Bicycle Sharing and Transit: Does Capital Bikeshare Affect Metrorail Ridership in Washington, D.C.?

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ABSTRACT

Bicycle sharing programs have emerged as a global trend as an affordable, convenient, and sustainable travel option with various benefits. One of the benefits of such programs is touted to be their positive impacts on transit ridership by extending transit catchment area and providing much needed last-mile connection. Thus, locating bicycle sharing programs in transit station areas is believed to benefit both. However, the question of how and to what extent bicycle sharing programs affect transit ridership remains to be answered despite the attempts of few empirical and quantitative studies. From the microeconomic perspective, bicycle sharing can be a substitute, complement or both to transit use. In this paper, we examine impacts of bicycle share program on rail transit ridership using Washington, D.C. as a case study. Specifically, we explore the Capital Bikeshare program’s impact on Metrorail’s ridership. Two sets of analysis are conducted (1) an Origin-Destination analysis is conducted to map quarterly Capital Bikeshare trips, (2) a regression analysis. The first analysis showed that Metrorail stations have been important origin/destination of Capital Bikeshare trips. Six out of seven bikeshare stations with more than 500 trips are close to Metrorail stations. The result of regression analysis show Capital Bikeshare ridership in Metrorail transit catchment area is associated with higher transit ridership. Results suggest that 10 percent increase of CaBi ridership will lead to 2.8 percent increase in Metrorail ridership. Based on the results, potential policy implications and recommendations are discussed.

Key Words:
Bicycle sharing, transit ridership, Capital Bikeshare (Cabi), Washington D.C.
1. Introduction

Bicycle sharing is a public-accessible short-time bike rental program in which users share a bicycle fleet located at multiple stations. It has become a widespread application across the world with successful programs in the North America, South America, Europe and Asia. As of 2011, 135 bicycle sharing programs are in operation in 160 cities and 16 countries, offering approximately 236,000 bicycles(1). In the United States, the number of bicycle sharing programs have reached to 15, with 5,238 bicycles and 172,070 members (2).

Bicycle sharing programs provide an affordable and equitable travel choice with numerous benefits including providing low-cost and flexible mobility and convenient alternative for short trips such as shopping and recreation. They can have a significant role in solving the “last/first mile” access by connecting to/from transit stations to/from their final destination/home, reducing pressure on expanding transit service (3). Bicycles are also environmentally friendly as they help reduce congestion and emissions. For most cities, offering a bicycle sharing program is a strong demonstration of commitment to addressing climate change and livability (4).

Most studies on bicycle sharing focus on benefits of the programs and successful operation of the systems while only very few explored the interaction between bicycle sharing and public transportation systems. Similarly, on the transit side, few studies considered impact of bicycle sharing programs on transit ridership. The aim of this paper is to explore the relationship between bicycle sharing and rail transit ridership. Particularly, we ask two research questions:

1. Is there a relationship between the spatial pattern of bicycle sharing trips and the rail transit station location?
2. Does the existence of bicycle sharing station in the vicinity of a rail station help increase transit ridership?

To answer these questions, we start by discussing whether bicycle sharing and transit use substitute or complement each other from a microeconomic perspective, and review findings on the effects of empirical studies in Section 2. We use Washington, D.C. region, the home to Capital Bikeshare (CaBi hereafter) program and the WMATA (Washington Metropolitan Area Transit Authority) Metrorail system, as our case study for this paper. In Section 3, we introduce CaBi and analyze user behavior focusing on transit based on a customer survey. In Section 4, we conduct an Origin-Destination (O-D) analysis of CaBi trips. O-D maps illustrate that CaBi trips tend to cluster around Metrorail transit stations. In Section 5, we analyze the impacts of bicycle sharing program on transit ridership using regression analysis. Based on our findings, in Section 6, we suggest research and planning for bicycle sharing programs and rail transit to be done in conjunction to maximize the benefits.

2. Literature Review: Bicycle sharing and Rail Transit Ridership

In this section, we review the relationship between bicycle sharing program and rail transit ridership from two perspectives: microeconomic theoretical analysis, and empirical analysis.

2.1 Bicycle sharing and Transit: Substitute or Complement?
In microeconomics, there are two types of relationship between goods: substitutes and complements. Substitutes are goods with the same utility that both can meet users’ satisfaction. Consumers choose between goods based on the utilities of the goods as well as their taste or preferences. When the price of one good increases, the demand for the other good will increase due to substitution. A classic example of substitute goods is coffee and tea. In some cases, two goods are almost identical in their function and other features, and demand is very sensitive to price. In these cases, the two goods are perfect substitute goods.

Complements are goods which people tend to use together, such as coffee and sugar. When the demand for one good increases, such as coffee, the demand for the other, sugar, will increase. Therefore, the demand for sugar is “induced” by the demand for coffee.

Are bicycle sharing and transit substitutes or complements? This question is much more complicated than the sugar/tea-coffee analogy. First, bicycle sharing and transit utilities are not identical. As discussed above, bicycle sharing has various benefits and can be used for different purposes other than transportation. For example, transit is not a substitute for bike share users with recreation or exercise purposes. Therefore, substitution relationship between transit and bicycle sharing is complex and depends on many factors such as trip distance, trip purpose, weather conditions, and individual preferences.

Bicycle sharing is not a perfect substitute for transit. First, bicycling is heavily affected by weather and temperature. One can expect that in a chilly winter morning people tend to ride transit, even if there is a bicycle sharing station nearby. Second, bicycling is limited by travel distance, typically up to 5 miles for commute trips. Therefore, the substitutability of bicycle sharing to transit is sensitive to distance, that is, at a certain distance threshold, the substitutability will decrease dramatically. Based on literature, this threshold distance is about 2.5 miles (5) (6). On the other hand, bicycle sharing can be substitute for transit if the trip purpose is commuting and the distance is feasible for cycling. In fact, bicycle sharing is advantageous because transit relies on fixed infrastructure, while bicycle sharing users can take any suitable street. In most cases, bicycle friendly streets are more accessible than transit system. In addition, large-scale bicycle sharing systems typically have good station coverage providing easy access for many residents. For example, CaBi program offers more than 300 stations in D.C. region, compared to 86 Metrorail stations. Since bikeshare stations are more accessible and widespread, bicycle sharing can be considered as a potential substitute for transit in D.C.

Bicycle sharing can also be a complement to transit. For example, one of the barriers for increasing transit ridership is known as “last mile” or “first mile” problem which refers to the gap between transit stations and origins/destinations which are underserved by public transportation. Bicycle sharing can be a significant part of the solution to this problem in conjunction to other vehicle sharing systems such as shared cars. With bicycle sharing, transit users with last-mile problem can have a faster alternative to walking or transferring to another mode. Research on bicycle sharing route choice confirms that there is a strong preference to biking over walking (7). From this perspective, bicycle sharing can complement transit service and increase ridership by help reducing the “last mile” issue.

2.2 Bicycle sharing and Transit: Empirical Studies

Empirical studies on the relationship between bicycle sharing and transit, although helpful, have not adequately answered the question of substitution versus complementarity. Various studies found that being in the proximity of a transit station is a key factor to the success of bicycle
sharing programs. The number of rail transit stations within a 400-meter walking distance of a bicycle sharing station was found a significant (at 95% level) factor in affecting the use of bicycle sharing program (5). Another study conducted in Helsinki, Finland concluded that combining bicycle sharing and public transportation would save about six minutes per travel, which leads to an average reduction of 10% in travel times for the whole region (8). These findings support the complementarity argument, that bicycle sharing programs could make existing public transportation systems more attractive and sustainable by reducing total travel times, and increasing peak our capacity. Results are consistent with another survey findings where 63% of (1,432) respondents reported that they would be willing to combine bicycle and public transit for a trip in Montreal, Canada (9).

In fact, bicycling as an access mode has been considered as an important factor in increasing transit ridership. In Germany and other European countries, bicycling has been recognized by public transportation companies and city planners as a feeder and distributor service for public transportation (10). For example, the German Railways’ designed an innovative ‘Call a Bike’ program in Berlin which sends access code for shared bikes per customer’s request via phone calls or smart phone applications as one way to attract transit riders (11).

3. Capital Bicycle sharing in Washington, D.C.

3.1. History

Fully established in September 2010, CaBi offered the largest bicycle sharing service in the US at the time. Built on the foundation of its predecessor SmartBike D.C., CaBi expanded the original coverage area to nearby Virginia and Maryland. With a coalition between the D.C. Department of Transportation (DDOT) and local transit authorities in Arlington and Alexandria in Virginia, and later in Montgomery County, Maryland, SmartBike D.C. expanded area coverage and availability of bikes and became Capital Bikeshare. The program is a public-private venture with Alta Bicycle Share Inc. and has since expanded from its initial 10 stations and 120 bicycles to 321 stations and 2,500 bicycles as of July 2014.

Expansion plans have been drafted to include areas in Prince George’s County, MD as well as additional stations in heavily traversed locations such as Dupont Circle. However, the announcement of Alta Bicycle Share Inc.’s bankruptcy in February 2014 has since stalled such plans including an anticipated deal to introduce bike sharing in College Park, MD. The program also struggles with attracting lower income and minority groups. Officials in the governing sub-regions have begun to make pushes to attract these groups in awareness events and promotional canvassings to increase membership. CaBi remained as the biggest bike sharing service in the US until New York City introduced its CitiBike Program in 2013.

As a sustainable mode of transportation, CaBi receives partial funding from the Federal Highway Administration. Local governments have also taken the initiative to offer financial assistance for low income demographics in order to increase ridership. Montgomery County, MD sponsors a bike share subsidy through its Job Access Reverse Commute (JARC) Program.

3.2. How CaBi works

The program relies on a membership system. Users must sign up as a daily, monthly, or annual subscriber and rent the bikes at hourly rates which vary by membership type and total time. With the memberships, the first 30 minutes of a trip is free and incremental charges are added per hour afterwards. Bicycles may be rented at any station and returned to any station, giving users
flexibility. As of May of 2014, the program has 450,746 total members and reached to a million rides at the end of 2013.

The early CaBi Stations were planned based on a demand analysis. The demand model was created based on the assumption that built environment factors can significantly impact demand for bicycle sharing. Factors taken into account included population and employment density, proximity to transit and bike infrastructure, and bike to work rates. A series of “heat maps” were created to identify potential CaBi locations (5). For the new stations, a demand-based approach is followed where individuals can propose a location for a CaBi station through the program’s website (13).

3.3. Demographics

With a 2013 Customer Survey, the program’s user demographics breaks down as follows: 63% of member are under 35, 57% of users are male and 80% are Caucasian, 95% possess a four-year college degree with 56% holding advanced degrees, 90% are employed, and 78% work and live in D.C. The majority of users agreed that bikesharing was important to getting around more easily, faster, and traversing shorter distances (91%). 80% looked at bikesharing as a new travel option, or as a one-way travel option. 57% found bikesharing a good way to exercise and 52% found bikesharing helpful at reducing their transportation cost as well as pollution. It is also significant to acknowledge that the program draws a large number of non-residents and tourists annually. In 2013, visitors took in excess of 200,000 rides through the CaBi System.

3.4. Relation to Metrorail

One source to explore the relationship is the customer survey that CaBi conducted in 2010 and 2013. In this section, we focus on findings from the customer survey on the interaction between Metrorail and CaBi ridership. Note that since the survey was CaBi users/members only, there is self-selection bias, and the findings may not apply to all commuters.

54% of 3,731 respondents reported Metrorail station as their trip origins/destinations. Among them 9% made trips starting/ending at Metrorail stations more than 10 trips in one month. Compared to other public transportation, Metrorail stations play more important roles in attracting bikeshare trips (21% bike to/from bus stops, and 10% to commuter rail stations, which includes MARC, VRE, and AMTRAK). When asked how they would travel if the CaBi program was not available, 44% respondents stated that they would take bus or Metrorail instead. After joining the CaBi program, 61% reported that they used Metrorail less and 4% more often. 17% respondents stated that they would support expansion of the CaBi program near Metrorail stations.

4. Capital Bicycle sharing Origin-Destination (O-D) Analysis

In this section, we mapped the origins and destinations of the CaBi trips to examine the spatial patterns and the relationship to Metrorail station locations. Two O-D analyses were conducted to investigate change in trip patterns: (1) by time (year), (2) by season. In the first analysis, we mapped trips of the third quarters of 2011, 2012, and 2013, to understand trip growth by year. We chose the third quarter because people tend to bike more in mild temperatures. In the second analysis, we mapped quarterly trips of 2013, the most recent year, to identify the seasonal patterns.
Trip data is collected from the CaBi program website. Since our focus is on bike commute trips, we excluded all the weekend trips because they are more likely for recreation purpose. In addition, we excluded the trips starting and ending in the same location as the trips with the same origin and destination tend to be for shopping, recreation and other types of non-work activities. We used ArcGIS 10.2 toolkit “spider diagram” for O-D visualization.

4.1 Capital Bikeshare Trips by Year

Figure 1a-1c illustrates the O-D trips in 2011, 2012 and 2013 respectively. Yellow lines represent the O-D pairs with trips more than 100 and less than 500 trips, green lines represent the pairs with trips more than 500 and less than 1,000 trips and the red lines represent the O-D pairs with more than 1000 trips.

Comparing the third quarter bikesharing trip patterns by O-D in 2011, 2012, and 2013, we reach two conclusions: (1) the maps clearly show the increase in bicycle share program over three years as well as the increase in number of trips (note the increase in number and thickness of green and red lines in 2013 compared to 2012 and 2011). This increase is likely a result of the expansion of the CaBi system. In 2012, there were about 30 new bikeshare stations installed in Arlington and Alexandria, Virginia. Consequently, several new bike trip links with more than 100 trips (yellow) per quarter were observed in Arlington, VA in 2012 and 2013 maps. Similarly, three new bikeshare stations were installed in the Tidal Basin area in 2012. Thus, the bike ridership in this area was also increased annually: in 2011 there was no bike trips, in 2012 the number of biking trips increased significantly, and in 2013 the area became a hot spot among the CaBi stations in terms of ridership with more than 1,000 trips between the Lincoln Memorial and the Thomas Jefferson Memorial, and more than 500 trips between the Lincoln Memorial and the Smithsonian Castle.

Second, the three maps reveal the hot spots, the areas with the highest CaBi ridership. Seven areas, the Zoo, Dupont Circle, Union Station, Easton Market, Tidal Basin, Crystal City, and Court House Neighborhood in Virginia, have the highest bikeshare ridership. Except Tidal Basin, all other six areas shared several built environment features. For example, all six areas have Metrorail stations within ¼ mile (e.g. walking distance). The Zoo area, Dupont Circle, and Union Station areas are close to the Red Line stations, Clarendon is in the vicinity of the Orange Line stations, and Eastern Market and the Crystal City are near Blue Line stations. Besides being close to Metrorail stations, all six hot spots have high-density residential development. The Capitol Hill region, in which the Eastern Market and the Union Station are located, is the largest historic residential neighborhood in Washington, D.C. with rowhouses. Similarly, Dupont Circle is home to high-rise apartment buildings and row houses and Crystal City is a planned urban community with high-rise residential buildings. Trips in Court House Neighborhood in Virginia
also show similar characteristics where origins/destinations are typically high-rise apartments.

(Data source: Capital Bikeshare website)  
(Note: To get the best display, we only show O-Ds with more than 100 trip links.)

4.2 Capital Bikeshare Trips by Season

The temperatures in D.C. region are typically pleasant in spring (second quarter) and fall (fourth quarter) but cold in the winters (first quarter) with annual snowfall, and hot and humid in the summer (third quarter). Therefore, it is expected to see higher intensity of bicycling activities in the second and fourth quarters. The seasonal changes in CaBi trips are illustrated in Figure 2a-2d. The highest numbers of CaBi trips were observed in the second and third quarters of 2013, indicated by the denser lines within each trip number category (yellow, green and red) in Figure 2b and 2c. It is observed that the summer season, despite the hot weather, the number of trips are higher, making the second and third quarters the seasons with highest trips. This could be a result of many factors, such as increased number of tourists in the region in summer months, preference to be outdoors in the summer time. The significant increase in bicycle sharing trips in the Tidal Basin and the National Mall in the third quarter to more than 1,000 trips while it remained lower in the rest of year suggests that recreational trips has a role in the increase. As the major tourist attraction in D.C. with waterfront and public space, these two areas attracted a large number of tourists as well as local residents who used CaBi for recreational purposes and exercising.

One exception to this finding that the warmer weather induces more bikeshare ridership is universities. American University, located in the Northeast D.C., has been an important origin/destination for bicycle sharing trips between Van Ness-UDC Metro and Dupont Circle stations. In each of the first and fourth quarters, more than 100 trips were generated. However, the number of bikeshare trips dropped below 100 trips in the second and third quarters. One explanation could be that university students are major users of Capital Bicycle sharing program and during the summer, the ridership dramatically decreases since students leave the city for the summer.
Despite the seasonal change, the O-D analysis reveals permanent demand for bicycle sharing. Two areas in D.C., Dupont Circle in the Northwest and Capitol Hill to the east of the Capitol Building, had high bicycle sharing ridership around the year. Dupont Circle is home to embassies, offices and restaurants. It also has hotels and high-end apartments converted from historic row houses. As the most vibrant district in the city, Dupont Circle has attracted young professionals and artists who are opt to outdoor activities. Similarly, Capitol Hill is the largest historic residential neighborhood with mixed-use characteristics. Due to its proximity to the Union Station, it gradually introduces more office spaces into the neighborhood. The Eastern Market has been a destination for both tourists and local residents for fresh goods and community events. Large CaBi ridership in Dupont Circle and Capitol Hill in all four quarters demonstrates a lasting demand in residential and mixed-use historic areas.
Figure 2a–2d. Capital Bikeshare Trips O-D Pattern, The 1st, 2nd, 3rd, and 4th Quarter of 2013.
(Data source: Capital Bikeshare website)
(Note: To get the best display, we only show O-Ds with more than 100 trip links.)

4.3 Summary of O-D Analysis

The O-D analysis leads to several important findings about the Capital Bikeshare program users’ biking behavior. First, all maps point out the bikeshare trips’ distance range. In 2013 the third quarter, for frequent bikeshare trips (defined by links with more than 100 trips per quarter), the trip (Euclidean) distance range from 0.11 mile to 3.1 miles. The shortest trips were made in the Crystal City and the longest one were from American University to Dupont Circle. The majority of trips are between 0.62 and 1.24 miles. These findings from O-D analysis are consistent with survey results. The 2013 Customer Survey showed that bikeshare members travel much shorter distances to work than other commuters.

Second, as more CaBi docking stations have been installed, trips followed. The number of trips vary by season, but still a lot trips are made in the first and fourth quarters which it is cold and snowy in D.C. region. The O-D analysis demonstrates that there is a high demand for bike share program, and the service the CaBi program offers meets this demand well.

Third, O-D maps showed that being proximate to Metrorail station may increase bikeshare ridership. On one side, six out of seven areas with the most CaBi ridership have Metrorail stations nearby. On the other, new docking stations in Virginia were followed by trips made from nearby residential area to Metrorail station immediate areas.

5. Regression Analysis

To quantitatively measure the Cabi’s impact on Metrorail ridership, a regression analysis is conducted in this paper. Previous studies found that rail transit ridership results from three groups of factors: (1) transit service level (2) socio-demographics, and (3) built environment. However, as mentioned earlier, few studies incorporated bicycle sharing facilities as a factor in the analysis. The goal of our research is to provide an additional discussion on the effects of Cabi on transit ridership.

The study area covers the National Capital Region, which also encompasses the Metro service region. Metrorail and Metrobus serve a population of 5 million within a 1,500 square-mile area. The transit coverage areas consist of the District of Columbia, the suburban Maryland counties of Montgomery and Prince George’s and the Northern Virginia counties of Arlington, Fairfax and Loudoun and the cities of Alexandria, Fairfax and Falls Church. Overall, 45 percent of employment working in the center core and parts of Arlington County uses Metro transit. Metro system delivers 1.2 million customer trips daily, which anchors the region’s growth and economic competitiveness (14). There are five lines and a total of 86 stations are included in our analysis (Figure 3).
FIGURE 3. Capital Bikeshare Docking Stations and Metrorail Stations

5.1 Data

Data are grouped into four categories: transit services, CaBi ridership, built environment, and socio-demographic characteristics. Table 1 listed our variables for each category, variable description, sources, and available geography. There are five major data sources: transit service variables are obtained from the WMATA. Transit connectivity index is gathered from the NCSG data inventory (16). Capital Bikeshare data are obtained from DDOT and CaBi website. Station built environment data are collected from the Smart Location Databased (SLD). SLD was developed by the Environmental Protection Agency’s (EPA) to address the growing demand for nationwide data and tools that are related to built environments and travel behavior. It summarizes several demographic, employment, and built environment variables at the Census block group level. The commonly cited “D” variables were calculated, including: density, land use diversity, design, access to destinations, and distance to transit (15). In addition, socio-demographic variables are gathered from the U.S. Census. We used ¼ mile buffer to identify the station catchment area. Detailed data manipulation process was discussed in next section. Table 2 present the descriptive statistics of all the variables that we tested.
### TABLE 1 Data category and sources

<table>
<thead>
<tr>
<th>Category</th>
<th>Variables</th>
<th>Description</th>
<th>Data source</th>
<th>Geography</th>
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</thead>
<tbody>
<tr>
<td><strong>Transit service</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Transit ridership2013</td>
<td>Average Daily boardings of walk or bike as egress and access modes</td>
<td>WMATA, 2013</td>
<td>station</td>
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<tr>
<td></td>
<td>Park-and-ride</td>
<td>1, transit station has Park-and-ride facility; 0, otherwise</td>
<td>WMATA, 2013</td>
<td>station</td>
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<tr>
<td></td>
<td>ParkingUsage2013</td>
<td>Usage of WMATA-owned parking facilities</td>
<td>WMATA, 2013</td>
<td>station</td>
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<td></td>
<td>BusStops</td>
<td># of bus stops in transit catchment area</td>
<td>GTFS, 2014</td>
<td>location</td>
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<tr>
<td></td>
<td>TPHPeak</td>
<td>Number of trains in both directions in AM peak</td>
<td>WMATA, 2013</td>
<td>station</td>
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<td></td>
<td>Terminal</td>
<td>1, station is a terminal station; 0, otherwise</td>
<td>WMATA, 2011</td>
<td>station</td>
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<td></td>
<td>Transit connectivity</td>
<td>Composite index including transit routes, coverage, speed, capacity, urban form, etc</td>
<td>NCSG 2010 (16)</td>
<td>station</td>
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<td><strong>Bicycle sharing Program (¼-mile buffer)</strong></td>
<td>B2013</td>
<td># of CaBi bicycle sharing stations in transit catchment area</td>
<td>DDOT, 2013</td>
<td>location</td>
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<td></td>
<td>BR2013</td>
<td>CaBi Bikeshare ridership in transit catchment area</td>
<td>CaBi and DDOT, 2013</td>
<td>location</td>
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<tr>
<td></td>
<td>B13</td>
<td>1, transit station has bikeshare facility; 0, otherwise</td>
<td>DDOT, 2013</td>
<td>location</td>
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<tr>
<td><strong>Station built environment (¼-mile buffer)</strong></td>
<td>Density</td>
<td>Housing density, Population density, employment density</td>
<td>SLD, 2012</td>
<td>Block group</td>
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<td>Employment mix index</td>
<td>8-tier Entropy employment mixture index</td>
<td>SLD, 2012</td>
<td>Block group</td>
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<td></td>
<td>Street network connectivity</td>
<td>Number of intersections around station</td>
<td>OSM, 2013</td>
<td>Location</td>
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<td>Centrality</td>
<td>Index of block group working age population accessibility relative to max CBSA accessibility</td>
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<td>Block group</td>
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<td>Auto30tq/transit45tq Regional Job Accessibility</td>
<td>Number of jobs that can be accessed within 30 minutes by auto or 45 minutes by transit</td>
<td>NCSG, 2012</td>
<td>Station</td>
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<td>Pblack</td>
<td>Percent of black population of the block group in which Metrorail station is located</td>
<td>American Community Survey (ACS), 2007-2011</td>
<td>Block group</td>
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</table>
demographics

(% mile buffer)

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<th>Variables</th>
<th>Description</th>
<th>Source</th>
<th>Scale</th>
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<td>ACS, 2007-2011</td>
<td>Block group</td>
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<td>PHispanic</td>
<td>Percent of Hispanic population of the block group that Metrorail station is located</td>
<td>ACS, 2007-2011</td>
<td>Block group</td>
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<tr>
<td>Ppoverty</td>
<td>Percent of household under poverty</td>
<td>ACS, 2007-2011</td>
<td>Block group</td>
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<td>Medianincome</td>
<td>Median income of the block group in which Metrorail station is located</td>
<td>ACS, 2007-2011</td>
<td>Block group</td>
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<tr>
<td>Pct_a0o</td>
<td>Percent of household without a vehicle</td>
<td>SLD, 2012</td>
<td>Block group</td>
</tr>
<tr>
<td>householdsQ</td>
<td>Number of households in transit catchment area</td>
<td>ACS, 2007-2011</td>
<td>Census tract</td>
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1) Transit Service Variables:

Transit ridership: WMATA provided average weekday ridership from fare gates for September 2013, by 4 time periods (AM peak, PM peak, mid-day, and evening) of all metro lines. These are then split out by access/egress modes, using percentages from WMATA 2012 Rail Passenger Survey. Walking/biking modes ridership was used as the dependent variable.

ParkingUsageSept2013: The number of daily parking transactions at WMATA-owned parking facilities at certain transit stations, from the WMATA fare system. System-wide totals should be around 50,000 per day. Only 42 Metrorail stations have paid parking. Due to the skewness of the data, a parking dummy variable was also created as an interactive term to test the interaction between parking facilities and the number of households within station catchment areas.

BusStop: The General Transit Feed Specification (GTFS) of WMATA system was converted to transit lines and stops in ArcGIS. The number of bus stops within a ¼-mile buffer of Metrorail stations were calculated.

TPHPeak: Trains per hour that a customer can board at the AM peak hour, averaged by both directions and metro lines.

Transit connectivity index: a composite index of the overall transit service level. This measurement incorporates a graph theory to quantitatively determine the performance of large-scale multimodal transit networks at the node, line, transfer center, zone level by integrating routes, schedules, socioeconomic, demographic, and spatial activity patterns (16). The node level index was used in this analysis.

2) CaBi Variables
B2013: CaBi data includes bike station, launch year, location, dates and time of the trips, trip origins and destinations. B2013 is the number of CaBi stations of year 2013 within the transit station catchment areas.
BR2013: number of bike trips originates from CaBi bicycle sharing stations.

3) Built Environment Variables

**Density**: population, household and employment density data at the block group level are gathered from the SLD dataset. Area allocation method is used to merge the data to the 1/4-mile buffer transit catchment area. Densities of population, households, and jobs within the area of the station catchment areas are calculated.

**Employment mix**: 20 industry types are considered in this study. This measures how evenly different industries is distributed within the station catchment areas.

The index is calculated as follows:

\[
\text{Employment mix index} = \frac{(-1)/\ln(n)}{\sum_{i=1}^{n} p_i \ln p_i}
\]

Where,

- \( p_i \) is the percentage of industry \( i \) of the total employment and \( n \) is the total number of different industry types.
- \( n \) is the number of observed industry types. The index ranges from 0 (homogeneous industry) to 1 (most mixed). Data were gathered from LEHD 2012.

**Street network connectivity**: the number of intersections within the transit catchment areas. Street network data were obtained from the Open Street Map (OSM) database.

**Centrality**: Centrality is a relative accessibility index. It is calculated by taking the ratio of Job45i score for each block group to the max score of the Census Core-based Statistical Area (CBSA).

**Auto30tq and transit45tq**: A gravity-based accessibility measure is used to define accessibility from a zone to all other zones. The gravity-based accessibility measure provides accurate estimates of the accessibility of zone \( i \) to opportunities in all other zones in the region, where fewer and/or more distant opportunities provide diminishing influences. Accessibility measure for zone \( i \) in a region with \( n \) TAZs \( (i = 1, 2, ..., n) \), \( A_i \), is represented as a function of number of opportunities in zone \( j \) \( (j = 1, 2, ..., n) \) and impedance function between zones \( i \) and \( j \) as follows:

\[
A_i = \sum_{j} O_j f(C_{ij})
\]

where

- \( A_i \) accessibility for TAZ \( i \);
- \( O_j \) number of relevant opportunities in TAZ \( j \);
- \( C_{ij} \) travel time or monetary cost for a trip from TAZ \( i \) to TAZ \( j \);
- \( f(C_{ij}) \) is the impedance function measuring the spatial separation between TAZ \( i \) and TAZ \( j \); The impedance function, \( f(C_{ij}) \), is an indicator of the difficulty of travel between TAZ \( i \) and TAZ \( j \). A commonly used mathematical formula of the impedance function \( f(C_{ij}) \) is based on
the theoretical work of Wilson (1971), and is expressed as $f(C_{ij}) = \exp(-\beta C_{ij})$, where $\beta$ is an empirically calibrated parameter. The travel impedance data were obtained from MSTM 2012. Employment data that were used to represent the opportunities in TAZ $j$ in calculating accessibility were obtained from LEHD 2012.

4) Socio-demographic Variables

Median household income: Previous literature suggests that low-income households tend to rely more on transit than higher-income households. Median income is available at the block group level then merged to Metrorail station catchment area.

Racial composition: For each race, the number of population is divided by the block group’s total population. White, African American, Asian, and Hispanic population percentage were calculated. The ACS 2007-2011 5-year estimate is the data source.

Percent of household without a vehicle: ACS reported the number of owner-occupied housing units and the number of renter-occupied housing units without any vehicle. The total number of housing units without a car is then estimated to the household by EPA. EPA SLD is the data source for this variable.

Percent of individuals below poverty line: The number of individuals in poverty status in the past 12 months is divided by the total population in the block group. The ACS 2007-2011 5-year estimate is the data source.

### TABLE 2 Descriptive statistics of WMATA stations

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
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<td>Transit Ridership2013</td>
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<td>4823.82</td>
<td>5310.97</td>
<td>122</td>
<td>24234</td>
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<tr>
<td>Park-and-ride</td>
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<td>0.41</td>
<td>0.49</td>
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<tr>
<td>ParkingUsage2013</td>
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<td>1116.1</td>
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<td>5324.07</td>
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<td>16.43</td>
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<td>96</td>
</tr>
<tr>
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<td>0.31</td>
<td>0</td>
<td>1</td>
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<tr>
<td>TransitConnectivity</td>
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<td>1.83</td>
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<td>B2013</td>
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<tr>
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<td>354.0881</td>
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<tr>
<td>B13</td>
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<td>0.50</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Huden</td>
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<td>11.29</td>
<td>8.01</td>
<td>1.95</td>
<td>38.69</td>
</tr>
<tr>
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<td>12.53</td>
<td>3.66</td>
<td>64.21</td>
</tr>
<tr>
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<td>66.77</td>
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<td>250.93</td>
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<tr>
<td>Empmix</td>
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<td>0.12</td>
<td>0.18</td>
<td>0.76</td>
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<tr>
<td>StreetConnectivity</td>
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<td>8.93</td>
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<td>centrality</td>
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<td>0.14</td>
<td>0.035</td>
<td>0.58</td>
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<tr>
<td>Auto30tq</td>
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<td>186647.60</td>
<td>196473.90</td>
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<tr>
<td>Transit45tq</td>
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<td>90495.70</td>
<td>104859.20</td>
<td>0</td>
<td>648208</td>
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</table>
5.2 The Ordinary Least Squares Regression Analysis

We developed multiple regression models to test the impacts of bike-share programs on transit usage. Each measurement is discussed in details below.

Ordinary Least Square (OLS) regression model is a typical practice to estimate what and how the independent variables affects transit ridership (17). In this paper, we tested the models using different combinations of independent variables. Many interactive terms were tested in the model to capture the interaction of transit connectivity, number of households, and parking usage. We also tested the log-log form regression model. After model validation by checking the multicollinearity and heteroskedasticity, some independent variables were eliminated from the model. Table 3 presents the final full model and parsimonious model specifications. Parsimonious model only includes the significant variables and can provide simplified results. The results are not very different from the full model, which indicate that the final model is robust. The adjusted $R^2$ of parsimonious model indicates that roughly 82 percent of the variation in the transit boardings of WMATA stations is explained by all the variables in combination.

As Table 3 shows, in the full model, Capital Bikeshare program ridership, trains-per-hour, employment density, number of bus stops, and median income are statistically significant variables at the 90% confidence level and have expected signs. Among all, Capital Bikeshare station ridership was found significantly associated with Metrorail ridership. Results show that a 10% increase in bicycle sharing ridership will lead to 2.8% increase in transit ridership. This result is crucial for the current TOD development. With easier access to transit station, bikeshare program will provide higher access to “first mile” and “last mile” of transit. Results of other independent variables are consistent with previous studies that transit service, built environment, and socio-demographic characters in rail transit station areas affect ridership. In terms of impact magnitudes, trains-per-hour is the strongest predictor: 10% increases in transit frequency will lead to 4.9% increase in transit boardings. Both employment density and bus connection have positive impacts on transit boardings. While many TOD planning practices tend to focus on residences, this result suggests that employment concentration at the transit station areas has even stronger impacts on transit ridership. The TOD strategies should focus on placing more employment around transit stations, in addition to more housing. Bus connection is statistically significant and positive, which suggests that we can provide easy bus egress and access connections to attract higher transit ridership. Therefore, multimodal access combining different modes is important to increase transit ridership. Median income has a positive impact on transit boarding, indicating that a relatively affluent neighborhood around Metrorail station may increase transit patronage. A 10% increase in median income of the neighborhood will lead to 0.4% increase in transit ridership. This result indicates that Metro captures more transit riders than transit dependents. This result suggest that TOD-related policies should also address the
social equity issues that how public transit policies can affect low-income and minority urban residents.

It is also interesting to see that transit connectivity index, number of households within \( \frac{1}{4} \) mile buffer, and street connectivity are not significant. These variables bear further discussion. We hypothesize that these variables should have positive relationships with transit ridership. We created some interaction terms of transit connectivity and number of households to see how these two variables interact with each other. When we focus on transit ridership limited to only walking and biking egress and access modes, parking usage doesn’t play an important role in estimating ridership. The interactions of spatial configuration of households, transit connectivity and street connectivity are very complicated. The majority of the households concentrate in suburbs while the transit connectivity and street connectivity are high in the D.C. core. The high performance transit service attracts people from the suburbs to commute. Lumping all the information may skew the results. We can disentangle this complexity by stratifying transit ridership by access/egress modes and by grouping the stations based on location (urban core or suburbs). Since such data are still lacking, we can explore this in the future research.

### TABLE 3 Regression models estimating WMATA stations ridership

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<td>1.0</td>
<td>0.000</td>
<td>4.33</td>
<td>0.72</td>
<td>0.000</td>
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<td>logBR2013</td>
<td>\textbf{0.28}</td>
<td>0.06</td>
<td>\textbf{0.000}</td>
<td>0.26</td>
<td>0.05</td>
<td>0.000</td>
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<td>logtransitConnectivity</td>
<td>0.04</td>
<td>0.09</td>
<td>0.669</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>logTPHPeak</td>
<td>\textbf{0.49}</td>
<td>0.20</td>
<td>\textbf{0.025}</td>
<td>0.49</td>
<td>0.19</td>
<td>0.018</td>
</tr>
<tr>
<td>logHouseholds000025miles</td>
<td>0.03</td>
<td>0.08</td>
<td>0.69</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Logempden</td>
<td>\textbf{0.14}</td>
<td>0.06</td>
<td>\textbf{0.018}</td>
<td>0.16</td>
<td>0.05</td>
<td>0.001</td>
</tr>
<tr>
<td>logBusStops</td>
<td>\textbf{0.21}</td>
<td>0.12</td>
<td>\textbf{0.096}</td>
<td>0.20</td>
<td>0.11</td>
<td>0.081</td>
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<td>logIntersectionQ</td>
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<td>0.12</td>
<td>0.301</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>logmedianincome</td>
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<td>0.01</td>
<td>\textbf{0.003}</td>
<td>0.04</td>
<td>0.01</td>
<td>0.001</td>
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<tr>
<td>Adjusted R²</td>
<td>0.81</td>
<td>0.82</td>
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<td></td>
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<td></td>
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</tbody>
</table>

*Notes: in the full model, significant independent variables are labeled in bold.

### 6. Conclusion and Policy Implications

Bicycle sharing programs has experienced rapid growth in North America, providing affordable, convenient, and sustainable travel option with various benefits. One of the major benefits of bicycle sharing program is the positive impact on transit ridership. In this paper, the results from the O-D analysis suggest that Metrorail stations have been important origin/destination of Cabi trips. Six out of seven bikeshare stations with more than 500 trips are close to the Metrorail stations. The regression analysis shows that the increase in trips generated from bikeshare stations is associated with higher transit ridership.

Evidence from this study suggests several key policy implications:

First, it begins by answering the question on how to expand bicycle sharing program in both urban core districts and suburban areas. In urban centers, such as D.C. downtown, a large number of bicycle sharing trips are generated in denser, mix-used, vibrant historic districts well
served by rail transit. Therefore, adding bicycle sharing stations in TOD areas and densify station network are strategies for cultivating successful program in urban areas. In terms of expanding CaBi stations in suburban areas, there are twofold considerations. The O-D analysis demonstrated the success of adding new stations in Alexander and Arlington, VA, thus the demand in suburbia for bicycle sharing. However, both the O-D analysis and regression analysis illustrate that being proximate to transit stations is the key role for the CaBi program’s success in these two areas. Therefore, the co-location of major transit stations and Cabi stations should be prioritized when considering expanding CaBi program to suburbs in the future.

Second, in terms of analysis framework for modeling and predicting bicycling/bicycle sharing use, transit usage shouldn’t be neglected. After reviewing the current literature, we have noticed that a lot research on factors of successful bicycle sharing system failed to address the proximity to transit stations. For example, in exploring urban features’ effect on bicycle sharing ridership, Zhao, Deng and Song (2014) did not include any variable on docking stations’ relative location to transit stations (18). The interaction between bicycle sharing program and transit could also be used to seek good bikeshaing station locations. Distance to transit stations have not been widely accepted as a criterion while socio-demographics features have been given a lot attention. For example, in finding potential locations for bicycle sharing program in Richmond, VA, Bryant considered population density, employment density, retail and commercial activity, tourist attractions and recreation areas, and residential areas (19). This analysis could be further enhanced if transit station and ridership information could have been added.

Third, the results presented in this paper focus on exploring the bike share usage and interactions of bikeshare program and transit ridership. The objectives of this study was to develop an understanding of how bike-share program evolve and whether this evolvement will have some impacts on increasing transit use. The regression results show that the bikeshare program has begun to alter people’s travel behavior by providing options to access public transit. As the bikeshare programs in D.C. continues to increase, so do a new landscape emerges. We will keep exploring its remarkable ability to attract modal share by incorporating additional data and advanced modeling efforts.

Acknowledgement

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References

\footnote{Job45: A Measure of the number of jobs accessible within a 45-minute commute time. Centroid of each block group is taken as travel origin. A O-D travel time matrix based on Network Analysis using NAVTEQ street database was used to identify block groups accessible in 45 minutes. The sum of jobs in all accessible block groups then weighted by travel time impedance.}