Where do Bikeshare Bikes Actually Go?
An Analysis of Capital Bikeshare Trips Using GPS Data
by Jon Wergin and Ralph Buehler

Jon Wergin, MURP (corresponding author)
Urban Affairs and Planning
Virginia Tech, Alexandria Center
1021 Prince Street, Suite 200
Alexandria, VA 22314
phone 804-837-1397
jswergin@vt.edu

Ralph Buehler, PhD
Associate Professor in Urban Affairs and Planning
Virginia Tech, Alexandria Center
1021 Prince Street, Suite 200
Alexandria, VA 22314
phone 703.706.8104
ralphbu@vt.edu

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Note: This research was conducted based on data collected by the District Department of Transportation (DDOT).
ABSTRACT
Bikeshare systems with docking stations have gained popularity in cities throughout the United States—increasing from six programs with 2,300 bikes in 2010 to 74 systems with 32,200 bikes in 2016. Even though bikeshare systems generate a wealth of data about bicycle check-out and check-in locations and times at docking stations, virtually nothing is known about routes taken and activities undertaken between check-out and check-in of the bikes. This information could greatly enhance future expansion of bikeshare systems, placement of new docking stations, as well as the location for new bike lanes and paths. To study this, the District Department of Transportation (DDOT) placed GPS trackers on 94 Capital Bikeshare (CaBi) bikes in the spring of 2015. Based on these data this GIS analysis distinguishes riders by type of CaBi membership, identifies popular routes, analyzes bicycle infrastructure usage, and examines stopping and dwelling times at places of interest. Results show strong differences in trip attributes between short-term users (24h or 3-day memberships) and monthly or annual CaBi members. Trips taken by short-term users were longer in distance, slower, and concentrated off-road on parkland in and around the National Mall. Trips by CaBi members were shorter, faster, and were concentrated away from the National Mall in popular mixed-use neighborhoods. Short-term members rode 12 percent of miles on dedicated bicycle infrastructure, 61 percent in parks, and 27 percent on roadways with motorized traffic, while the shares for members were 33, 17, and 50 percent respectively. Based on routes taken this study also recommends potential locations for bicycle infrastructure improvements and new bikeshare stations.
INTRODUCTION
Cities around the world try to promote cycling to make their transport systems more sustainable and reduce environmental, economic, and social costs [1]. Bikeshare systems may help increase city cycling by making it more attractive and convenient, providing the opportunity to get around by bicycle without having to use (and own) a private bike and the option to make one-way trips by bicycle returning with another mode of transport [2, 3]. With bikeshare docking stations placed throughout an area, a user may check out a bike and return it to any docking station in the system [4]. Users do not have to worry about locking or maintaining a personal bike, making it attractive to commuters and tourists alike [5]. In recent years, bikeshare has been booming in US cities, growing from six programs with 2,298 bikes in 2010 to 74 systems with 32,200 bikes at the time of writing [6].

Even though bikeshare systems generate a wealth of data about bicycle check-out and check-in locations and times at docking stations, virtually nothing is known about routes taken and activities undertaken between check-out and check-in of the bikes. Numerous studies and online visualizations examine check-in and check-out locations of CaBi bikes and typically assume a direct line travelled between stations. However, none have been able to utilize GPS data to examine actual routes taken on CaBi. This is the first to do so and only the second such study in the United States, analyzing GPS tracks of 94 bikeshare bicycles between stations in the Washington, DC area. The analysis distinguishes riders by short (24h or 3-day) and long-term (monthly and annual) CaBi membership. Goals of the analysis are: (1) to provide a snapshot of the geographic areas where bikes are taken; (2) identify individual roadway segments used by CaBi bicycles; (3) correlate routes taken by CaBi with bicycle infrastructure supply; (4) highlight gaps in the bike infrastructure network; and (5) describe dwelling behavior of CaBi users to see where users stop without checking bikes back into a CaBi station. Results provide new information needed to support cycling policy and planning for both CaBi and the District Department of Transportation (DDOT), suggesting effective places to install new CaBi stations and cycling infrastructure.

SHORT OVERVIEW: CAPITABL BIKESHARE (CaBi)
CaBi is the bikeshare system for the Washington, DC area including DC, Arlington, VA, Alexandria, VA, and Montgomery County, MD. The system replaced a smaller program called SmartBike D.C., which operated from 2008-2010 [7]. CaBi comprises over 3,000 bicycles and 350 stations. As of 2014, the system registered 27,600 annual or 30-day members [8].

A membership is required to rent a CaBi bike and several membership options are available: 24-hour and 3-day memberships are classified as short-term or casual users, and 30-day and annual subscriptions are recorded as members. Once registered, the first 30 minutes of each trip are free, after which fees apply that increase by time used. This structure encourages short trips and frequent docking of bikes. For extended trips, CaBi recommends renting from a local bike rental shop. Bulk annual CaBi memberships may be purchased by local corporations as a benefit to their employees. Hotels may also purchase daily memberships for their guests. Key fobs may be obtained by members for quick access to bicycles without having to use the touchscreen system to check out a bike at a docking station.

CaBi trip data are publicly available. The data include the following information for every trip (between check-out and check-in of a bicycle) made in the system: duration, start station, start time, end station, end time, subscription type, and bike number. In addition, CaBi
collects data on its members as part of the membership subscription process. Several studies have used surveys of members and users to summarize demographic data of CaBi users [5, 7, 8].

For example, Buck et al. [5] completed a study on both member (monthly and annual) and casual (daily and 3-day) CaBi users. Casual users had an average age of 35, 52 percent were female, and 53 percent cited tourism as their trip purpose. Furthermore, the average casual user was a frequent cyclist, a domestic tourist, and travels with a group [7]. The most recent study of member users shows 63 percent under 35 years old, 59 percent male, and 74 percent at least occasionally using bikeshare for commuting to work [8].

About 50 percent of CaBi members cited lack of cycling infrastructure as a barrier to cycling, 43 percent cited poor connectivity between bike paths/lanes, and 30 percent cited lack of separation of bike lanes from car traffic [8]. Casual users were generally unsatisfied with DC bicycle infrastructure, 43 percent expressing some level of dissatisfaction, versus 29 percent expressing satisfaction. 30 percent of casual users requested more stations around the National Mall [7].

The share of residents regularly biking to work in Washington, DC increased from 0.8 percent in 1990 to over 4.5 percent in 2013. During the same time the city has greatly expanded its bicycle infrastructure. DDOT [9] reports that the city has 56 miles of trails, 69 miles of bike lanes, and 6 miles of cycle tracks. Areas within the National Parks, including the National Mall, also provide roads with low motorized traffic volumes and sidewalks on which to ride. The city welcomed 20.2 million visitors in 2014 and was the 8th most popular U.S. destination for foreign tourists [10].

**LITERATURE REVIEW: STUDYING BIKESHARE USER BEHAVIOR USING GPS**

Based on a search of the Transportation Research Board’s TRID database, the Web of Science, and Google Scholar, no prior study has analyzed routes of CaBi bicycles between docking stations using Global Positioning Systems (GPS). Similarly, our literature search only identified one study analyzing routes of bikeshare bikes between docking stations using GPS [11]. Therefore, the review below includes studies using GPS to identify routes of both bikeshare and cycling in general. The review also briefly highlights possible advantages of using GPS compared to stated preference surveys and post-trip revealed preference surveys of route choice.

Using GPS data to study bicycle route choice has several advantages. Previous literature has relied heavily on stated preference surveys to examine route choice [12]. This method makes data collection easier, allowing participants to choose their preferred route based on photos or maps. However, the accuracy is routinely called into question, as there is not always a direct correspondence between the stated preference and actual behavior [13]. As noted by Broach et al. [14], other drawbacks include strategic bias—when a respondent changes answers in an effort to influence policy decisions—as well as inability of cyclists to accurately recall previous routes.

Revealed preference studies seek to solve this issue by asking respondents to trace routes that they have actually taken. While such post-trip questionnaires are still subjective tools prone to recall error, GPS tracking permits objective measurement of routes [15]. GPS tracking is a form of revealed preference. However, carrying a device and being aware that one’s preference is being recorded may influence behavior—noted as a problem in a GPS study by Dill & Gliebe [16]. That study tasked participants to activate a GPS device during bicycle trips, and found that cyclists generally do not travel on the shortest route possible—rather they go out of their way to ride on bicycle facilities and low traffic streets. Harrison et al. [17] completed a similar study of bicycle routes to school using GPS devices.
Smartphones with GPS technology have recently allowed researchers to complete studies without the need for separate devices. Hood et al. [18] completed such a study using the mobile app CycleTracks. Users opened the app, entered trip purpose and other information, and went on their way. Melson et al. [19] used a similar smartphone application to estimate the impact of bridge attributes on cyclist behavior. Halldorsdottir et al. [20] combined GPS devices with travel diaries to study bicycle route choice. Krenn et al. [15] also distributed GPS trackers to members of a group that had previously participated in a route choice study by drawing routes on a map. Menghini et al. [21] filtered bicycle data out of a large GPS dataset of multiple travel modes in Zurich, Switzerland.

Some bikeshare systems, such as Phoenix’s Grid Bikeshare have built-in GPS trackers in each bicycle and allow users to leave bikes at non-station locations. Parkes et al. [22] report that built-in GPS receivers can alert operators when a bike has left a certain area. They also can give riders real-time information on dock availability through an on-board tablet, such as those present in Copenhagen’s new system. Operators may also use GPS data to learn about the route choices of its users (as this study does), as well as to assist with re-balancing efforts [23].

Our literature search only found one previous study examining route choice using bikeshare GPS data (based on the Phoenix system) [11]. Khatri employed a map-matching system developed by Dalumpines & Scott [24] using Network Analyst in ArcGIS, and also used by Hudson et al. [13] in a non-bikeshare based study. This method involves creating a buffer around each GPS point transmitted by the bicycles and then calculating the shortest route between origin and destination of GPS points within the buffer. This allowed for detailed analysis of route characteristics in the two studies. Khatri’s work represents the only other known study of bikeshare GPS data, looking at Phoenix’s Grid Bikeshare bikes with the built-in GPS receivers. Hudson et al. studied bicycle route choice in Austin, Texas, using the same CycleTracks application as Hood et al. [13].

Overall, a recent literature review identified that past studies using stated and revealed preference methods, and including GPS-based studies, tend to agree that cyclists prefer separate facilities over cycling with fast moving and high volume motorized traffic [12]. Such studies have demonstrated that cyclists and non-cyclists seem to have a hierarchy of preferences. On the low end is cycling on streets with on-street parking and a large volume of motorized vehicles travelling at high speeds. When cycling on streets cyclists prefer roadways with lower travel speeds and less motorized traffic. However, revealed and stated preference surveys show that cyclists prefer riding on dedicated bike infrastructure, with physically separated lanes and paths as the most preferable option.

A recent literature review on bikesharing found that convenience, affordability, and geographic proximity to bikeshare stations are prime motivators for the use of those systems [23]. Annual members of bikeshare programs were found to use bikeshare primarily for commuting and other utilitarian trips, as opposed to cyclists using their own bikes who are more likely to ride recreationally than bikeshare users. Differences in trip purpose between annual members of bikeshare systems and casual users have also been found in other studies. In the case of Capital Bikeshare, annual members make the majority of their trips for utilitarian purposes, however more than 50% of trips taken by casual users were found to be purposes of tourism [5].

**DATA**

Occasionally CaBi bikes require maintenance that cannot be performed in the field, and bicycles are taken to a facility in Southwest Washington for service. Here, DDOT affixed ‘iGotU’ GPS
trackers encased in protective waterproof boxes beneath the saddles of 130 bikes. The trackers were programmed to only record location while in motion, and did so until the battery was depleted. After being repaired and equipped with the GPS device, bikes were distributed around the system beginning April 20, 2015. Half of the GPS-equipped bikes began their data collection in Washington, DC and a quarter each in Arlington County and the City of Alexandria in Virginia.

No demographic data about riders was collected, only the routes taken by bicycles between docking stations. However, bicycles with GPS could be identified (via ID numbers) in the system that recorded check-ins and check-outs at docking stations. Based on check-in and check-out information, membership status of the rider was known: casual (short-term membership) user or annual/monthly member. This allowed comparison of route choice between casual users and CaBi members. Compared with some previous GPS route-choice studies, riders in this sample were not aware of the tracking and therefore could not alter behavior in an attempt to influence study outcomes and policy recommendations. This advantage is only possible in studying bikeshare bikes and in particular with the data provided by DDOT for this study. Even newer bikeshare systems with built-in GPS units are susceptible to this bias, since users may be aware of a system’s tracking capabilities.

As bikes returned to the maintenance building, the devices were removed. In total, 94 GPS trackers were recovered—36 were lost or damaged. Data was downloaded from the 94 trackers individually and the following data for each GPS point or “ping” were recorded: date, time, latitude, longitude, and altitude. Speed, direction, and distance were also recorded based off of movement between pings.

**Data Cleaning**

Upon initial observation of the data, it became clear that the devices occasionally reported motion while bikes were actually stationary at docking stations. This was evident by the appearance of short distance movements centered on docking stations. Furthermore, trips taken in a van as part of the system’s rebalancing efforts had been recorded. Using the trip start and end times from the publicly-available trip data (matched by the number of the bicycle), the unwanted data was removed. Any ping falling outside of the timeframe of an actual trip was deleted, leaving only pings that were recorded while a bike trip was actually being taken. For each valid ping, trip data were appended. This process revealed 3,596 trips that contained GPS data, totaling around 329,000 pings altogether, and over 7,200 total miles ridden.

After loading the data into GIS it was possible to see on a map where the CaBi bikes were actually going, and to separate routes taken by user type. Upon initial mapping, it became clear that more data-cleaning was necessary. The initial approach of using a map-matching system pioneered by Hudson et al. [13] and Khatri [11] was not viable, as it was not effective for sight-seeing trips—where riders often take circuitous routes and where bicycles often leave the existing road and bike network to access tourist sights. Given that a large percentage of CaBi trips are for such a purpose, this map-matching method could not be used. Moreover, this map-matching approach required a complete network of streets, paths, and trails to be created in ArcGIS. There were many trips where a cyclist had clearly ridden off road/path—across the National Mall for example—that would have been discarded. This study instead created polylines from the GPS points and simplified them to remove abnormalities.

As documented by several studies on GPS data [25-27], location is often skewed when in close proximity to tall buildings, or so-called “urban canyons.” This results in a route appearing...
to jump back and forth across roads, into buildings, and sometimes across the city. These sudden movements were removed by deleting line segments whose length was more than three standard deviations from the mean. Tracks that were obviously sporadic and did not follow any streets or paths were also manually removed. After all data-cleaning, only GPS pings and associated data that were part of actual trips and mostly not affected by faulty tracking were left for analysis.

**Summary of Data Collected**

The amount of data collected by each GPS tracking device varied from 17 to 80 trips—40 on average. Dates ranged from April 20th to May 16th. Devices lasted nine days on average—some as few as five because of their frequent use. The device that lasted until May 16th was used sparingly, including a six-day unused period. The sample collected was very similar to all of the trip data for the same time period (see Table 1) with respect to average trip times and ratio of member to casual riders. Percentage of member trips for the sample and overall dataset were 76.5 percent and 76.3 percent respectively, while average trip time differed by only seven seconds. A t-test showed that the values were not statistically significantly different (p-value <.01).

**RESULTS AND DISCUSSION**

We calculated the distance of each track and summed them by user type. Using trip duration from the publicly-available trip data, we also calculated average speed. The average trip took 19 minutes and was 2.0 miles long—with a speed of 6.3 miles per hour (see Table 2). Differences between member and casual riders were stark. The average casual user trip was nearly twice as long as the member trip in distance, took three times longer in duration, and had considerably slower average speed. The mean trip duration for casual users was heavily skewed by a few trips over the five-hour mark however. These results mimic those by Khatri [11], who found that casual users accounted for 56.5 percent of all trips, but 63 percent of the miles.

Comparing the average distance of trips taken to the average direct distance between stations (‘as the crow flies’) shows that casual users take less direct routes. Their trips were more than 177 percent longer than as the crow flies distance. Member users on average took more direct routes—only 35 percent longer than a straight line.

**Popular Areas**

Member and casual user tracks were separated and we generated a number of ‘heat maps’ identifying geographic concentrations of miles ridden. One set of heat maps shows popular areas for bikeshare use on a macro level for each type of user. The other set uses a smaller search radius to depict the most popular segments ridden by each type of user.

Generally, casual rider activity centered on the National Mall (see Figure 1). Member activity centered further north, in an area bounded roughly by 13th, 17th, K, and R Streets NW (see Figure 2). Thus, member riders tended to stay clear of the National Mall, and focused more on the dense, mixed-use neighborhoods of Dupont and Logan Circles. Pennsylvania Avenue served as a boundary between the dominant areas for each user type (see Figure 3).

**Popular Segments**

Looking at individual streets, most popular segments for casual riders were the sidewalks within the National Mall and the roads that border it (see Figure 4). The Mount Vernon Trail in Virginia was also popular among casual riders. The most popular segments for member riders were 14th,
15th, 18th, and R Streets NW (see Figure 5). Also popular was Pennsylvania Avenue in front of the White House and the Key Bridge, linking Georgetown with Arlington, VA. Most of these popular segments feature bicycle infrastructure separating cyclists from motorized traffic. The following section will examine infrastructure usage in more detail.

Bicycle Infrastructure Usage
To calculate facility usage, we generated three polygon layers based on (1) 20 meter buffers around cycling infrastructure (bike lanes, paths, and cycle tracks), (2) 20 meter buffers around roads without cycling infrastructure, and (3) land managed by the National Park Service (NPS). Roads within NPS land are generally low-traffic, with many sidewalks and paths present. Parts of Beach Drive in Rock Creek Park are also closed to cars on weekends. Of the recorded CaBi trips on this road, all were on the weekend. Bike trails within NPS land were considered part of the park layer. Length of the track lines within these three polygons was summed. Areas where different polygons were near or coincident with each other (mostly at intersections and overpasses) were removed, any tracks within them not counted. This left track sections taken on bicycle infrastructure only, on roads lacking infrastructure only, and in National Parks.

An analysis of DC GIS data reveals on-street bicycle facility mileage amounting to 7.6 percent of bikeable roadway mileage in the city, and 10.0 percent in the NW quadrant of the city where CaBi ridership was highest. In our sample, bicycle infrastructure was utilized for about 25 percent of miles ridden. This number jumps to 59 percent when National Parkland is included, indicating that all users combined ride on streets without any cycling infrastructure for about 41 percent of miles.

Further breakdown by membership type shows a large difference between the two user groups. Casual users ride the majority of their miles within National Park land—confirming the earlier heat map indicating concentration of trips around the National Mall—and ride on bicycle infrastructure for less than half of their other miles. Member riders heavily use bicycle infrastructure, but stay clear of the National Mall as previously mentioned. Half of their miles are ridden on roads without any cycling infrastructure.

To determine the most-traversed roadway sections without bicycling infrastructure, we further examined GPS tracks of member riders outside of cycling infrastructure, as these roadways could be prime candidates for cycling infrastructure improvements in the future. The most immediate observation is that the state-named diagonal streets are very popular, despite their heavier traffic and lack of infrastructure. This suggests that member riders may value directness over comfort, forgoing the quieter, less direct axial streets.

Most-traversed segments lacking infrastructure included M Street and Pennsylvania Avenue NW in Georgetown, and Louisiana Avenue NW and Massachusetts Avenue NE near Union Station. 14th Street NW between Florida and Columbia Avenues NW, and K Street between 3rd Street NW and 1st Street NE were also very popular. This is likely because these segments represent gaps in the current network of bicycling infrastructure where a bike lane ends and picks back up further on, essentially spilling a rider out onto a shared roadway for several blocks. DDOT has recommendations in its Multimodal Long-Range Transportation Plan for additional infrastructure in all of these sections except for the K Street segment identified in Figure 7. Cycletracks are proposed for the Louisiana, Massachusetts, and 14th Street sections identified, and a bike lane is proposed for M Street.

Stopping and Dwelling Behavior
A survey by Buck et al. [5] found that 53 percent of casual trips were for the purpose of tourism. Therefore, we created a density map to show where these casual riders had stopped their bikes to see the sights. Pings for casual riders that registered speeds of 0 miles per hour and were not near a CaBi station were analyzed. These pings were then manually counted near each site of interest—a standard buffer was not used given the difference in area between and around the sites. The majority of activity was located on the National Mall (see Figure 8). Most popular areas to stop included the World War II Memorial, Lincoln Memorial, the White House, and areas around the Tidal Basin including the Martin Luther King Jr. Memorial and FDR Memorial. Locations outside of the National Mall include Georgetown and Dupont Circle. Popular points in Virginia were at Gravelly Point, Arlington National Cemetery, and the Iwo Jimna Memorial. Many of these locations currently do not have a CaBi station nearby. The ones that do are among the most popular stations in the entire CaBi system.

DDOT addresses many of these popular stopping locations in their DC Capital Bikeshare Development Plan, which outlines expansion plans for the next three years. There is in fact a proposed station area slated for 2016 near the World War II Memorial. Other popular areas receiving a station in 2016 include another at the Lincoln Memorial, White House, and Washington Monument.

LIMITATIONS
With any GPS study, accuracy of the pings may be a problem. This is especially true in cities, where “urban canyons” can block satellite signals and create inaccurate tracks. The aforementioned map-matching method by Dalumpines & Scott [24] has been shown to be useful for cleaning direct routes. This data was also not accurate enough to differentiate between sidewalk and roadway riding. Although illegal in the downtown area, a sizeable percentage of miles were likely ridden on the sidewalk but counted as being ridden on the road.

Quality of bike infrastructure was not taken into account—all types of infrastructure were treated equally. Further research could look into popularity differences of various kinds of infrastructure. In this study, parkland was generally viewed as bike-friendly, though there may be some segments where this is not the case. Direction of travel was also not taken into account. This omission is particularly important when measuring CaBi usage of roads with steep slopes.

The sample period for our study was only about four weeks long, with the bulk of that data coming in a two-week period (before the trackers ran out of battery). Although yielding similar trip data to the system-wide collected check-in and check-out data, the spring-time weather may have encouraged more casual users than typical. Fewer tourists can be expected in the winter months, with even a greater share of trips taken by members in cold conditions. Percentage of member trips for winter quarters was between 85-89 percent, compared with the 74 percent in this quarter.

As mentioned above, our data did not include socioeconomic and demographic information about CaBi users. Adding this information would help expand the analysis to identify differences in the socio-economic and demographic background of CaBi users and their route choice behavior. Past studies have shown that socioeconomic and demographic characteristics of bikeshare users can differ significantly from the population at large and from cyclists riding their private bicycles. Thus, route choice of CaBi users may also vary by their socioeconomic and demographic characteristics. Previous studies on the equity of bikeshare systems have focused on accessibility of those systems for low-income and minority groups [28]. Findings from those studies showed that low-income and minority groups generally have less
access to bikeshare systems [29]. If accompanied by socioeconomic and demographic data of riders, GPS information on the routes taken by bikeshare users may prove useful in determining gaps in bikeshare systems.

CONCLUSIONS
This is the first study analyzing actual routes of CaBi bikes between docking stations. Besides providing a baseline about routes of bikeshare bikes, this study has two main findings useful for bikeshare planning in the Washington, DC area. First, both types of users seem to avoid roadways without bicycling infrastructure. Member users in particular use bike lanes, trails, and cycle tracks for about one-third of miles cycled—even though only 7.6% of roadway mileage has bike facilities. Patterns of roadway cycling of CaBi members identify current gaps in the bikeway network. DDOT could focus on improving cycling infrastructure on roadway segments without bike infrastructure but frequently used by CaBi members. Casual users mainly ride on National Parkland (61% of mileage), but do not use bike lanes and cycle tracks as much as CaBi members. Better signage and wayfinding to alert casual users that such on-road facilities exist could improve their cycling experiences in the city and make it more likely that they will consider cycling in the future.

Second, there is a big difference between member and casual user activity. Casual trips are significantly slower, longer in time and distance, and focused on the National Mall. More docking stations near popular stopping locations for casual users may encourage more tourist trips by CaBi and would give users a place to dock their bike while sightseeing. Combined with route signage, stations at Gravelly Point and Arlington National Cemetery could help bring more casual users across the Potomac River into Virginia.

Bikeshare programs will continue to offer attractive methods of transportation to locals and visitors alike. Improving systems and facilities to allow bikes to be more easily rented and ridden will only attract more users and help cities achieve their sustainable transportation goals. Other programs should be encouraged to use GPS technology to study movement of their bikes between stations. The data has been proven here to be valuable to the bikeshare systems themselves and to departments of transportation alike.

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TABLE 1  Representativeness of sample data: comparison of sample and overall CaBi trips

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<th>Sample Dataset Trips</th>
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## TABLE 2 Trip Data for Full Sample and by Membership Category

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