How Representative of Bicycling Populations Are Smartphone Application Surveys of Travel Behavior?

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Bicycle transportation increasingly has become a central focus of urban regions invested in the improvement of livability, sustainability, and public health outcomes. Recently, transportation agencies across North America have deployed travel surveys with a smartphone application to gain a better understanding of bicycling travel behavior to forecast travel, to invest in infrastructure, and for a variety of other purposes. A potential limitation of data sets crowdsourced with smartphones is sampling bias (i.e., the demographic characteristics of the smartphone application users may not match the characteristics of the cycling population). Such a bias can be caused by the passive nature of sample recruitment, by differences in access to smartphone ownership or in familiarity with the technology, or both. This study examined the characteristics of several user samples from bicycle smartphone application deployments in North America. Differences between these samples were highlighted, and the smartphone samples were compared with cycling samples from travel survey data sets. Whenever possible, a statistical test was used to calculate the statistical significance of the differences between smartphone samples and traditional travel survey samples. Compared with travel surveys, smartphone applications tended to undersample females, older adults, and lower-income populations and to oversample some minority ethnicity populations. The analysis also revealed that, for cities in which travel survey sample sizes were small, smartphone applications could provide higher-resolution data and larger sample sizes of bicyclists. For transportation agencies, all of these findings are useful to plan future travel survey and sample recruitment efforts.

Bicycle transportation increasingly has become a central focus of urban regions committed to the improvement of livability, sustainability, and public health outcomes. Improvement of the built environment for cycling has proved to be a successful strategy to increase the prevalence of cycling as a mode of transport (*1, 2*). However, improvement of the cycling environment often requires infrastructure investment, and the commitment of resources and road space to cycling infrastructure has been contentious in an era of increasingly constrained transportation budgets and growing automobile congestion in urban areas. Given these constraints and others, transportation agencies desire to maximize the benefit of potential investments in bicycle infrastructure. Transportation planners are also interested in identifying those locations that are problematic for cyclists from a safety and comfort perspective. Improvement at such locations not only could enhance the experience of existing bicyclists but could also yield positive effects on cycling mode shares. Evaluations of infrastructure investment alternatives and safety issues consequently have led to an increased interest in bicycle travel data collection, so that transportation planners may better examine the travel patterns and preferences of existing cyclists. Through their understanding of existing cyclists' behaviors and preferences, transportation planners may be able to account better for such factors in the improvement of the built environment for cycling.

One method of collecting bicycle travel behavior, preference, and safety data that has gained prevalence in recent years is the use of smartphone applications to crowdsource information about opt-in participants. This paper outlines the brief history of these applications applied to the collection of data from bicyclists in North America. A significant concern of interested researchers and transportation planners is the bias inherent to data collected about cyclists through these smartphone applications; samples from smartphone applications are suspected not to be representative of their target populations. This paper explores the differences between published smartphone survey samples with these applications and comparable samples sourced from traditional travel surveys, which are purported to be more representative of regional populations. To study the extent to which smartphone survey samples are representative of regional cycling populations can help to highlight improvements that researchers who use these smartphone applications can make to their survey designs and sampling methodologies.

BACKGROUND

Travel Surveys

Household travel surveys collect information on transportation, sociodemographic, and other characteristics about a sample of travelers within a geographic region. The information that travel surveys collect is used for a variety of applications, including transportation policy development and travel modeling. Sociodemographic information is collected for at least two reasons: (*a*) these variables have proved to be significant covariates of travel behavior, and (*b*) the collection of this information allows users of the data to gauge sample bias and control for segments of the population that may be over- or undersampled (*3*). Travel surveys that are more representative of a target population are more likely to represent

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Transportation Research Record: Journal of the Transportation Research Board, No. 2587, Transportation Research Board, Washington, D.C., 2016, pp. 78–89.
DOI: 10.3141/2587-10

the preferences of that target population accurately. If undersampling does occur, the preferences of some groups may be underrepresented in travel survey outcomes, such as in the travel demand modeling process. Weighting can be used to account for the effects of undersampling. Overall variation in preferences within a subgroup of the sample may still not be accounted for, however.

Travel surveys have been conducted for more than 40 years (*4*), but recent advancements in survey methods were of particular interest here (*4*). In the past two decades, the use of GPS devices to supplement question-based travel surveys has gained prevalence (*5*). GPS devices allow researchers to collect revealed preference information about participants' travel behavior in addition to the stated preference information provided by question-based surveys.

Travel survey administrators also have begun to experiment with travel surveys administered through web or mobile device platforms. The use of these platforms has at least three primary benefits:

1. The unit cost per travel survey administered can be lowered (to allow for increases in sample size or decreases in total administration cost).
2. Additional segments of the population not captured by traditional travel surveys can be reached (and potentially result in broader or more representative samples).
3. Additional information not measurable through traditional travel surveys can be collected.

However, one shortcoming of travel survey methods with a web or mobile device basis often is cited: when such methods are used in isolation, significant portions of the population may be undersampled because of the cost of access to these technologies (in financial and technical aptitude terms) and because of differences in the desire to participate. The study reported in this paper investigated how representative smartphone applications are in the collection of travel information about bicyclists.

Smartphone Ownership

Smartphones devices were first marketed to consumers in 2007 and 2008 by a number of large hardware and software companies (e.g., Apple, Microsoft, Google) and have since changed the mobile device market irreversibly (*6*). In 2015, an estimated 64% of U.S. adults owned a smartphone device (*7*), and market penetration is expected to continue to grow (*8*). As overall smartphone ownership has grown, the differences between demographic categories (e.g., gender, age, income) have decreased. However, several of the differences between demographic groups in terms of smartphone ownership are still significant, and present possible issues for agencies that plan to use smartphones as methods of travel survey administration. Table 1 presents the results of a 2015 Pew Research Center study of smartphone ownership (*7*).

TABLE 1 Smartphone Ownership by Demographic Characteristics (*7*)

Demographic Characteristic	U.S. Adults in Each Group Who Own a Smartphone (%)
All adults	64
Gender	
Male	66
Female	63
Age (years)	
18–29	85
30–49	79
50–64	54
65 and older	27
Ethnicity	
White, non-Hispanic	61
African-American, non-Hispanic	70
Hispanic	71
Education	
High school graduate or less	52
Some college	69
College+	78
Income ($/year)	
Less than 30,000	50
30,000 to 49,999	71
50,000 to 74,999	72
75,000 and more	84
Residential context	
Urban	68
Suburban	66
Rural	52

History of Smartphone Applications to Bicycle Planning, North America

In 2009, the San Francisco County Transportation Authority (SFCTA) in California developed and released a smartphone application called CycleTracks (for the Android and iOS smartphone platforms) to collect GPS and survey data about cyclists in the San Francisco area. CycleTracks uses a smartphone device's built-in GPS to track users' time and space trajectories, while it records a bicycle trip. CycleTracks also can provide some (optional) user demographic information (e.g., age, gender). The demographic information is collected to study self-selection and overrepresentation of some user groups. More information about the application functionality can be found on CycleTracks' website (*9*) and in Charlton et al. (*10*).

The initial survey sample collected more than 7,000 trips from 1,083 users between November 2009 and April 2010. SFCTA then developed a bicycle route choice model from this sample and incorporated that model into its SF-CHAMP regional travel demand model (*9*). The CycleTracks source code is open-source and available free to the public (https://github.com/sfcta). All subsequent smartphone applications reviewed here were built on the original CycleTracks source code. Many other cities, regions, and states besides those reviewed here are experimenting with or using CycleTracks or apps built from the CycleTracks source code; these applications are listed in Table 2.

After the initial success of CycleTracks in San Francisco, researchers at the Texas A&M Transportation Institute worked with SFCTA to deploy CycleTracks as part of a pilot research project in Austin, Texas. Between May and October 2011, the Texas A&M Transportation Institute collected more than 3,600 trips from more than 300 users. The goal of the project was to test whether the use of this data collection method was feasible in another region and would provide useful information for decision making in planning bicycle networks and infrastructure. At the conclusion of the study, the researchers remarked that "the amount of information provided by the use of CycleTracks far exceeds what would be available using other data collection methods" (*11*).

TABLE 2 CycleTracks and Derivative Applications

Month and Year First Released	City or Region	Rebranded or Improved App?	Application Name	Project Link
Nov. 2009	San Francisco	NA	CycleTracks	http://www.sfcta.org/modeling-and-travel-forecasting/cycletracks-iphone-and-android
2011	Lane County, Oregon	Yes	Cycle Lane	http://www.thempo.org/611/CYCLELANE---Bike-routes
April 2011	College Station, Texas	Yes	AggieTracks	NA
May 2011	Austin, Texas	No	CycleTracks	http://ntl.bts.gov/lib/45000/45700/45731/Hudson_11-35-69.pdf
June 2012	Minneapolis–Saint Paul, Minnesota	No	CycleTracks	http://www.minneapolismn.gov/www/groups/public/@publicworks/documents/images/wcms1p-094499.pdf
Oct. 2012	Atlanta, Georgia	Yes	Cycle Atlanta	http://cycleatlanta.org/
Summer 2012	Fort Collins, Colorado	No	CycleTracks	http://today-archive.colostate.edu/story.aspx?id=7744
July 2013	Montreal, Quebec, Canada	Yes	Mon RésoVélo	http://ville.Montréal.qc.ca/portal/page?_pageid=8957,112451619&_dad=portal&_schema=PORTAL
Jan. 2014	Reno, Nevada	Yes	RenoTracks	http://renotracks.nevadabike.org/
May 2014	Lexington, Kentucky	No	CycleTracks	http://www.kentucky.com/2014/05/04/3227486/lexington-bicyclists-help-sought.html
June 2014	Philadelphia, Pennsylvania	Yes	CyclePhilly	http://www.cyclephilly.org/
Nov. 2014	Toronto, Ontario, Canada	No	Toronto Cycling App	http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=5c555cb1e7506410VgnVCM10000071d60f89RCRD&vgnextchannel=6f65970aa08c1410VgnVCM10000071d60f89RCRD&appInstanceName=default
Nov. 2014	State of Oregon	Yes	ORcycle	http://www.pdx.edu/transportation-lab/orcycle
April 2015	Sacramento, California	Yes	CycleSac	http://cyclesac.org
NA	Monterey, California	No	CycleTracks	http://www.cycletracksmonterey.org/home.html
NA	Raleigh, North Carolina	No	CycleTracks	http://www.creativisibility.com/westernblvd/CycleTracks.html
NA	Seattle, Washington	No	CycleTracks	http://www.psrc.org/transportation/bikeped/cycletrack/
NA	Salt Lake City, Utah	No	CycleTracks	NA
NA	Los Angeles, California	No	CycleTracks	NA
NA	Charlottesville, Virginia	Yes	C-Vill Bike mAPP	http://www.tjpdc.org/cvillebikemapp/
NA	Hampton Roads, Virginia	Yes	NA	NA

Note: NA = not available.

In 2012, researchers at the Georgia Institute of Technology worked with the City of Atlanta, Georgia, and the Atlanta Regional Commission to modify CycleTracks for deployment in the Atlanta region. CycleTracks was rebranded as Cycle Atlanta, and several features were added to the application. In addition to recording trips, users could now record "notes," which indicated geolocated bicycle deterrents (e.g., pavement issues, traffic signal problems) and bicycle amenities (e.g., bicycle racks, water fountains.). Other user typology questions were added (e.g., with respect to ethnicity, household income, and rider type).

In 2013, researchers at McGill University in Montreal, Quebec, Canada, worked with the city to develop Mon RésoVélo, which was built from the CycleTracks and Cycle Atlanta open-source code bases. This application was again rebranded, and the user interface was modified. User questions were added, and the application came loaded with a complete French-language user-interface option to reach the francophone population of Montreal. Jackson et al. summarized the preliminary sample results from 2,300 trips and 500 users (*12*). Strauss et al. have since expanded on this work to combine GPS routes from Mon RésoVélo, with point bicycle counts and geocoded crash data to develop an injury risk model (*13*).

In 2014, researchers in the Transportation, Technology, and People Laboratory at Portland State University in Portland, Oregon, began to work with the Oregon Department of Transportation in Salem to develop a smartphone application for a pilot deployment across the state of Oregon. The Oregon Department of Transportation's primary research objective for the application was to test the feasibility and usefulness of collecting bicyclist revealed and stated preference data with smartphones. The results are available in Figliozzi and Blanc (*14*). The application was built in part from the open-source code bases for the applications referenced in Table 2 and was customized to meet the Oregon Department of Transportation's unique needs. The result was ORcycle, released in November 2014, which rebranded and improved the open-source codebase with additional features targeted to collect more information about users, trips, infrastructure issues, and crashes. More information about the ORcycle project and its goals, as well as ORcycle and its features, can be found at http://www.pdx.edu/transportation-lab/orcycle.

DATA DESCRIPTION

With data from the smartphone application samples and comparable travel surveys, the study presented in this paper compared collected smartphone samples with comparable samples of cyclists from

TABLE 3 Smartphone Application Samples

City or Region	Smartphone App Name	Study Period	Data Source
San Francisco	CycleTracks	2009–2010	Charlton et al. (*10*)
Austin	CycleTracks	2011	Hudson et al. (*11*)
Atlanta	Cycle Atlanta	2012	Misra et al. (*15*)
Montreal metro area	Mon RésoVélo	2013	Jackson et al. (*12*)
Lane County	Cycle Lane	2011–2014	Roll (*16*)
Oregon (state)	ORcycle	2014–2015	Data available to authors
Portland metro area	ORcycle	2014–2015	Data available to authors

traditional travel surveys. The assumption was that (primarily as the result of more rigorous sampling methodologies) traditional travel surveys were a more accurate assessment of the characteristics of the regional population in question. Users of the smartphone application would be a self-selected and biased subsample of the regional population. Many data sources were used to tabulate these comparisons, which are presented in this paper's section on results. Brief descriptions of each primary data source follow.

Past Smartphone Application Studies

Aggregated statistics from many of the smartphone app samples were available in white papers or on web pages. Data from the initial sample (November 2014 to May 2015) of the ORcycle smartphone application deployment were available for in-depth analysis. These data were used to draw comparisons for the Portland metropolitan area and the state of Oregon in general. All of these data sources are cited in Table 3 (*10–12, 15, 16*).

Travel Surveys

Where available, recent travel surveys were used to present descriptive statistics of cycling and noncycling populations in comparison with those collected by the smartphone applications. All of these data sources are cited in Table 4 (*17–21*).

RESULTS

Overall Region Description

Before the smartphone versus traditional travel survey comparisons of bicyclists is delved into, it is pertinent to illustrate the overall composition of travelers (including nonbike commuters) in each region as reported from the traditional travel surveys. These distributions should be representative of each region's population, which is one of the main objectives of traditional travel surveys. The demographic distributions differ by region, so to illustrate the overall composition in each region (Table 5) gives the reader some context. The demographic characteristics not analyzed in the following section were not considered in the overall regional description plots provided in Table 5.

In Table 5, several notable differences between the regions can be observed. Age distributions vary widely in the Oregon samples (Lane County, Portland metropolitan area, and Oregon statewide). The ethnicity distributions in the state of Oregon and in Portland mostly are concentrated around white Americans, while Atlanta is more diverse: 20% of the travelers sampled identified themselves as African-American. In all areas examined besides Atlanta, females comprised a slight majority of the gender distribution. The household income distribution in Atlanta looks bimodal, with concentrations in higher- and lower-income strata, while the income distributions in metropolitan Portland and Oregon statewide appear closer to being normally distributed (Table 5).

Travel Survey Comparison

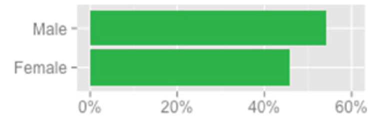
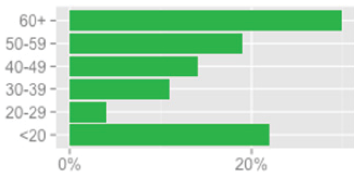
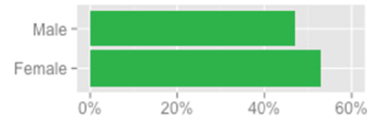
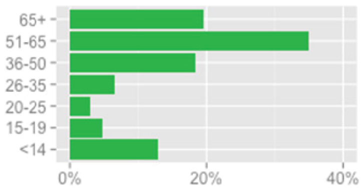
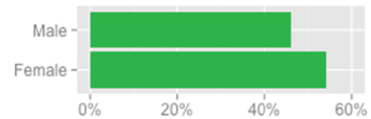
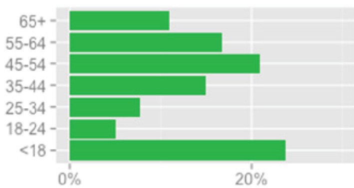
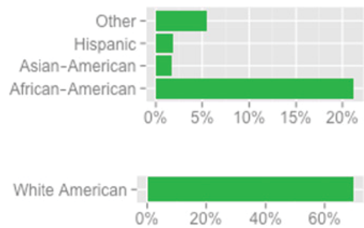
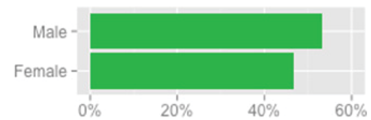
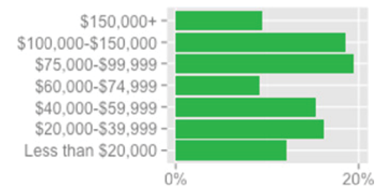
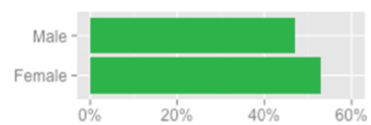
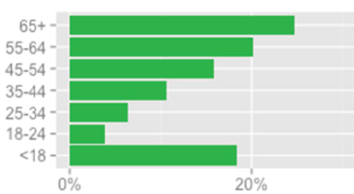
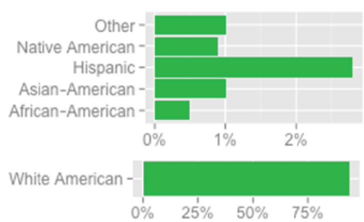
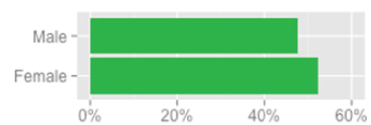
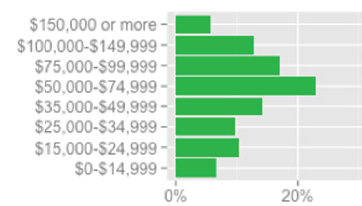
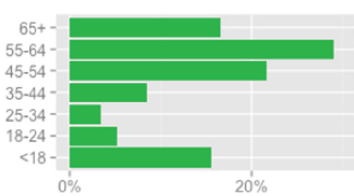
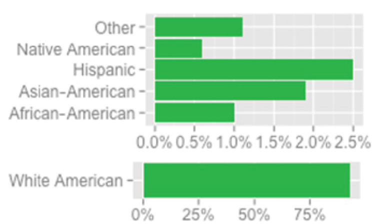
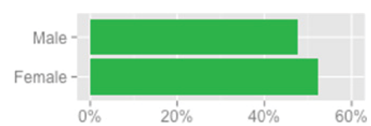
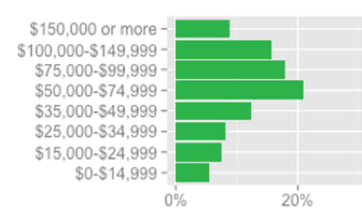
In each city or region studied, demographic group proportions were compared between user samples collected by each area's smartphone application and the sample of bicycle commuters captured by the area's traditional travel survey. Bicycle commuters were extracted from each travel survey data set with use of the response to the question in each survey that indicated a person's main transportation mode to commute. This was the best indication available in the surveys of a respondent's use of a bicycle for transportation. In a comparison of the smartphone application sample with the bicycle commuter sample, differences can be observed in the proportions of cyclists described by the two survey types. A statistical test (either chi-square or z-test of proportions) was used (if possible) in each case to determine the statistical significance of the differences between the two samples.

TABLE 4 Travel Survey Listing

City or Region	Travel Survey Name	Survey Period	Data Source
San Francisco	California Household Travel Survey	2010–2013	California Department of Transportation (*17*)
Austin	National Household Travel Survey	2009	Austin Area Transportation Databook (*18*)
Atlanta	Atlanta Regional Commission Regional Travel Survey	2011	Atlanta Regional Commission (*19*)
Montreal metro area	2008 Origin–Destination Survey	2008	van Lierop et al. (*20*)
Lane County	OHAS	2009–2011	Oregon Department of Transportation (*21*)
Oregon (state)	OHAS	2009–2011	Oregon Department of Transportation (*21*)
Portland metro area	OHAS	2009–2011	Oregon Department of Transportation (*21*)

NOTE: OHAS = Oregon Household Activity Survey.

TABLE 5 Demographic Results for All Travelers in Travel Surveys

Region	Age (years)	Ethnicity	Gender	Household Income
San Francisco (2009)	Not analyzed	Not analyzed		Not analyzed
Austin (2011)		Not analyzed		Not analyzed
Lane County (2011)		Not analyzed		Not analyzed
Atlanta (2012)				
Montreal (2013)	Not analyzed	Not analyzed		Not analyzed
Oregon (2014)				
Portland metro area (2014)				

Age

Studies have shown that smartphone adoption and use have differed significantly by age group (*7*). Statistical tests that compared each smartphone sample with a travel survey sample of bicycle commuters were able to calculate for six of the seven regions examined, and distribution plots of the sample could be created for six of the seven regions examined. These results are presented in Table 6. In Lane County, Portland, and Oregon statewide, differences between the age distributions were significant, with older cyclists underrepresented in those samples. Differences between the age distributions were not significant for San Francisco and Atlanta. No statistical test could be calculated for Montreal, although the trend looked to follow the other samples in the undersampling of older users. The samples described by smartphone applications in general were younger than the samples described by traditional travel surveys. This trend is intuitive. As corroborated by the study presented in Table 1, smartphone owners tend to be younger. This finding may indicate that agencies that use smartphone survey methods should emphasize the recruitment of older users (Table 6).

Gender

Smartphone ownership differences between genders have lessened over time (*22*). Ownership rates were nearly identical in 2015 (Table 1). However, gender differences in participation in the smartphone application surveys were statistically significant in four of the seven regions examined. Statistical tests and distribution plots of the gender differences between the samples are presented in Table 7.

In general, cycling females were undersampled by the applications, although this difference was not statistically significant across all of the areas studied. Females were undersampled by a statistically significant proportion in the comparisons in Montreal, Oregon statewide, and metropolitan Portland. Several reasons may explain why the proportion of female application users was lower than the proportion of female bicycle commuters in the travel survey. Smartphone ownership may have been somewhat responsible in the earlier studies, although that factor is becoming less significant. It appears that the later studies had a more significant problem with undersampling. Another possible reason for the discrepancy is that females may have less of a motivation than males to participate in sharing information through the application. Finally, the discrepancy may have arisen because only bicycle work trips were considered in the travel surveys. However, research has shown that females are more likely to use bicycles for nonwork trips than for work trips (*23*). Thus smartphone surveys may be predicted to indicate female bicycling behavior better as trip purposes besides work are considered. That was not the case in these surveys. Overall, the indication may be that agencies that use smartphone survey methods should emphasize recruitment of female users in smartphone survey samples (Table 7).

Ethnicity

Ethnicity is a significant covariate of smartphone ownership; members of nonwhite ethnic groups are more likely to own a smartphone. Part of the reason for this differential smartphone ownership is that members of nonwhite ethnic groups are more likely to depend on smartphones for access to the Internet (*7*). Ethnicity could be examined statistically and graphically in three of the seven regions examined (Table 8). Only the Oregon sample comparison had a statistically significant difference (at the $p < .1$ level) in distributions of ethnicity. However, the Atlanta and Portland samples did have a similar pattern, although not a statistically significant one. Across the three samples, Hispanics were overrepresented in the smartphone samples, while African-Americans were underrepresented or not represented at all. These differences in sampling may have been the result of differences in smartphone ownership, or differences in the smartphone survey participation behavior of nonwhite ethnic groups (Table 8).

Household Income

Household income typically has a significant effect on smartphone ownership: smartphone devices cost more than traditional cell phones and may have more utility to those in higher-income jobs. However, this trend was not clear across the areas studied. Household income was examined statistically in three of the seven regions considered and was illustrated graphically in four of the seven regions considered (Table 9). Differences between the samples across household income were significant in Atlanta and Oregon.

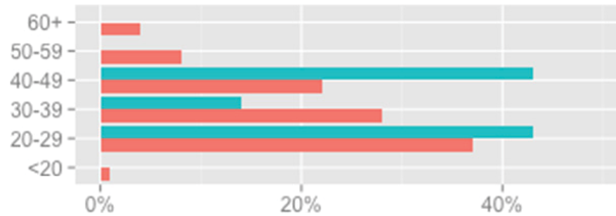
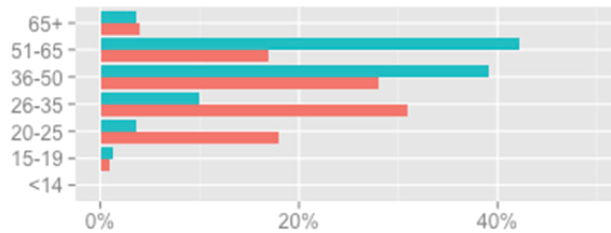
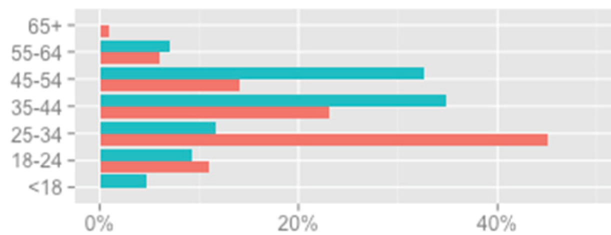
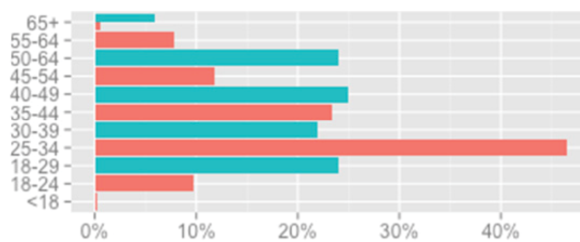
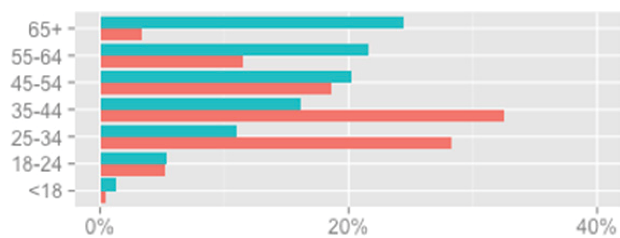
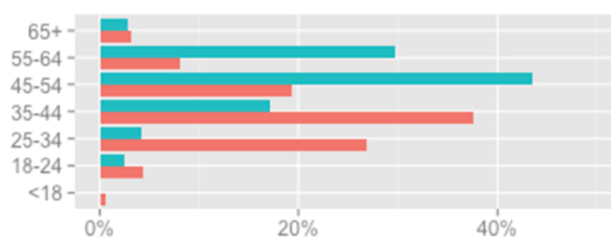
In Oregon statewide and in metropolitan Portland, users of ORcycle in general had higher incomes than cyclists described by the Oregon Household Activity Survey. However, in Atlanta, the opposite trend was more pronounced. The distributions in Montreal were relatively similar between the two survey types. These differences between the travel survey methods across household income may indicate a need for transportation agencies to reach out to underrepresented groups in high- and low-income strata, depending on the smartphone ownership demographics of their regions (Table 9).

Outcomes for Agencies

This study indicated significant differences between the bicycling population segments reached on the basis of smartphone applications rather than through traditional travel surveys. Because of these differences, traditional travel surveys are unlikely to be phased out for some time. The study also indicated that little information about bicyclists was available from traditional travel surveys, especially in areas that had small samples to compare with, such as Austin and Atlanta. This lack of information highlights the importance of the use of these smartphone crowdsourcing methods to collect data: although samples can be biased, the data acquisition is relatively cheap and expedient. Travel surveys can take years to administer properly. These applications can help provide valuable insights in a matter of months. With requisite publicity, these applications can crowdsource information from large numbers of bicyclists.

The use of these two survey types in tandem may facilitate broader and larger samples, and it is likely that the differences will decrease with time as smartphone adoption continues to increase. In the interim, agencies that use smartphone application surveys can make explicit efforts to reach undersampled populations. Smartphone applications designed to operate in languages other than English may help to reach members of some ethnic groups. Targeted sampling, as opposed to opt-in sampling, also may improve how representative of the population the results of these applications are. Future traditional travel survey efforts could include a subcomponent, which used an application like those reviewed here to collect combined revealed and stated preference data.

TABLE 6 Age Comparisons Across Regions

City or Region (study year)	*N* (smartphone sample)	*N* (travel survey sample)	Test Statistic	Significance	Distribution Plot
San Francisco (2009)	366	153	$t = -9.36$, DF = 364	$p < .001$	NA (only mean age was given, so no distribution plot could be generated) Smartphone survey mean age = 34 years (SD = 9) Traditional survey mean age = 45.3 years (SD = 11.2)
Austin (2011)	304	7	$\chi^2 = 2.56$, DF = 10	Not significant	
Lane County (2011)	93	161	$\chi^2 = 41.84$, DF = 12	$p < .001$	
Atlanta (2012)	881	43	$\chi^2 = 64.05$, DF = 12	$p < .001$	
Montreal (2013)	NA (category bins differed between smartphone sample and travel survey sample)				
Oregon (2014)	209	818	$\chi^2 = 104.26$, DF = 12	$p < .001$	
Portland metro area (2014)	160	319	$\chi^2 = 108.55$, DF = 12	$p < .001$	

NOTE: DF = degrees of freedom.

TABLE 7 Gender Comparisons Across Regions

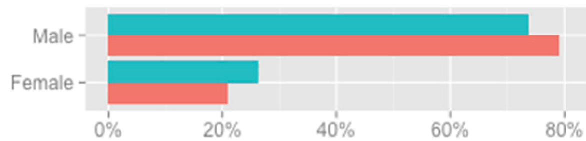
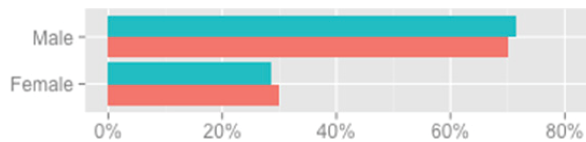
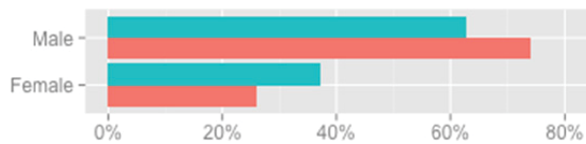
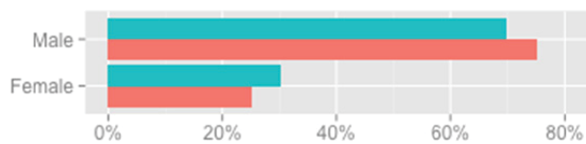
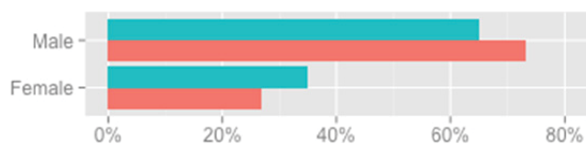
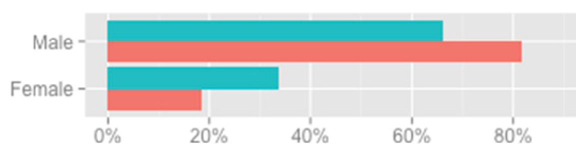
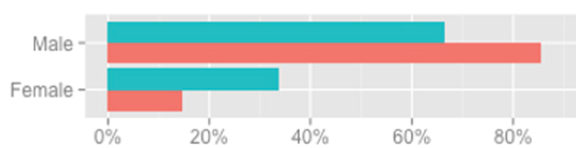
City or Region (study year)	*N* (smartphone sample)	*N* (travel survey sample)	Test Statistic	Significance	Distribution Plot
San Francisco (2009)	366	153	$z = 1.028$	Not significant	
Austin (2011)	302	7	$\chi^2 = 0.01$, DF = 2	Not significant	
Lane County (2011)	93	161	$\chi^2 = 3.38$, DF = 2	Not significant	
Atlanta (2012)	866	43	$\chi^2 = 0.59$, DF = 2	Not significant	
Montreal (2013)	379	1,577	$\chi^2 = 8.99$, DF = 2	$p < .05$	
Oregon (2014)	209	802	$\chi^2 = 31.59$, DF = 2	$p < .001$	
Portland metro area (2014)	160	319	$\chi^2 = 19.40$, DF = 2	$p < .001$	

TABLE 8 Household Income Comparisons Across Regions

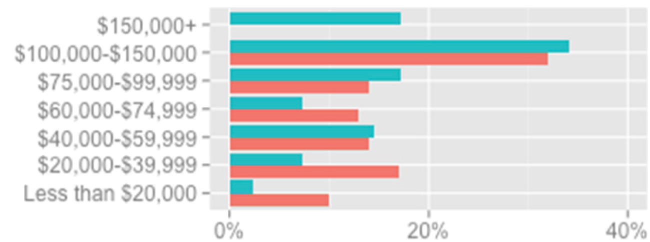
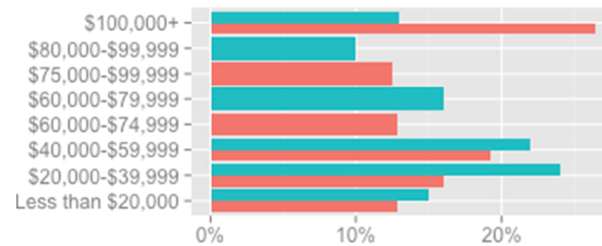
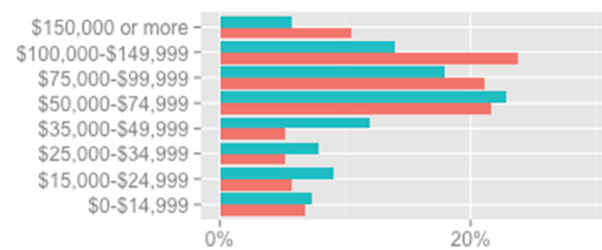
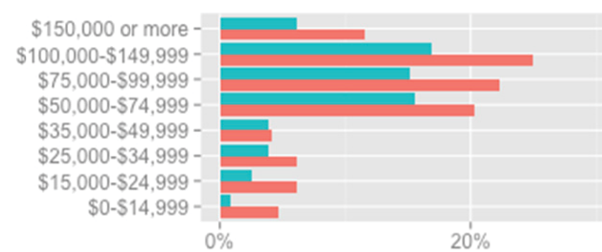
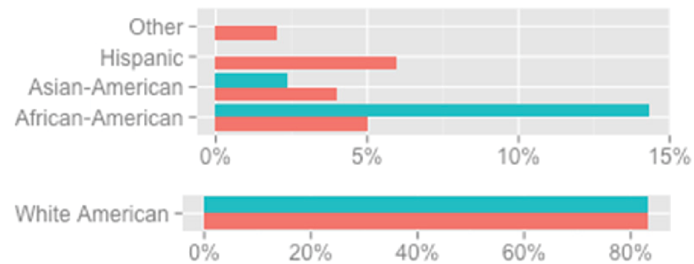
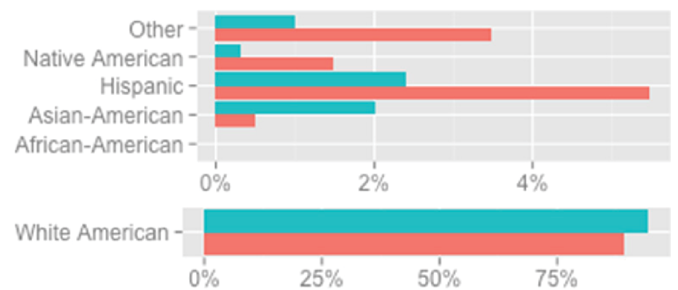
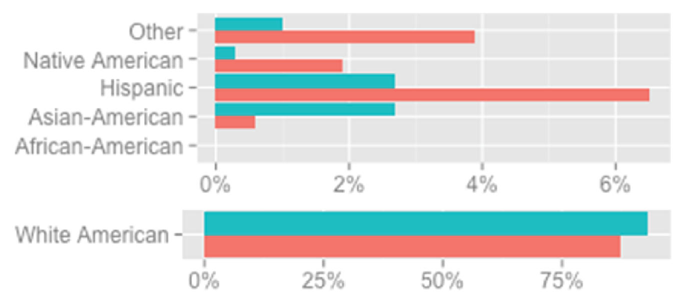
City or Region (study year)	*N* (smartphone sample)	*N* (travel survey sample)	Test Statistic	Significance	Distribution Plot
San Francisco (2009)	NA				NA
Austin (2011)	NA				NA
Lane County (2011)	NA				NA
Atlanta (2012)	684	41	$\chi^2 = 122.60$, DF = 12	$p < .001$	
Montreal (2013)	NA				
Oregon (2014)	190	690	$\chi^2 = 23.80$, DF = 14	$p < .05$	
Portland metro area (2014)	148	250	$\chi^2 = 5.40$, DF = 14	Not significant	

TABLE 9 Ethnicity Comparisons Across Regions

City or Region (study year)	*N* (smartphone sample)	*N* (travel survey sample)	Test Statistic	Significance	Distribution Plot
San Francisco (2009)	NA				NA
Austin (2011)	NA				NA
Lane County (2011)	NA				NA
Atlanta (2012)	824	42	$\chi^2 = 9.95$, DF = 8	Not significant	
Montreal (2013)	NA				NA
Oregon (2014)	201	711	$\chi^2 = 17.62$, DF = 10	$p < .1$	
Portland metro area (2014)	155	291	$\chi^2 = 12.96$, DF = 10	Not significant	

Several limitations were associated with the results outlined here. Sample sizes for bicycle commuters in some of the travel surveys were small ($N = 7$ in Austin and $N = 43$ in Atlanta) and were not large enough to indicate statistically significant differences across several of the demographics tested. In fact, given the small sample of bicyclists available for comparison, another potential conclusion from this paper is that bicycle travel survey sampling sizes should be expanded considerably to understand better the unique aspects of bicyclists' demographics and travel behavior. Moreover, the travel survey samples categorized only self-classified bicycle commuters. Bicycles are used for many other trip purposes, and these other trip purposes may have different demographic distributions (*24*). Household travel survey data also are not entirely representative of the population; research has indicated that household travel surveys tend to oversample higher-income households and English-speaking households (*25, 26*).

With respect to ORcycle, the sample described here was taken across 7 months (i.e., November through May) during which most weather typically was not considered optimal for cycling (i.e., low temperatures, frequent precipitation). User characteristics may be different for a sample taken during the summer time. These results also are relevant only with respect to the comparison of bicycling travelers. The use was not considered here of smartphones to administer travel surveys to other mode users. Finally, it was assumed that the travel surveys used in this study were methodologically sound and reasonably representative of the regional population. Yet it was likely that sample biases also were present in these surveys.

Future Research

Several pursuits could make this research more robust and useful for field professionals. First, user statistics for the other smartphone samples (besides ORcycle) were restricted to what had been published typically after initial deployments, although these applications are still collecting data. Perhaps if the agencies that managed the other applications were approached, access could be obtained to customizable aggregations of sample statistics. Other user characteristics would also be valuable to examine, such as vehicle ownership or housing type, although such information is not elicited in all of the applications. More robust comparisons may yield additional information valuable to agencies interested in using these applications to collect travel information.

CONCLUSION

This paper highlights the differences in the user samples collected by smartphone applications and comparable samples of cyclists collected by traditional travel surveys. These differences point to the need of agencies that use such applications to invest in efforts to reach out to undersampled population segments, because such segments may contribute to the aggregate preferences concluded about the sample. The undersampled population segments highlighted in this study usually included females, older age groups, some minority ethnic groups, and lower-income groups. It is likely that other population segments are being undersampled that were not considered in this research. Despite limitations, smartphones are an invaluable tool for travel behavior research, and they are likely to become increasingly important in the conduct of travel surveys. This research highlights improvements that agencies should consider in their efforts to assess their cycling populations as accurately as possible. To reach undersampled populations, the use of smartphone applications in tandem with other travel survey methods or the administration of targeted sampling efforts is necessary.

ACKNOWLEDGMENTS

The authors acknowledge the work of all researchers whose statistics are cited here. A meta-analysis such as this one would have been impossible without the earlier smartphone application studies applied to bicyclists. The authors acknowledge the support of the Oregon Department of Transportation (DOT) in Salem, which funded the development of the ORcycle smartphone application, and the feedback and support of the SPR 768 Technical Advisory Committee. The work of Robin Murray and Bikram Maharjan of the Transportation Technology and People (TTP) Laboratory also was crucial to the successful development of the ORcycle application. The authors acknowledge the time and goodwill of beta testers and anonymous ORcycle users who provided data and in many cases detailed comments and feedback. Without the support of the Oregon DOT, TTP lab members, and ORcycle users, this research would not have been possible. Bryan Blanc also received valuable support from an FHWA Dwight David Eisenhower Transportation Fellowship Program fellowship during his graduate studies at Portland State University.

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Any errors or omissions are the responsibility of the authors.

The Standing Committee on Bicycle Transportation peer-reviewed this paper.