Accuracy of Bicycle Counting with Pneumatic Tubes in Oregon

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Interest in counting bicycles and establishing nonmotorized counting programs is increasing, but jurisdictions still struggle with how to integrate bicycle counting into standard practice. In this paper, the authors share findings and recommendations for how to minimize error for bicycle counting from tests conducted in conjunction with the Oregon Department of Transportation. This research studied three types of off-the-shelf pneumatic tube counters for counting bicycles, including equipment from five manufacturers: two bicycle-specific counters, three varieties of motor vehicle classification counters, and one volume-only motor vehicle counter. Tests were conducted both in a controlled environment and in on-road mixed traffic to better identify problems in accuracy. Equipment studied generally undercounted cyclists, especially those in groups. Results from the controlled test with standard bicycles showed that within 10 ft of the counter, the undercounting error ranged from 0% to −12%. In the mixed-traffic test, all the equipment tested tended to undercount with mean percent error ranging from −10% to −73%. Each counter type has pros and cons, but in general, counting accuracy decreased with increases in bicycle and motor vehicle traffic and longer tube lengths. Higher accuracy can be achieved by careful selection of equipment type, classification scheme, and tube configuration. Bicycle speeds given by off-the-shelf pneumatic counting equipment were accurate.

Over the past decade, there has been increased interest in counting bicycles and establishing nonmotorized counting programs, as exemplified by an entire chapter in the 2013 edition of the *Traffic Monitoring Guide* devoted to bicycle and pedestrian counting methods and technologies (*1*). However, jurisdictions still struggle with how to integrate bicycle counting into standard practice.

Would it be possible for jurisdictions to use the same pneumatic tubes that are used for short-duration motor vehicle counts to count bicycles? If so, how can this be accomplished? In this paper, the authors address these questions and share findings and recommendations for how to maximize accuracy while minimizing the number and types of counters needed for bicycle counting; the findings are from tests conducted in conjunction with the Oregon Department of Transportation (DOT).

Although others have also addressed these questions (*2, 3*), this study examines more types of pneumatic tube equipment than have previously been included in one study and compares equipment performance in a controlled environment and in mixed traffic to better identify problems in accuracy. This research studied three types of off-the-shelf pneumatic tube counters, including equipment from five manufacturers: two bicycle-specific counters, three varieties of motor vehicle classification counters, and one volume-only motor vehicle counter. This study also examined speed estimates using pneumatic tubes and how bicycle and automobile traffic volume affect accuracy.

BACKGROUND

Bicycle and pedestrian counting techniques are continuously evolving. To summarize the state of the practice, TRB's bicycle and pedestrian data subcommittee developed a research circular in 2014 (*4*).

Another recent research report, *NCHRP Report 797,* provides a broader overview of the steps necessary to establish counting programs, reviews technologies for counting nonmotorized travel, and provides case studies of jurisdictions' experiences with collecting bicycle and pedestrian count data (*5*). A number of technologies have been used to count bicycles for short- and long-term purposes.

The most widely used automated technologies for counting bicycles are inductive loops, pneumatic tubes, and infrared (in combination with inductive loops or pneumatic tubes to distinguish bicycles from pedestrians). Automated video imaging, piezoelectric strips, magnetometers, radio beams, and thermal imaging are also used. For short-duration bicycle counts, pneumatic tubes, infrared, and manual counts are commonly used. Automated counters are preferred because manual counts (collected in the field or by reducing video in the office) require more staff time per hour of data collected. Previous research has found that at least 1 week of counts is desirable to minimize error in estimating annual bicycle traffic volumes (*6–8*). Of the two common portable automated count technologies (infrared and pneumatic tubes), only tubes are able to identify and count bicycles without counting pedestrians or equestrians. Therefore, this paper will focus on pneumatic tubes.

Pneumatic tubes are commonly used to gather short-duration motor vehicle counts. Recently, there has been a push to adapt this technology to count bicycles in addition to motor vehicles. Pneumatic tube equipment consists of two main elements: pneumatic tubes laid across a roadway or path and a data recorder. As vehicles or bicycles pass over the tubes, pulses of air travel through the tubes to the data recorder, which detects them because of the change in pressure. These tubes are portable and a widely available technology. Three types of pneumatic tubes are available commercially:

- Bicycle-specific counters, which are dual tube configurations specifically designed for bicycle counts. They differentiate between

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motor vehicles and bicycles, but provide bicycle counts only and can be used in a shared lane with mixed traffic.

- Classification counters, which are dual tube configurations for motor vehicle classification counts. Some equipment in this category can classify both motor vehicles and bicycles in mixed traffic, when adjustments are made and bicycle-specific classification schemes are used.
- Volume counters, which are single tube configurations for motor vehicle traffic volume counts without any classification ability. These counters can be used to count bicycles in a dedicated bicycle lane or path, but they cannot distinguish between bicycles and vehicles in mixed traffic.

There is limited research on the performance of pneumatic tubes to count bicycles. Boulder County, Colorado, evaluated the performance of one type of classification counter and bicycle-specific pneumatic tube counters at various sites (*2*). The results revealed that bicycle-specific counters were more reliable and accurate than classification counters when counting bicycles; however accuracy was reduced as the distance from the counter increased (*2*). A Norwegian study also tested classification counters and bicycle-specific tube counters and found high accuracy for bicycle-specific counters (more than 95%), but only 70% to 75% accuracy for the classification counter (*9*). A study from New Zealand also examined a bicycle-specific tube counter and a classification counter with similar results: nearly 100% of bicycles were counted with the bicycle-specific tubes and 85% to 90% with the classification counter (*10*).

More recently, Brosnan et al. also conducted tests of two classification counters and bicycle-specific tube counters on two facilities in Minnesota (*3*). The results revealed lower error on the lower-volume facility. In addition, undercounting was a significant issue, primarily because of occlusion, where two vehicles simultaneously cross the tubes such that the air pulses cannot be differentiated. The researchers found that bicycle-specific counters had higher accuracy than general traffic counters and developed factors to adjust for the error.

Ryus et al. also tested bicycle-specific tube counters and found that they typically undercount, with some models outperforming others. Mean percent error (MPE) of 11% and 53% undercounts were obtained for the two products (*11*).

The purpose of this study is to provide guidance for agencies that seek to integrate bicycle counting with their existing short-duration motor vehicle counting programs by examining the performance of off-the-shelf pneumatic tube counters for counting bicycles. Using the same tubes to count bicycles and motor vehicles can help minimize the number of counters that an agency has to maintain in inventory.

EQUIPMENT

The research team tested three types of off-the-shelf pneumatic tube counters: volume, classification, and bicycle-specific counters (Table 1). For simplicity of reference, each piece of equipment tested is designated by a letter and number combination. The diameters of the tubes themselves varied, but were generally in two categories: road tubes and mini tubes. Exact dimensions are given in Table 1. Tube lengths also varied as shown in Figures 1 and 2.

Two bicycle-specific counters were studied, B1 and B2. Both are available commercially and provided by the same manufacturer. Like the classification counters, these counters use two tubes placed on the roadway; however, they provide only binned, not time-stamped, counts (15-min bins) and do not provide axle hit data. B1 provides bicycle counts only, whereas B2 provides bicycles and motor vehicles separately, but provides no classification for motor vehicles.

Three classification counters were tested, referred to as C1 through C3, as listed in Table 1. The vendors for each claimed that the equipment was able to classify and count bicycles and motor vehicles in mixed traffic. Installation consists of two tubes laid across the roadway. These classifiers record every axle that passes over the tube and use a classification scheme to classify the axle hits into vehicle types, including bicycles. C1 and C3 provide time stamps and speed for each vehicle classified, whereas C2 provides counts in 1-min bins. C2 and C3 allow the user to select classification schemes.

One volume-only counter was tested, referred to in this paper as V1. It does not distinguish between bicycles and motor vehicles. Installation consists of a single road tube laid across the roadway. Data for each counter were downloaded and processed with vendor-supplied software.

TABLE 1 Equipment Tested

Type and Designation	Make	Model	Tubes[a]	Comments
Bicycle-specific				
B1	Eco-Counter	Bicycle-only TUBES	0.3-in. ID 0.6-in. OD	Vendor-specific tubes
B2	Eco-Counter	Bicycle–motor vehicle TUBES	0.3-in. ID 0.6-in. OD	Vendor-specific tubes
Classification				
C1	JAMAR Technologies, Inc.	TRAX Cycles Plus	0.2-in. ID 0.4-in. OD	Also estimates speeds
C2	Time Mark Corporation	Gamma	0.3-in. ID 0.7-in. OD	Also estimates speeds
C3	MetroCount	MC5600	0.2-in. ID 0.4-in. OD	Natural rubber tubes
Volume				
V1	Diamond Traffic Products	TT-6	0.3-in. ID 0.7-in. OD	Single tube

[a]ID = inside diameter; OD = outside diameter.

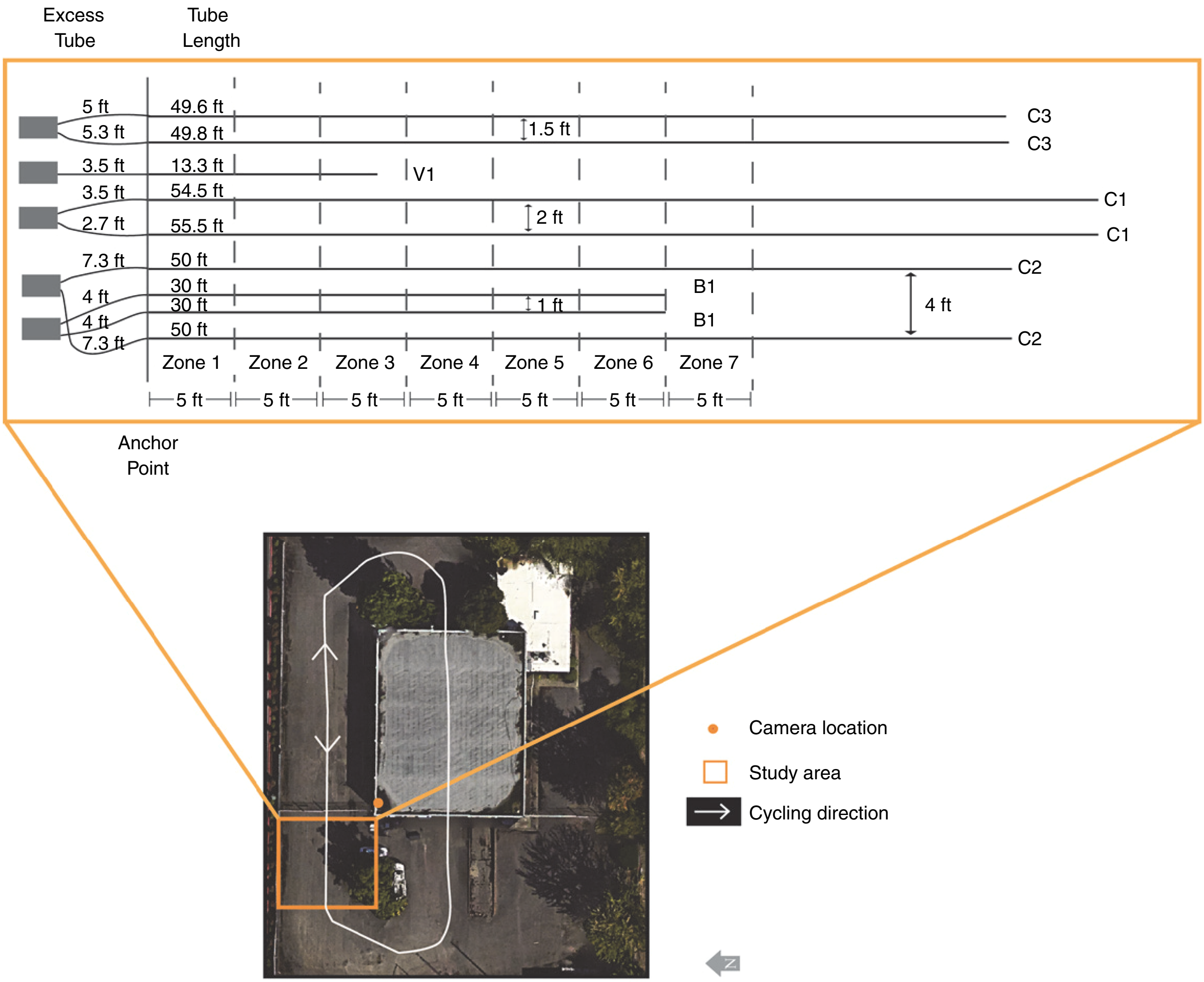

FIGURE 1 Layout of pneumatic tube counters for controlled environment test.

METHODS

The research team conducted two tests: a controlled environment test with only bicycle traffic and a mixed-traffic test on a state highway. Each will be discussed below, followed by a discussion of performance metrics.

Controlled Environment Test

The purpose of the controlled environment test was to (*a*) understand the limitations of the equipment in the situation most advantageous for accurate counts, (*b*) study the ability of each counter to correctly count bicycles in especially challenging cases, and (*c*) potentially eliminate some counting technologies from the mixed-traffic test on the basis of their performance. This test was also an opportunity for the Oregon DOT crew and Portland State University research team to gain further understanding of the equipment setup.

The test was conducted at Oregon DOT's Traffic Systems Services Unit parking lot in Salem, Oregon, on Monday, February 23, 2015, a sunny day with a high temperature around 60°F. Figure 1 shows the pneumatic tube setup, including tube length and distance between tubes. The excess tube length shown in Figure 1 is the length of tube between the anchor point (nail) and the counting device (box). For example, for the V1 tubes, the distance between the anchor point and the counting device is 3.5 ft. Device B2 was not tested in this first test because it was not available at the time of testing. Traffic video cameras mounted on poles recorded the test to count bicycles for ground truth, or information provided by direct observation.

Before the test, the research team met at the test site with vendors of various pieces of equipment to ensure that the equipment was set up and calibrated properly. The research team also recruited volunteers from Oregon DOT staff and other transportation professionals to ride over the pneumatic tube. Participants were asked to ride over the tubes first in one direction for half an hour and then in the opposite direction for half an hour. This was repeated twice for a total of 2 h of testing. Each half hour was broken into 5-min increments, one 5-min increment for Zones 1 through 6 (Figure 1). Zone 7 was tested separately for one 10-min period consisting of 5 min in each

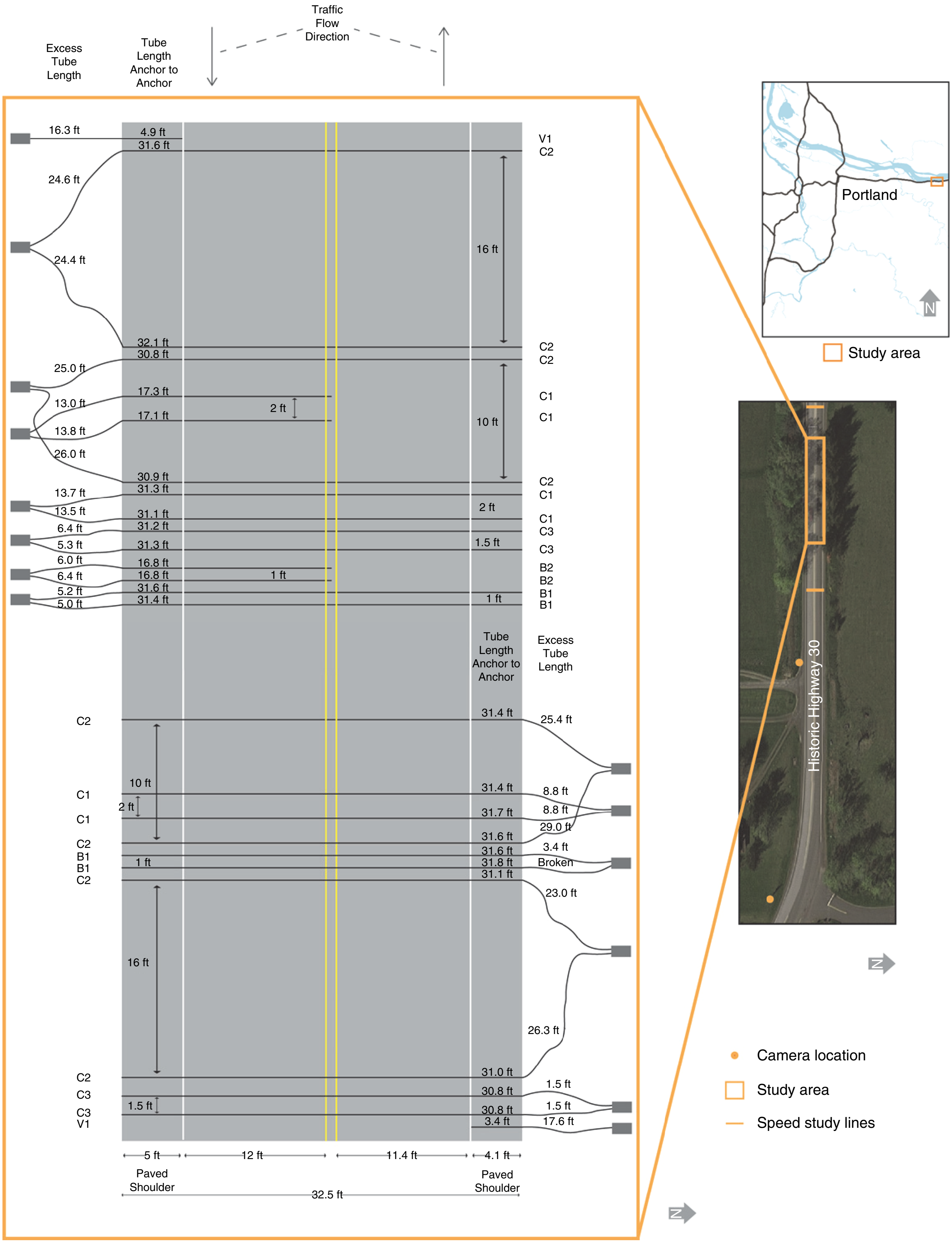

FIGURE 2 Layout of pneumatic tube counters for mixed-traffic test.

direction. The ability of the technologies to detect and count bicycles in both directions and at various distances from the counting device was tested.

Before the tests, the clocks for the counting equipment were synchronized to enable comparison with the recorded video. In addition to obtaining manual counts from video, the research team also counted bicyclists manually by time and zone during the test. The bicycles used during this phase of testing consisted of standard wheelbase, steel and aluminum frame, mountain, hybrid, and road bicycles ridden by eight adult volunteers.

After the test of standard bicycles, special cases were investigated: tandems, bicycles with trailers, carbon fiber bicycles, cargo bicycles, and bicyclists riding one behind the other and side by side. The purpose was to understand how well the technologies are able to count special cases of bicycles that are encountered less frequently on the roadway. For the special cases, bicyclists were asked to ride in Zone 1 at all times.

Mixed-Traffic Test

To evaluate the performance of the counting equipment in a real-world scenario, the pneumatic tube counters were tested on a state highway with relatively high bicycle volumes. To minimize tube displacement caused by turning, accelerating, or decelerating vehicles, the team sought a relatively flat and straight section of roadway in a rural setting. Other criteria for selecting a site included proximity to Portland to minimize travel time, moderate to high bicycle traffic volume, and a cross section representative of Oregon DOT highways. The highway section selected was a two-lane section with 4- to 5-ft shoulders on the Historic Columbia River Highway, a road used by tourist traffic and cyclists to access a scenic portion of the Columbia River Gorge east of Corbett, Oregon. The slight grade provided the opportunity to study one direction with higher bicycle speeds (15 to 30 mph) and the other with slower bicycles (5 to 15 mph). The roadway width of 32.5 ft allowed researchers to test how well one counter could count cyclists on both shoulders.

It was important to study actual traffic, not traffic generated by volunteer riders, because actual bicycle traffic may behave differently than recruited riders. To maximize the number of bicycles observed during the test, a 3-day holiday weekend with high bicycle volumes was selected: Memorial Day weekend, Friday, May 22, through Monday, May 25, 2015. The weekend contained hours of both high and low bicycle and motor vehicle traffic, partly cloudy skies, high temperatures between 60°F and 70°F and some rain. A total of 576 cyclists, 300 eastbound and 276 westbound, were observed during daylight hours (8:00 a.m. to 8:00 p.m.) from the manually counted video during the 4 days (46 h) studied. On Sunday, 2 h were lost because of camera downtime while data storage cards were switched. The video was collected by using two Oregon DOT traffic observation cameras: one mounted on a luminaire pole and the other on a signpost. Two cameras were installed for redundancy, but only the closer camera on the signpost functioned properly.

Because preliminary results for all the equipment tested were sufficiently accurate (less than 10% error for bicycles 10 to 15 ft of the counter), the same equipment that was used in the controlled environment test was tested in the mixed-traffic test, with the addition of B2, which was not available previously. As shown in Figure 2, tubes were laid out on both the north side and south side of the roadway. This layout was used to test the hypothesis that counts closer to the detector would be more accurate; the hypothesis was based on the results of previous studies and findings from the controlled environment test. Thus, an effort was made to repeat the tube setup on each side of the roadway. Oregon DOT transportation monitoring staff set up all of the tubes and the V1 and C2 data loggers. To test both standard setup for motor vehicle classification counts (16-ft spacing) and a spacing recommended by the manufacturer for bicyclists and motor vehicle classification (10-ft spacing), Oregon DOT set up two sets of C2 equipment on each side of the road with different tube spacings. The Portland State University research team set up the C1, C3, B1, and B2 data loggers.

The volume count tubes, V1, were set up only on the shoulder because they cannot differentiate between motorists and bicyclists. They were included to study whether bicyclists would avoid the tubes or motorists would drive over them. To test whether cyclists avoided the tubes, they were set up in front of the other tubes so that cyclists could avoid them, although they could not avoid the other tubes.

To ensure that the ground truth video counts were accurate, the three researchers who counted bicycles for the study all counted the same 1 h of video from the Sunday test from 10:00 a.m. to 11:00 a.m. Although counts between researchers were slightly different in the classification of motor vehicles, all three counted 32 bicycles during the hour (100% reliability).

Performance Metrics

The following metrics were used to compare accuracy: overall error, MPE, and mean absolute percent error. These metrics are equivalent to the average percent deviation and average absolute percent deviation metrics used in *NCHRP Report 797.* To compute these metrics, the counts from the automated equipment were compared with ground truth counts. The ground truth for the controlled environment and special cases tests was the count collected by manual counters in the field, which was later verified by video counts. The ground truth for the mixed-traffic test was manually counted video.

Overall error is computed for the entire study period: 2 h for the controlled environment standard bicycle test, 20 min for each category in the special cases test, and 46 h for the mixed-traffic test. Overall error was calculated as the difference between the ground truth and counting equipment count divided by the total ground truth count for the study period, as explained in Equation 1.

$$\text{overall error} = \frac{c - m}{m} \quad (1)$$

where m is the ground truth count for the study period and c is the tube count for the study period.

Although overall error gives a view of the big picture, it does not reveal the likelihood of a false negative (a cyclist is present but not counted) or a false positive (a cyclist is counted when not present). If each counter provided time stamps for every event, these false positives and false negatives could be counted. Because some of the equipment measured data in of 1-min (C2) and 15-min (B1 and B2) bins, it was not possible to compute the true number of false positives and negatives across all equipment types. However, by binning the data, it is possible to compute the error per bin or count interval and observe overcounts and undercounts per count interval. The count intervals varied by equipment for the controlled environment and special cases test, ranging from 5 min to 15 min. The count interval for the mixed-traffic test was 1 h for all equipment types. In inter-

TABLE 2 Error for Controlled Environment Test by Zone—or Distance from Counter—for Standard Bicycles Only

Type	Overall Error by Zone (%) 1 (n = 69)	2 (n = 85)	3 (n = 92)	4 (n = 95)	5 (n = 93)	6 (n = 90)	7 (n = 73)	MPE (%)	MAPE (%)
B1[a]	0.0	0.0	0.0	–1.06	–1.06	–1.06	na	–0.6	1.7
C1	1.5	0.0	0.0	–10.5	–38.0	–49.5	–26.0	–15.7	16.7
C2	–7.3	0.0	–5.3	–6.3	–25.0	–53.9	–82.2	–16.2	16.6
C3	–7.3	–1.2	–18.1	–26.3	–63.0	–64.8	–98.6	–30.8	30.8
V1	–11.6	6.0	3.2	na	na	na	na	–7.6	9.9

NOTE: na = not applicable. Tubes were not long enough to reach these zones.
[a]B1 tube counters provided data in 15-min bins, so error is reported for Groups 1 to 3 and 4 to 6.

vals with no bicycles and no counts, the interval error was assigned a zero value.

$$e_i = \frac{c_i - m_i}{m_i} \tag{2}$$

where

e_i = interval error = error for the count interval i,
m_i = ground truth count for count interval i, and
c_i = tube count for count interval i.

MPE was calculated by averaging the errors for each count interval for the entire study period.

$$\text{MPE} = \frac{1}{h}\sum_{i=1}^{h} e_i \tag{3}$$

where h is the total number of count intervals counted in the study period.

Similarly, the mean absolute percent error was calculated by averaging the absolute value of the errors for each count interval for the entire study period.

$$\text{MAPE} = \frac{1}{h}\sum_{i=1}^{h} |e_i| \tag{4}$$

where MAPE is the mean absolute percent error.

FINDINGS

Controlled Environment Test

Table 2 shows the errors across zones for all tube counters that were tested, with undercounting observed for all equipment. In Zones 1 through 3, most of the tube counters were fairly accurate. As the distance from the counter increased, all three classification counters showed higher errors. Of all the counters tested, for standard bicycles, B1 was the most accurate, with MPE of –0.6%, indicating a slight undercount. The number of cyclists for each zone (n) was the same for all the equipment types, but varied by zone and averaged 85 cyclists per zone.

Because of sharp turns adjacent to the tube layout, cyclist speeds for this test were relatively slow, averaging 8 mph, as reported by C1. Speeds were especially slow for Zones 4 through 7, which averaged only 7 mph.

The results indicate that all of the pieces equipment studied are viable technologies for counting bicycles within 10 ft. of the tube counter, approximately up to the width of one general traffic lane. In addition, one particular counter is a viable technology to count in the range of 0 to 30 ft., approximately up to two general traffic lanes. These results agree with findings from a previous study, in which researchers reported drop in accuracy beyond 27 ft. for both bicycle-specific and general purpose tube counters (*2*).

Table 3 shows the accuracy of the pneumatic tube counters during the special cases test. In the category of tandems and bicycles with trailers, both V1 and C2 counters showed the lowest error, with V1

TABLE 3 Error of Pneumatic Tube Counters with Special Cases

					Standard Bicycles			
	Tandem, Bike with Trailer		Carbon Fiber, Cargo Bicycle		One Behind the Other		Side by Side	
Tube Counter	n	Overall Error (%)	n	Overall Error (%)	n	Overall Error (%)	n	Overall Error (%)
B1	24	–75	24	–4	68	–74	70	–59
C1	46	–50	54	–50	116	–2	118	–46
C2	46	–4	54	–6	116	–65	118	–38
C3	46	–96	54	–56	116	–95	118	–57
V1	46	4	54	–9	116	–4	118	–36

overcounting by 4% and C2 undercounting by 4%. In the category of carbon fiber and cargo bicycles, B1 was most accurate, with undercounting errors of 4%. Both C1 and B1 were fairly accurate when counting bicycles riding one behind the other. All the tube counters showed high errors when counting bicycles traveling side by side, indicating the limitation of the technology.

Mixed-Traffic Test

Error attributed to each counter varied substantially during the mixed-traffic test, as shown in Table 4. Undercounting was encountered with all counters, and error for all counting equipment was high (≥10% undercount MPE). The bicycle-specific counters had a relatively low error rate (20% to 23% undercount MPE). The classification counters varied widely, with the error of the least accurate equipment (C2 with 44% to 73% undercount MPE) twice as high as the most accurate counters, C1 and C3 with the Boulder County (BOCO) classification scheme (10% to 28% undercount MPE). The volume-only counter performed unexpectedly well, with only 20% undercount MPE.

For C1, the manufacturer now provides bicycle-specific software, which can improve accuracy but was not available at the time of this test. For C3, Boulder County's improved classification scheme, BOCO (*2*) (not supplied with the manufacturer's software) greatly improves the accuracy of the C3 compared with the manufacturer supplied scheme, ARXCycle.

Another metric of interest is the number of overcounts in a given hour bin. These overcounts for each technology are shown in the last column of Table 4. These overcounts are especially obvious for hours in which no cyclists were observed in the video. Such overcounts are especially concerning if they are caused by misclassified motor vehicles; such misclassification could cause the counters to report biased data with incorrect traffic patterns for bicycles. Such errors can be especially problematic for roads with low bicycle counts, a condition prevalent on state highways in the United States. Whereas B1 and C3 show relatively few overcounts, C1, C2, and V1 show more.

The research team also compared bicycle speeds recorded by various counters with measured speeds obtained by observing when each bicyclist passed a set of points during the mixed-traffic test. The two points are shown in Figure 2. This comparison of average speeds for the study period shows that on average for each hour, the speed estimates for C1 and C3 agreed with each other and with the manually computed speed. The bicycle speed for both directions combined averaged 17 to 19 mph, with an average of 12 to 13 mph in the eastbound (uphill) direction and an average of 20 to 22 mph in the westbound (downhill) direction.

As found in the controlled environment study, error was found to be significantly higher for bicyclists farther from the equipment. The error for cyclists on the opposite side of the road from the equipment was on average about one and a half times higher than the error for cyclists riding on the side nearest the equipment.

The excess tube length between the anchor and the data logger (Figure 2) increased the effective distance between the bicyclists and the equipment. The C2 tubes had the longest excess tube length (25 ft or more) and the highest error. Although it may have been beneficial to test the counters with shorter and similar tube lengths, the tubes for C2 and V1 were on loan from Oregon DOT, which uses them as part of its vehicle count program, and the length could not be altered.

A related question is whether shorter tubes that only covered one vehicle lane and the shoulder (half road) would yield more accurate results than longer tubes that covered the entire road. However, the error for the two half-road cases (B2 and C1 half road) is not substantially lower than that for comparable equipment (B1 and C1).

Error also varied by direction, as shown in Figure 3, which shows generally higher error for equipment on the eastbound direction than that for equipment in the westbound direction. Perhaps this result reflects higher error for lower-speed bicycles because bicycle speeds were higher in the westbound (downhill) direction. However, analysis

TABLE 4 Summary of Error for Mixed-Traffic Tube Test

Counter Name	*n*	Bicycles Counted	Overall Error (%)	MPE (%)	MAPE (%)	Total Hourly Overcounts
B1, north side (total)	576	361	−37	−23	26	2
B1, south side (total)	576	378	−34	−20	23	3
B2, south side (half road)	300	183	−39	−20	26	2
C1, north side (total)	576	409	−29	−18	22	9
C1, south side (total)	576	400	−31	−13	31	15
C1, south side (half road)	300	185	−38	−23	24	1
C2, north side, 10 ft (total)	576	170	−70	−50	55	3
C2, north side, 16 ft (total)	576	200	−65	−44	50	12
C2, south side, 10 ft (total)	576	142	−75	−60	60	1
C2, south side, 16 ft (total)	576	79	−86	−73	73	3
C3, north side (total), ARXCycle	576	236	−59	−43	43	0
C3, south side (total), ARXCycle	576	288	−50	−32	32	0
C3, north side (total), BOCO	576	380	−34	−28	29	1
C3, south side (total), BOCO	576	495	−14	−10	10	1
V1, north and south sides (total)	576	425	−26	−20	27	20

NOTE: ARXCycle and BOCO are classification schemes.

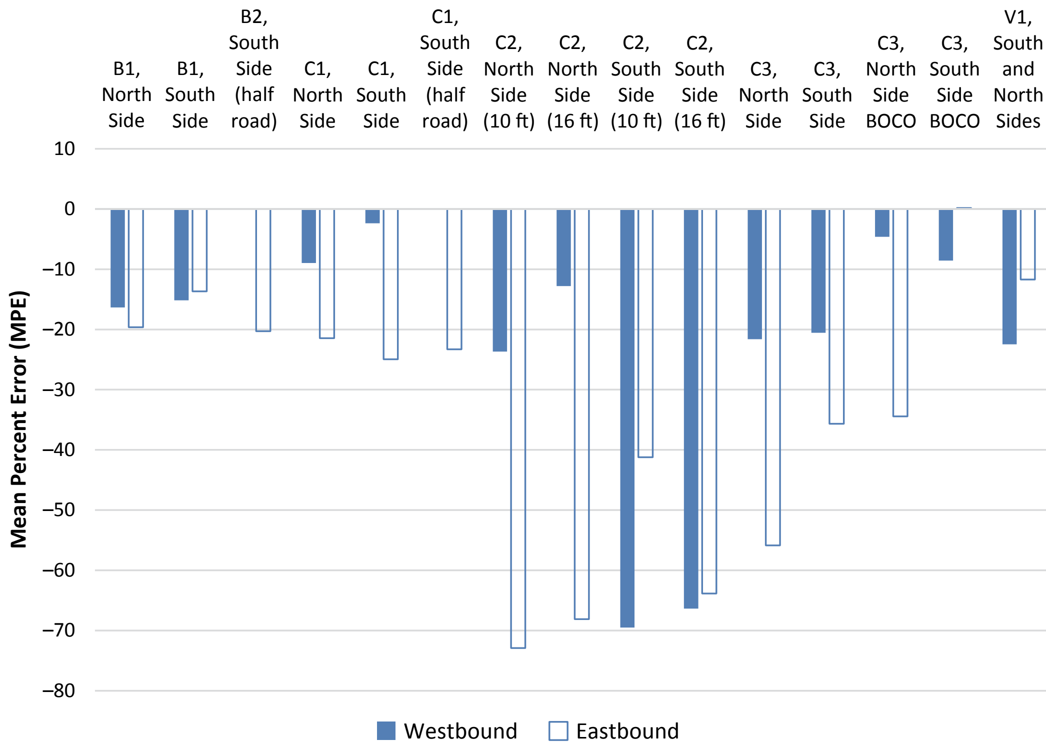

FIGURE 3 Error for pneumatic tube counters in mixed-traffic test.

of error with speed did not show a clear relationship between bicyclist speed and equipment accuracy.

The spacing between tubes may also play a role in accuracy. The classification counters with the highest error (C2) also had the widest separation between tubes, but there does not appear to be a big difference between the 10-ft and 16-ft spacings for C2.

Does tube diameter affect error? This study did not identify a clear link between error and tube diameter. The large-diameter tubes used with the C2 equipment did yield high errors, but the same tubes were used with the V1 equipment and did not result in high error.

What is causing the error? Figure 4 shows error per count interval with bicycle and motor vehicle traffic volumes. From this figure, error appears to increase with increasing bicycle traffic volumes and to a lesser extent with increasing motor vehicle volumes. These results are intuitive because passing vehicles cause occlusion, obscuring the pulse of air from the bicycle that should be counted. Bicycles traveling in groups are similarly difficult to count as shown in the earlier results from the controlled environment special cases tests (bicyclists riding side by side and one behind the other). Some of the pieces of equipment tested were better than others at separating these cases.

Another cause of error is the classification scheme used for the classification counters. For example, when the BOCO scheme was used on the same data for C3, it increased the accuracy of the bicycle counts.

CONCLUSIONS AND RECOMMENDATIONS

Using the same pneumatic tubes for counting motor vehicles and bicycles is desirable but challenging. Weaker air pulses from bicycles can be harder to detect, and occlusion can prevent bicycles from being counted. Some bicycles have longer-than-normal wheelbases or additional wheels, and cyclists like to ride side by side or in platoons. Despite these obstacles, jurisdictions would like to be able to count bicycles using the equipment they already have in their inventory: an array of motor vehicle counting equipment.

This study reviewed three types of pneumatic tube counting equipment: bicycle-specific, classification, and volume-only counters. The first two are able to distinguish between bicycles and motor vehicles. The second two are commonly available to those who monitor motor vehicle traffic. Bicycle-specific counters have been found to be accurate in mixed traffic, but do not provide speed or classify motor vehicles. Classification counters offer the opportunity to count bicycles, classify motor vehicles, and provide speed data, but accuracies vary widely. Volume counters should be used only in places where motor vehicles are rare, such as paths or some road shoulders.

Findings from the controlled environment test with no mixed traffic revealed that all of the equipment tested was capable of counting standard bicycles with an error rate of less than 10% within 10 to 15 ft of the count equipment when no other vehicles are present and only one bicyclist rides over the tubes. The results from the test of special cases showed that bicycles traveling side by side, bicycles traveling one behind the other, bicycles with trailers, and bicycles with long wheelbases are particularly difficult to count using pneumatic tubes.

Findings from the mixed-traffic test are listed below.

- The error rate for all of the equipment tested was high. All equipment in the two-lane highway test undercounted bicyclists, with MPE ranging from −10% (C3) to −73% (C2).
- Generally, higher bicycle and motor vehicle traffic lead to higher undercounts, likely due to occlusion, especially for classification counters.

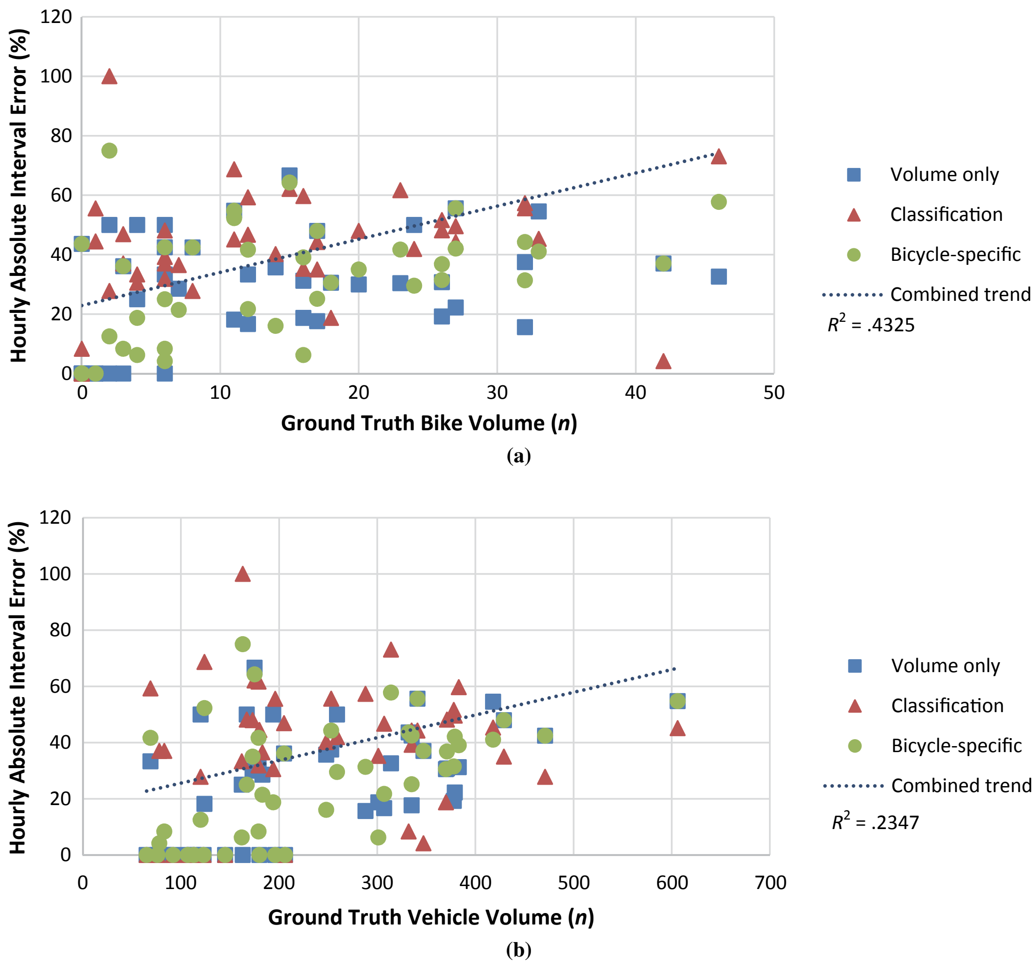

FIGURE 4 Hourly absolute interval error with traffic volume in mixed traffic.

- Greater error was observed farther from the counting equipment.
- Accuracy can be improved through bicycle-specific changes to classification schemes.
- Bicyclist speed estimates from two classification counters, C1 and C3, are consistent with each other and with observed speeds from video.
- A clear relationship between error and bicyclist speed was not observed.
- Some counters (C1, C2, and V1) were more likely to count false positives, which can lead to an incorrect understanding of bicycle travel patterns.

False positives, counting motor vehicles as bicycles, should be carefully watched in future studies. Low bicycle traffic on highways means that even low numbers of vehicles incorrectly identified as bicycles could lead to substantial error and mislead those studying bicycle travel patterns.

When standard motor vehicle counting equipment is used to count bicycles, error can be high, but not for all devices. Bicycle-specific counters and some classification counters have lower error. Unexpectedly, in this test, simply using single-tube volume counters on the shoulder had similar error to the bicycle-specific and the two best classification counters. However, this approach should be used only where bicycles travel predictably on the shoulder and motor vehicles avoid the shoulder, and where bicycle volumes are similar to or greater than those observed in this study.

This research contributes to the academic literature on bicycle counting with pneumatic tubes in three ways: it (*a*) verifies that bicycle speeds given by off-the shelf pneumatic counting equipment are accurate; (*b*) shows that in the tested situation, volume-only tubes placed on the shoulder were as accurate as classification counters placed over the entire road; and (*c*) reports error in bicycle counting for three types of off-the-shelf pneumatic tube counters and from five manufacturers—more than any previous study.

Regardless of what equipment is used, verification testing should be conducted and care should be taken when setting up the equipment and processing the data. Bicycle counting using pneumatic tubes is a more challenging task than counting motor vehicles and should be approached with attention to detail.

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