5 percent Accuracy</td>
<td>3 percent</td>
<td>1 percent</td>
</tr>
<tr>
<td>Shared Roadway</td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>227</td>
<td>79 percent EAI</td>
<td>21 percent</td>
<td>5 percent</td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>142</td>
<td>88.0 percent EAI</td>
<td>12 percent</td>
<td>5 percent</td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>41</td>
<td>90.2 percent EAI</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>New Zealand (8)</td>
<td>Unknown</td>
<td>37</td>
<td>75.7 percent EAI</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norway (15)</td>
<td>Unknown</td>
<td>109</td>
<td>83.5 percent Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>122</td>
<td>500</td>
<td>23 percent AAPD</td>
<td>23 percent</td>
<td>4 percent</td>
</tr>
</tbody>
</table>

* Calculated from published data where available.

Note: “USA” indicates current study.
The accuracy reported in this study is comparable to other reports of Zelt detector accuracy. The single-loop counter on a separated bicycle path (13th Street southbound) seems to be more accurate than other similar facilities tested. Perhaps the manufacturer is improving, or the location and installation on 13th Street was particularly well suited for accurate detection. The multiloop system on a shared roadway tested herein seems to be performing slightly worse than other detectors studied but within the confidence interval of at least one of the detectors studied in New Zealand.

These international tests, in addition to the tests performed in this study, provide a full picture of the accuracy of this technology at the present time. The manufacturer continues to refine the technology, so future studies may show improved results.

Conclusions

Inductive loop technology is capable of detecting bicyclists on shared roadways with relatively high accuracy, but under and overcounts of individual bicycles do occur. Overall, the Eco-Pilot loop detector on the separated path counted bicycles with a 3 percent undercount, but looking at the average absolute percent difference (AAPD), 7.6 percent of the bicycles passing were either not counted or double counted by the detector (92 percent accuracy). For the single-loop detector on the shared roadway, there was an overall 4 percent overcount, and 23 percent of the bicycles passing the detector were incorrectly counted (77 percent accuracy). However, it was very rare for a motor vehicle to be detected as a bicycle.

While AAPD is a good metric for the academic study of bicycle detector accuracy, overall accuracy may be a more important metric for those interested in installing automated detectors. The accuracy of total daily counts reflects the overall accuracy rather than whether or not a particular bicycle is detected. Thus, the overall percent differences computed (3 percent undercount and 4 percent overcount for the single and multiloop locations, respectively) indicate that inductive loop technology can provide relatively accurate counts for the purposes of quantifying bicycle use.

The point at which the inaccuracy converges to 5 percent or less AAPD roughly equates to counts per bin of 60 cyclists or more, which is a common bicycle hourly count for frequently used bicycle routes during peak hours. Thus, the accuracy of the inductive loop counters for hourly counts on high-frequency bicycle routes is likely to be more than 95 percent.

The special cases tested led to the following conclusions:

- Long wheel base bicycles and bicycles with trailers are not usually counted by either loop configuration;
- Bicycles riding side by side are counted correctly by the multiloop configuration but were counted as a single cyclist by the single-loop configuration;
- Bicyclists riding one behind the other were counted as a single cyclist by the multiloop detector but were counted correctly by the single-loop detector; and.
- When bicycles are ridden slowly over the detectors, they were correctly counted.

Refinements in detector and data-logger software and setup have made it possible to distinguish bicycles from motor vehicles. However, care must be taken in installation and maintenance to ensure the counters are accurate. Loop detectors should not be installed at locations with electrical interference problems, which prevented the Folsom bicycle-lane detectors from being included in our study. Thus, loop detectors should not be installed in close proximity to power lines, other
inductive loops, or in any location with high electrical interference, which can be measured prior to cutting loops by using equipment provided by the manufacturer.\textsuperscript{6,13}

Counting bicycles on shared roadways such as bicycle boulevards is increasingly important for planners and engineers seeking to quantify bicycle use in a similar ways to quantifying motor vehicle miles traveled. This study shows that inductive loop technology provides an automated method to quantify bicycles on such shared roadways. While the technology is not flawless, it can provide more accurate counts and useful data on shared roadways (when properly installed and maintained) than other bicycle-detection systems.

Acknowledgments

The work recorded herein was truly a team effort. Volunteer riders and counters made this study possible: Becky Shoag, Joe Cooper, Pat Noyes, Josh Sperling, Eric Stonebraker, and Kurt Nordback. Loop installation was made possible by Jean-François Rheault of Eco-Counter and City of Boulder staff: Mike Gardner-Sweeney, Joe Paulson, and Jeff Bunker. Funding was provided by the Dwight David Eisenhower Transportation Fellowship Program and the National Science Foundation through the Integrative Graduate Education and Research Traineeship (IGERT Award No. DGE-0654378).

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