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REDISTRIBUTION OF THE CHICAGO'S DIVVY BIKE-SHARE STATIONS USING  
LINEAR OPTIMIZATION MODEL: AN EQUITY PERSPECTIVE

by

Md Mehedi Hasan

A thesis submitted to the Graduate College  
in partial fulfillment of the requirements  
for the degree of Master of Arts  
Geography  
Western Michigan University  
June 2016

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## REDISTRIBUTION OF THE CHICAGO'S DIVVY BIKE-SHARE STATIONS USING LINEAR OPTIMIZATION MODEL: AN EQUITY PERSPECTIVE

Md Mehedi Hasan, M.A.

Western Michigan University, 2016

Public bike-share infrastructure has the potential to play an important role in sustainable transport systems by enhancing environmental, public health and economic outcomes. In this research, the temporal distributive equity of bike-share infrastructure was examined for initial (300) and expanded (477) bike-share stations across the city of Chicago using eleven accessibility indices. The eleven accessibility indices were calculated using counts of bike share stations within neighborhood boundaries, buffered catchment areas and network distances. By examining the accessibility indices, it was recommended to re-distribute the bike share stations for optimal allocation across the different economic hardship categories. In this study, Linear Optimization Model was configured for the re-distribution of bike share stations. The number of expanded bike share stations was used to limit the value for re-distributed stations. Two LP models were calibrated by using the composite accessibility, which was essentially a combination of nine suitability indices. A general comparison was revealed with some statistical analysis to check the significant relationship between the models. LP model with constraining the categorical economic hardship zones was selected as the best model in terms of equitable re-distribution of bike-share stations.

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Md Mehedi Hasan

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## CHAPTER I

### INTRODUCTION

#### 1.1 The Problem

As an important part of infrastructure, transportation network plays a decisive role in urban development. Now a days, extensive growth in road transportation with motor vehicles is expedited in developing and emerging economies. Therefore, various environmental and infrastructural problems associated with transportation are emerging at an alarming rate. So, sustainable and low-carbon modes with avoidance of motorized transportation is imperative for our society (Cavill, & Watkins, 2007). Public transportation with cycling and walking can be a viable option to mitigate the traffic related problems such as traffic jams, pollution, expensive road infrastructure, accidents, and congestion (Jäppinen, Toivonen, and Salonen, 2013).

Indeed, bicycling has become an increasingly popular method of travel and many people use bikes as their primary means of transport (Horton, Rosen, and Cox, 2007). Bike-sharing system is one of the effective way to manage and ride the bicycles across the city. It is an innovative transportation system by considering short distance travel with bicycles by self-serving picking and returning systems. Bike-sharing systems also help actively in distribution of bikes with more efficient way. The increased use of public bike-sharing systems has lessened the environmental impacts of our transport activities. Bike-sharing systems are considered as a viable part of transport infrastructure for the 21st century (Lin

and Yang, 2011). Gilles Vesco, Vice President of Greater Lyon, stated that “There are two types of mayors in the world: those who have bike-sharing and those who want bike-sharing” (Brakeman, n.d.). Since the city’s bike-share programs are widely accepted by the user’s of Greater Lyon, the above statement made a strong support from the government perspective as well. The statement provides evidence that there has been thought of constructing bike-sharing systems in each town and city around the countries of Europe.

However, equitable distribution of bike-share systems is a big factor in determining the degree of benefits that is shared by diverse communities from transportation equity perspective. Many of the bike-sharing infrastructures are not equitably distributed over the cities and towns, especially from the point of view of different economic hardship groups. For example, in 35 public bike-sharing systems across the USA, about 75 percent of all stations were located in areas with low economic hardship (Smith, Oh & Lei, 2015). In the city of Chicago, in particular about 67% of the bike-share infrastructure is located in lowest economic hardship zones.

The purpose of this study was to examine how bike-share infrastructure could be equitably re-distributed using the Chicago’s DIVVY bike-share as a case study. The study explored that how the equitable distribution which was defined in terms of accessibility by different economic hardship categories to the current DIVVY bike-share stations, could be achieved using the linear optimization technique. Specifically, this thesis has three objectives

1. To compute the different accessibility indices for the census tracts to bike share stations for different economic hardship groups;
2. To examine the result of accessibility on the basis of equity;

3. To use the linear optimization model for spatially redistributing the DIVVY stations in improving equitable distribution for the planning process.

## 1.2 Conceptual Framework

Transportation equity refers to the fair and appropriate distribution of impacts on the environment. Bike-sharing has significant equity impacts on transportation planning decisions required of decision makers in municipalities at various spatial scales. Transportation equity is measured in respect to various types, impacts, measurements, and categories of people (Litman, 2015). Types of equity may be considered with horizontal, opportunity, market, vertical with economic criteria, and vertical with need basis. Horizontal equity refers the equal distribution of resources regardless the size or the different groups (Congestion Pricing Equity-Definition and Factors, n.d). In this study, horizontal equity is considered in broad sense for measuring the equity on bike share stations for different socio economic categories.

Income class is an important indicator for categorizing of people in evaluating equity variables. Economic hardship categories based on poverty rates for income class can be an effective variable for equity evaluation (Income-Based Equity Impacts of Congestion Pricing, n.d). User cost is an important factor which is considered as an impact category of transportation equity. Other type of impact categories are included with public facilities, service quality, externalities, and economic perspective in regulatory basis (Litman, 2015).

Transportation impacts can be measured in terms of accessibility that can affect equity analysis (Litman, 2003a). Accessibility is used to measure the spatial access from origin to destination. Different services, e.g. bike-share stations, bus stations, train stations



etc. can be used as the destination for the accessibility measurement from various economic groups. Accessibility is a key driver to equitable access of services for all socio economic groups (Foth et al, 2013). One of the main goals of bicycle Sharing Systems (BSS) have been to enhance accessibility by walking and cycling from the census tracts into equitable urban transportation systems (Corbin, 2015).

Redistribution of the objects for gaining optimal allocation with using linear programming and GIS tools are now widely available. Better implementation and integration of spatial data analysis is achieved by using linear model for obtaining suitable sites allocation (Guerra and Lewis, 2002). Optimization with cost-effective allocation of bikes in the bike-share stations has been implemented by using linear optimization model for years (Vogela, Ehmkeb, & Mattfelda, 2011). Integration of linear optimization and ArcGIS has opened a wide window for particular transportation planning purposes.

### 1.3 Study Area

The city of Chicago is considered as one of the most prominent cities in USA for use and promotion of bike-share stations (CDOT, 2012 and Pucher et.al, 2011). As the city of Chicago already has an enriched bike share stations, it is considered for the case study of this research. There is a rich history of bike sharing systems for Chicago. In 1963, the Lakefront Trail (LFT) was officially designated the bike path at first and then in 1971, the first on-street bike lane was constructed in Chicago. Later in 1991, the Mayor's Bicycle Advisory Council was created and Bike-2000 Plan was released in 1992. In 2001, Bicycling Magazine named Chicago as the best big city for bicycling in the U.S. In 2004, McDonald's Cycle Center was opened and later in 2006, Bike-2015 Plan was released. In

2011, the first barrier protected bike lane was installed on Kinzie Street, Chicago. In 2012, Chicago was recognized as the 5th most bicycle-friendly city of all cities with more than 95,000 residents (CDOT, 2012).

Chicago city has about 200 miles of on-street bikeways. It is the highest amount of bikeways in any single city in the United States. Additionally, it has about 36 mile of trails with about 12000 racks of bike parking. At present, Chicago has about 300 initial bike-share stations. Besides, an additional 477 stations in total have been proposed for the expanded plan. The Chicago Department of Transportation (CDOT) have announced the name as “DIVVY” for their bike-share systems (Hinds, 2013).

Several programs including educational with encouragement and enforcement for increasing bike-share stations have already been accomplished by the city Mayor of Chicago. These programs led to a tremendous increase in using bike-sharing systems throughout the various economic groups regardless of the equality usually associated with different economic hardship categories. The Chicago DIVVY bike-share system was therefore a good choice for this study.

#### 1.4 Methodology

Data were collected mostly from secondary sources, e.g. a municipal, state, federal sources and Chicago data portal website. Economic Hardship categories were calculated based on six inter-related component variables that is described in detail at methodology chapter. Arc Map 10.2 was used for calculating all of the counts and network distances for the accessibility indices. LP Solve IDE software was used to run the linear optimization model. SPSS software was used for statistical analysis as well.

## 1.5 Limitations of the Study

The station capacity information was not available for expanded DIVVY bike-share distribution. Only economic hardship category was considered in this study for exploring the equitable bike share stations. Other indicators were not considered due to the unavailability of the data source. Network distance was not able to calculate for the suitability value of bus stations, since there were large number of data set and that was beyond the capacity to handle by Excel software.

## 1.6 Organization of the Study

The rest of the thesis is organized into eight chapters. Chapter two reviews the relevant literature of the topic. Chapter three describes the detail methodology for this study. Chapter four presents the results of the analysis of the current distribution of (existing and expanded) Chicago DIVVY bike-share stations. Chapter five presents the results of the analysis of accessibility indices of the bike-share stations by different economic hardship groups. Chapters six and seven present the results of the linear optimization model, while chapter eight concluded the summery of the research with major findings and recommendation

## CHAPTER II

### LITERATURE REVIEW

This chapter reviewed the researches related to the topics of this study. Different literatures were reviewed for accessibility analysis with transportation equity perspective, bicycle sharing systems, bicycles as a transport mode, equity with bike-sharing systems, and application of linear optimization on bike-sharing systems in various cities within developed and developing countries. Various reports were studied on GIS based accessibility models, network distance measurement for travel time impedance and equitable transport system performance evaluation.

#### 2.1 Studies Regarding Accessibility Analysis with Transportation Equity Perspective:

Fan, Guthrie, & Levinson (2012), used transportation equity perspective in labor market including low, medium, and high-wage workers to examine the before-after job accessibility, after the opening of the Hiawatha light-rail line in the Twin Cities, Minnesota. Statistically significant gains in accessibility to low-wage jobs were achieved by the study through the proximity to light-rail stations and bus stops. More equitable transit policies were indicated as an outcome of the research.

An analysis of accessibility for different modes using GIS tool was performed for accessing sustainable transportation in London, UK. Employment accessibility was measured for the public and private vehicles including bus, light rail, rail, private car and bicycle. They measured accessibility in terms of generalized cost including monetary and

distance components. Origin-destination cost matrix was computed in Arc Map to calculate the accessibility with a spatial dimension. A number of current and future transport infrastructure scenarios were examined globally in respect to particular destination and across the whole city in the Greater London Authority Area. The result showed the private car as the least cost mode in terms of accessibility with playing a part of successive cost reduced modes in London (Ford et al., 2014).

A study was performed for improving a methodology on accessibility measurement to the cyclists by comparing the actual distance measurement with traditional distance measurement tool using geographic information system. The crow-fly and road network distances were compared within the actual travel distances by some statistical analysis for the city of Southampton, UK. The result showed that the distances measured by crow-fly method had overestimated the accessibility by 30 percent. On the other hand, the road network distance had underestimated the accessibility measurement by almost 3 percent. The combined output of both methods had given a greater level of accuracy in accessibility estimation (Wells et.al, 2007).

The concentrated and scattered manifestations of social exclusion and inclusion were identified through developing a matrix of area accessibility with transport mobility. The study suggested some appropriate policy responses with adaptation of the Amartya Sen's theory of entitlement. Results indicated some spatially and socially differentiated conceptualization of social exclusion which helped to identify policy responses. The critical outcome of the study was the problems of the socially excluded immobile that should not be analyzed in isolation from the socially included mobile (Preston and Rajé, 2007).

A systematic approach of increasing accessibility was discussed with development of the software tool AMELIA in light of the socially excluded people. The approach was implemented for the elderly people of St Albans in Hertfordshire in the Great Britain. AMELIA could be used in the public consultation process. It allowed the public to see the cost-effectiveness of policy actions that was suggested by both the planners and themselves (Mackett, Achuthan, and Titheridge, 2008).

Lepofsky, Abkowitz, and Cheng (1993), established a relationship considering accessibility analysis between geographic information systems for transportation (GIS-T) and spatial analysis in consideration with boundary problems and spatial sampling for alternative representations of geographic environments. Results indicated the enhancing accessibility with removing the boundary obstacles between spatial analysis, GISci, and transportation (Miller, 1999). Another study in application of Geographic information systems for transportation (GISTs) addressed the dynamic management in accessibility for particular incident in transportation hazard analysis. This method was used in several case study areas for the highway operations in California. The result of the discussion helped the decision makers to adopt policy decision to implement emergency plan for transportation hazard analysis. So, the dynamic management in accessibility for the bicycle sharing systems in the transportation is very important.

## 2.2 Studies Regarding Bicycle-sharing Systems:

A GIS based location-allocation model that combines accessibility analysis with a goal of minimizing impedance and maximizing coverage was created for optimizing the location of stations in bike-sharing programs in relation to potential demand (population,

activities and public transport stations) at central Madrid. The study showed that spatial structure of the proposed network played an important role for using bike-share stations. Less improvement was found in the case of accessibility to the bike-share stations in terms of increasing the number of the stations (García-Palomares, Gutiérrez, & Latorre, 2012).

In addressing the design of public bicycle systems, mathematical model was formulated by considering both the user's and the investor's point of view by adjusting the level of service provided to demand coverage, setup costs for bike stations and bike lanes, and travel costs. This study outlined a practical steps required to develop a formal model for incorporating demand variation and accurate estimation of bike inventory levels at rental stations (Lin and Yang, 2011).

A new scheme for a Beijing public bicycle system at China was introduced to connect users to public transit networks through analyzing the reasons of failure of the first generation of the city's public bicycle system. Unreasonable distribution and deteriorated conditions, lacking in safety, and inexplicit policy orientation were found to be the root causes of failure in the Beijing public bicycle systems (Liu, Jia, and Cheng, 2012). So, safety and adequate public policy of the proposed network is essential to consider for introducing the bicycle sharing system.

A global view of bike-sharing characteristics were analyzed by depicting the geographical locations. Demographics and intentions of user groups were used as potential factors for conducting the research in a consistent basis by using data from 38 systems which are located in Europe, the Middle East, Asia, Australasia and the Americas. The classification of bike-shares based on the geographical footprint of route areas and spatial variations in occupancy rates over time was completed by O'Brien, Cheshire, and Batty

(2014). What they called the Geo BI process used the data mining to gain insight into the complex bike activity patterns at stations so as to alleviate imbalance in the spatial distribution of bikes. The reviewed the hypothesis for the study as the usages of bike and customer demand depends on the stations' locations. The data mining process resulted in a better understanding of the system structure and helped support planning and operational decisions for the design and management of bike-sharing systems (Vogel, Greiser, and Mattfeld, 2011).

A comparative study of public bicycle systems throughout the world was completed to understand the infrastructural resources including charging method with technology applications for the implementation effect. Some experiences and lessons for the successful operation of public bicycle systems were identified through a variety of indicators regarding operation mode system (Liu, Shi, and Dong, 2013).

### 2.3 The Bicycle as a Mode of Transport:

Pucher, Buehler, and Seinen (2011) conducted an analysis related to cycling levels, safety, and policies in Canada and the USA over the past two decades combining with data for nine large cities (Chicago, Minneapolis, Montréal, New York, Portland, San Francisco, Toronto, Vancouver, and Washington). They indicated that cycling levels had increased both in the USA and Canada. The study reviewed that spatial variations related to socioeconomic inequality caused the difference in cycling rates.

Putcher et al. (2011) completed a comparative study of cycling levels between Australia's two largest cities (Sydney and Melbourne) which was carried out based on a wide range of statistical datasets, secondary reports, and interviews with a panel of 22



bicycling policy and planning experts. Favorable topography, climate, and accessible road networks as well as more supportive public policies were cited as reasons for increasing (almost double) in cycling levels for Melbourne as compared to that of Sydney (Pucher, Garrard, and Greaves, 2011). An accessibility model could consider the topography and road network and eventually help to establish policy recommendations while taking into access for public opinion.

The experiences and impacts of the combined use of bicycles and public transport for access trips were analyzed for the Netherlands. The introduction of flexible rental bicycles at train stations in Netherlands successfully resulted in a small reduction in car use with a growth in train trips as compared to the introduction of leasing bicycles for egress trips (Martens, 2007). Flexible rental bicycles could be introduced in the bicycle sharing stations by taking necessary steps both from the public and private bicycle transport agencies.

Social scientific research related to cycling has been developed often with consideration of the best way to promote cycling as a positive aspect for urban society. The study called for more research into cycling, and also contributes to a renaissance of cycling as a sustainable practice (Horton, Rosen, and Cox, 2007). Through the calculation of travel distances and analysis for initiating the exercise-based transportation such as cycling or walking, the benefits of using exercise-based transportation was shown in terms of weight loss, oil consumption and carbon emissions reductions in USA. Exercise-based transportation (cycling or walking) is important for all nations (Higgins, 2005). The use of the bicycle as a transport mode is really helpful for health as well as for environmental protection.

Cavill and Watkins (2007) completed an exploratory study of views about cycling through the use of focus groups incorporating members of identified community groups living near the Loop Line, a cycling and walking path in a deprived part of North Liverpool, UK. The paper found that the fear of bicycles being stolen was one of the strongest reported barriers to cycling for young boys of the Loop Line area. Personal safety issues and crime statistics should be considered when planning for the use of bicycle as a transport mode.

#### 2.4. Bicycle and Bicycle-sharing System with Equity:

NACTO (2015) published a paper regarding the equitable distribution of public bike-sharing stations regardless the disparity in different economic groups. The study mentioned that low income people are not considered for the equitable users of the US bike-sharing system. A five to ten minutes walking distance was considered as the key fact for increasing the use of bike-sharing systems with equitable distribution. The service quality needs of low income people must be met up to ensure the equitable distribution. Convenience, station density, and equal spacing from neighborhoods were highly recommended for equitable distribution of bike-share stations.

A study was conducted to explore the existing programs for reducing the barriers to the low-income communities in access to public bike-sharing stations (Buck, 2012). About 20 current and proposed North American bike-sharing systems were surveyed in the study. The existing attempts on those systems for reducing the lower access barrier to the bike-sharing stations were critically examined with survey data. A significant correlation with non-profit agency status was examined by the result of the study regarding the average programs associating with reducing barriers. Different proposals were recommended for

pursuing the programs related to reduce the access barriers to the low-income community for the public bike-sharing stations.

## 2.5 Linear Optimization Method for Bicycle-sharing Systems:

Henderson, O'Mahony, & Shmoys (2015) conducted a study for optimization of the bike-share stations using linear optimization model to rebalance the city-bike of New York City. Both of the routing problems and clustering problems for mid-rush and overnight time was considered in application of linear optimization model. Bike-share system data was used to manage the optimization program effectively. The output of the study was used as a method to operate the NYC bike-share LLC.

A study was performed to optimize the cost-effective allocation of bikes in the bike-share stations by using linear optimization model for the Vienna's "City bike Wien" (Vogela, Ehmkeb, & Mattfelda, n.d.). Trip data for up to two years was used to compute time-dependent origin-destination matrix. Intelligent data analysis by linear programming was conducted to optimize the allocation of bikes. Relocation regimes by linear programming were proved fruitful for Bike-share stations in terms of integrated planning system.

A linear programming algorithm was used with incorporating ArcGIS ground to allocate optimal location considering spatial analysis for wildlife reintroduction by Guerra & Lewis (2002) as an initial experiment of integration of LP (Linear programming) and GIS. An external linear programming solver and Microsoft Excel Solver was used for optimization calculation regarding LP design purposes. ArcGIS was used to convert the optimization solution into map information.

Kumar & Bierlaire (2012) conducted a study about the optimization of location analysis for the vehicle-sharing stations in and around the city of Nice. A linear regression model was built up for showing the relationship between the station location and other dependent variables including socio-economic perspective. Optimization model to locate new stations was run on the basis of attractiveness of the different localities. The outcome of the newly located stations in the study was validated after the real life implementation of the project.

## CHAPTER III

### METHODOLOGY

The study was completed in two phases. The first phase was completely based on comparative analysis using quantitative methods. The second phase was essentially based on the analysis of first phase by applying a linear optimization model. This chapter describes the data and the two phases of analysis that were conducted

#### 3.1 Data

Most of the data for this research were collected from the secondary sources. The detailed transportation route network (bike tracks, local streets, CTA bus and train route etc.) was accessed through Chicago open portal system. DIVVY bike share station (i.e., station and capacity) information, bus stations, L-train stations, recreational destinations (parks), and historical landmarks were also collected from Chicago data portal website.

The census tracts data with economic hardship categories, population, job density, bike and walking commuters to work were collected from US. Census bureau and various personal sources. Economic hardship categories were included with the six inter-related component variables from the 2013 American Community Survey (ACS), namely: (1) unemployment, defined as the percent of the civilian population over the age of 16 who were unemployed; (2) dependency, the percentage of the population that are under the age of 18 or over the age of 64; (3) education, the percentage of the population over the age of 25 who have less than a high school education; (4) more than 30 percent of income,

calculated as gross rent or owner costs as a percentage of household income in the past 12 months; (5) crowded housing, measured by the percent of occupied housing units with more than one person per room; and (6) health insurance, the percent of civilian non-institutionalized population of 18 years and over with no health insurance coverage. These six variables were selected because each of them represent distinct dimensions of economic performance while collectively encompassing a broad range of socioeconomic conditions.

The following Figure 1 depicts an overall organogram of the research methodology.

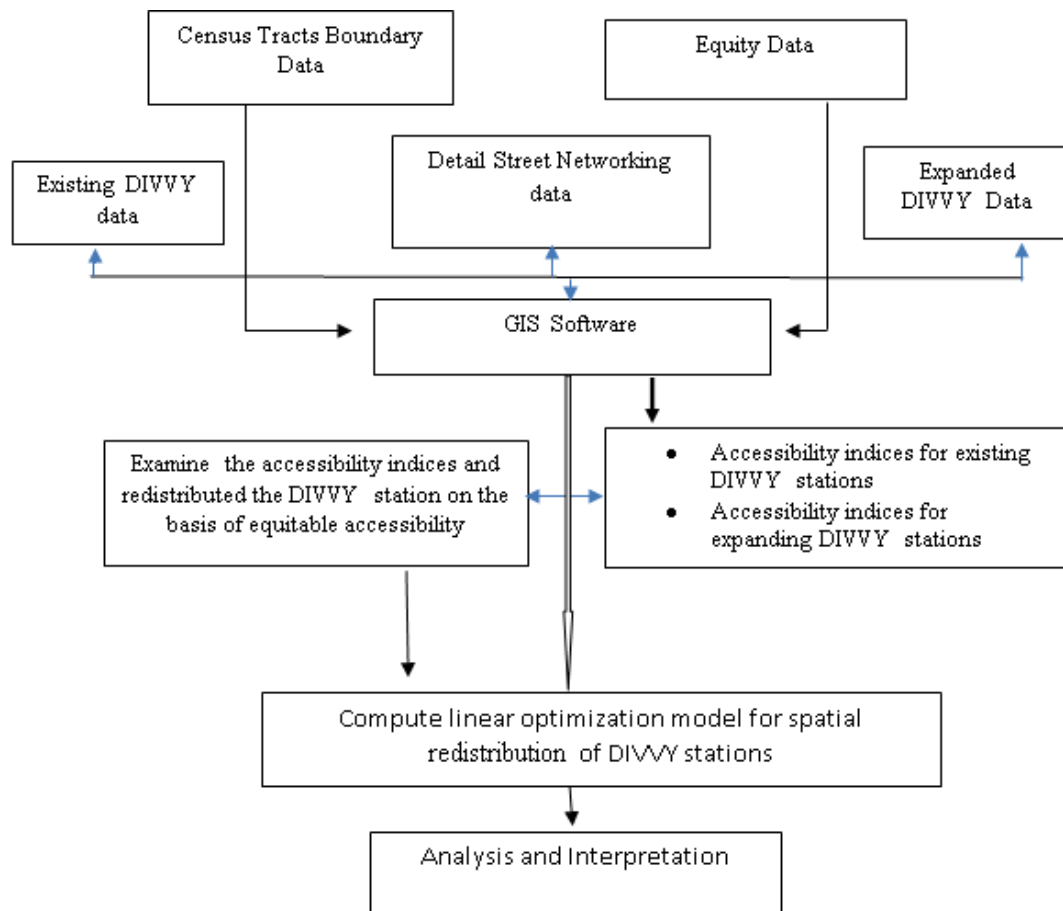


Figure 1: Organogram of the research

## 3.2 Analysis of Phase One

In phase one, all of the necessary data (DIVVY stations, Street networking, and census tracts data) were put into the software (ArcGIS) for configuring and calculating accessibility indices. All of the accessibility indices were examined in respect to equity perspective.

### 3.2.1 Accessibility Indices Based on Count Analysis

Accessibility can be measured in various representational frameworks. It can be calculated in different ways. Accessibility can be calculated from a zone based (census tracts) or a point based location in an aggregate spatial framework (Kwan et.al, 2003). Accessibility index based on counts within the census tracts is primarily considered as an important method of accessibility analysis on spatial network (Salze et.al, 2011). Counts of opportunities within a census tract centroid or buffer area is the most frequently used indices for measuring primary accessibility (Charreire at.el, 2010). However, raw counts could not be considered for accurate measurement of accessibility because of edge effect or boundary problem in spatial analysis (Miller, 1999). Besides, accessibility based on just the counts are basically the summation of the points which made the problem of modifiable area unit for spatial context (Kwan, 2012).

DIVVY stations within census tracts boundary: Accessibility to the bike share stations from each census tract was determined initially by a count of bike share stations within each census tract boundary. Spatial join was performed with initial (existing) bike share stations to the census tracts boundary in ArcGIS 10.2. After that, the attribute table was exported to get the number of stations against each census tracts. The same procedure

was done for the counting option for expanded bike share stations to each of the census tracts.

DIVVY stations within quarter, half and one mile buffer from centroid of census tracts: At first, the centroid was calculated by using the data management tool (feature to point) on ArcGIS 10.2. Then, quarter, half and one mile buffer was created from the centroid of each census tract. After that, the DIVVY stations were counted against each buffer zone through the spatial join in Arc Map. The counts of DIVVY stations were used as the initial accessibility measurement for each of the census tracts towards the stations. This procedure to create buffer zone for computing accessibility was repeated for both initial and expanded bike share stations.

DIVVY stations within quarter, half and one mile buffer from census tracts: quarter, half and one mile buffer was created separately from each of the census tract boundary in ArcGIS 10.2. The bike share stations were counted against each of the buffer zone by spatial joining in Arc Map to measure the accessibility. This was done for both initial and expanded bike share stations of Chicago.

### 3.2.2 Accessibility Indices Based on Network Distance

Accessibility can be computed with the capabilities offered by Geographic Information System (GIS) and spatial network (Miller, 1996). Euclidian distance (as crow-flies) and road-network distance methods are usually implemented by the authorities for measuring walking and cycling accessibility (Well et. al, 2007). Accessibility based on network-distance is an important application supported by ArcGIS software (Ford et. al, 2015).



The distance decay function using gravity model can be an important implementation of measuring the accessibility on spatial network (Iacono, Krizek, and El-Geneidy, 2008). Particular destination place with the particular mode choice (walking, bicycling etc) is preferred for distance decay function. Accessibility with distance decay function is basically considered for the equity perspective with the concept of non-motorized vehicles (walking, cycling etc.) (Litman, 2003a). The distance of quarter mile is assumed as the thumb rule for most destinations by walking from a particular origin (Untermann, 1984). User cost impedance for distance decay function is typically measured by travel time from origin to destination places. Travel time is usually achieved by the network link distance within constant travel speed (Ford et. al, 2015; Litman, 2015). In this study, a constant walking speed is maintained for measuring the travel time from the network distance.

The network dataset was created within the network analyst toolbar with an extension of Network Analyst for ArcGIS 10.2. All types of streets including the local accesses road is considered in the network dataset. The network distance was measured within an Origin to Destination (O-D) matrix. Origins were considered as the centroid of census tracts and the destinations were the bike-share stations. O-D matrices were computed for the quarter mile, half mile, and one mile cut-off walking distance and as well as computed for no cut-off distance.

The accessibility was measured in this study by using gravity based measurement. The cost was derived by the distance decay function. The following gravity based measurement (Hansen, 1959) was considered in this study for computing accessibility.

$$A_{ik} = \sum W_{kj} f_{ij}$$

Where,  $i$  was the origin and  $j$  was the destination.  $k$  was the number of destinations per origin (Centroid of census tracts).  $A$  was the total accessibility of each census tract for different destinations (bike share stations).  $W_{kj}$  was the sub weight of  $k$  number of destinations ( $j$ ). In this study, the weight was considered equally for every destinations. Since the station capacity data for expanded DIVVY stations were not available, individual weight for the stations were not considered in this study.  $f_{ij}$  was the cost of travel for the impedance in the distance decay function. Where,

$$f_{ij} = \exp(-b * C_{ij})$$

The cost ( $C_{ij}$ ) was considered as the travel time in minutes for walking distance from centroid of census tracts to bike share stations. The time taken for each link was calculated by considering the average walking speed of 3.1 miles per hour (Walking, n.d). The time was calculated as minutes per link distance. The value of  $\beta$  (Beta) was taken as (-0.1) for walking (Iacono et al., 2008) in calculating the accessibility within the distance decay function for this study.

### 3.3 Analysis of Phase Two

The second phase was based on the computation and analysis of linear optimization models. Spatially redistributed bike-share stations were examined by optimizing the linear programming with ArcGIS. In addition to phase two, in-depth interpretation and analysis for the outcome of the linear model were advanced with the research.

### 3.3.1 Calculation of Composite Accessibility for Linear Optimization (LP) Model

Seven suitability indices were considered for calculating the composite accessibility. The suitability indices were calculated through distance decay function and other parameters for each of the 840 census tracts. Distance decay function was used to calculate the suitability indices for Historical Landmarks, L-Train stations, and Recreational Locations (Parks) from the census tracts by using network distance. The count index was used to measure the suitability index of Bus Stations for siting the DIVVY stations. Besides, population density, job density, and total workers (above 25 years) commute by bike and walking, were also considered for the composite accessibility. The suitability indices were calculated by following function:

$$C_a = f(\text{Gravity based suitability, Census tracts centroid, Network Distance})$$

$$C_b = f(\text{Gravity based suitability, Census tracts centroid, Network Distance})$$

$$C_c = f(\text{Gravity based suitability, Census tracts centroid, Network Distance})$$

$$C_d = \text{Count Index}$$

$$C_e = \text{Resident Population} / \text{Area in Sq. Mile}$$

$$C_f = \text{Job Frequency} / \text{Area in Sq. Mile}$$

$$C_g = (\text{Commute by Bike} + \text{Commute by Walk}) / \text{Total Commuters} * 100$$

Where,  $C_a$  was the Historical Landmarks Index,  $C_b$  was L-Train Index,  $C_c$  was the Recreational Destinations (Parks) Index,  $C_d$  was the Bus Station Index,  $C_e$  was the Population Density Index,  $C_f$  was the Job density Index,  $C_g$  was the Percentage Commute by bike and walking Index.

Calculation of the composite accessibility: At first, the suitability indices for each of the 840 census tracts were standardized for each variable by computing z-scores. The

function  $((\text{value}-\text{mean})/\text{stdev})$  generating in excel as STANDARDIZE (VALUE, MEAN, STDEV) was used to calculate z-scores that converts all tract values for a particular variable to a common scale with an average of zero and standard deviation of one. After that, the z-scores were re-scaled for each variable such that the highest tract value was 100 and the remaining values were expressed as a proportion of the highest value.

$$\text{Re-scaled z-scores} = 100 * (\text{Max- Value})/\text{Range}$$

Finally, average re-scaled z-scores were calculated for each census tract across the all variables to get a composite accessibility index by the following formula:

$$\begin{aligned} \text{Composite Accessibility (C)} &= \text{sum of re-scaled z-scores}/\text{total number of variables} \\ &= (\text{Ca}+\text{Cb}+\text{Cc}+\text{Cd}+\text{Ce}+\text{Cf}+\text{Cg})/7 \end{aligned}$$

### 3.3.2 Maximization of Composite Accessibility Based on Linear Programming (LP) Model

LP Solve IDE software was used to maximize the composite accessibility and to build up the data model. A linear programming model was computed by using the LP solver to equally re-distribute the DIVVY stations based on 2015 data set (Expanded Bike-Share Stations). Two different models were computed for the composite accessibility values based on the seven suitability indices. One LP model was calculated without constraining the Economic Hardship Categories and another model was calculated with considering all constraints.

#### Objective Function Calculation:

About 840 census tracts were used for the objective variables. The suitability values were considered as coefficient to maximize the objective variables of the model.

$$\text{Max: } (C1 * x1 + C2 * x2 + \dots + C840 * x840)$$

## **C= Composite Accessibility Value**

### **x= Census Tract**

#### Constraints Function Calculation:

About six constraint equations were computed to run the data model. The total of about 477 DIVVY stations were considered over the 840 census tracts. The total number of DIVVY stations were also constrained by each of the five economic hardship categories. About 167 and 171 census tracts were considered as the Highest and High economic hardship category consecutively. About 167 census tracts were considered for Moderate economic hardship category. For the economic hardship category of low and lowest, about 167 and 168 census tracts were considered consecutively. About 100 DIVVY stations was considered as the constraint value for each of the five economic hardship categories in the view of gaining equitable accessibility.

1. **Total stations:**  $\sum (x_1+x_2+x_3+\dots+x_{840}) = 477$
2. **High category:**  $\sum (x_1+x_2+\dots+x_{171}) \leq 100$
3. **Highest category:**  $\sum (x_{172}+\dots+x_{338}) \leq 100$
4. **Low category:**  $\sum (x_{339}+\dots+x_{505}) \leq 100$
5. **Lowest category:**  $\sum (x_{506}+\dots+x_{673}) \leq 100$
6. **Moderate category:**  $\sum (x_{674}+\dots+x_{839}) \leq 100$

#### Variable Bounds Calculation:

The area of each of the 840 census tracts were considered for the variable bounds of the data model. About quarter square mile was considered as the service area for each of the DIVVY bike-share stations. Based on the above assumption, the total possible stations for each of the 840 variables (census tracts) were calculated and considered as the

variable bounds against each variable. The output for all of the variables were considered as the integer number.

**x1<=1; x2<=1; x3<=1; x4<=1; x5<=1; x6<=0;.....; x840<=0**

**int x1, x2, x3, x4,.....x840**

## CHAPTER IV

### THE CHICAGO DIVVY BIKE-SHARE INFRASTRUCTURE

#### 4.1 Historical Background for Bike-sharing Systems

The development of bike-share stations internationally started at the mid of the twentieth century and continued for three generations (DeMaio, 2003). On July 28 of 1965, the first generation of bike-sharing stations began with the White Bikes (DeMaio, 2009). It was started at the City of Amsterdam in Netherlands. The second generation of bike-share stations were started on 1993 at Nakskov, Denmark (Nielse, 1993). The second generation was expedited with new design changes of bike-share infrastructures around 1995-96 at Copenhagen. Many improvements of previous systems were made at the end of the twentieth century. The third generation of bike-sharing program was initiated at the beginning of the 21th century. About sixty updated bike-sharing infrastructures were launched globally by the end of 2007 (DeMaio, 2007). The fourth generation of bike-sharing stations will be updated with improved distribution, ease of installation, powering stations, tracking and pedal assistance (DeMaio, 2009).

A rapid development with double or triple times the number of bike-sharing stations is experienced in many cities with improved facilities (ABW, 2010). The development has spread throughout the Europe and other continents during this decade. Many states of the United States have been already advanced within the bike-sharing infrastructure incorporating with modern technology.

About 7.7 percent household of USA do not have any private vehicles which is stated by the National Household Transportation Survey (Guiliano, 2005). Public transit service is the most common method of transportation for that portion of people. But, public service may be reduced or nonexistent at the weekends and night time. So, the people often face problems with their jobs and emergency situation at night (Sanchez, Shen, and Peng, 2004). Therefore, bicycles as a transport mode, and associated bicycle sharing systems are in high demand for the city dwellers. The publication about bike-sharing techniques with smart bike by DeMario (2004) has tremendously increased the attention given to the emerging field of bike-sharing in USA.

The number and percentage of bike share trips in USA is described at National Personal Transportation Surveys (NPTS) of 1977–1995 and National Household Travel Surveys (NHTS) of 2001-2009 (Pucher, Buehler, and Seinen, 2011). The percentage of Annual trips of total bike-share and bike-share of workers are shown at Table 1. The percentage of annual bike trips have increased by almost 220 percent (1272 to 4081) from the year 1977 to 2009. The bike-share trips have increased by almost double during this time period. The bike-share of workers have increased by almost 10 percent during 1977 to 2009. From Table 1, it is showed that the trend line of annual bike-share of trips was literally slow during 1977-1990 and started to accelerate in gaining the percentage from 2000.



Table 1

Trends in cycling levels in USA, 1977–2009

| Year | Annual bike trips (millions) | Bike share of trips (%) | Daily bike commuters (thousands) | Bike share of workers (%) |
|------|------------------------------|-------------------------|----------------------------------|---------------------------|
| 1977 | 1272                         | 0.6                     |                                  |                           |
| 1980 |                              |                         | 468                              | 0.5                       |
| 1983 | 1792                         | 0.8                     |                                  |                           |
| 1990 | 1750                         | 0.7                     | 467                              | 0.4                       |
| 1995 | 3141                         | 0.9                     |                                  |                           |
| 2000 |                              |                         | 488                              | 0.4                       |
| 2001 | 3314                         | 0.9                     |                                  |                           |
| 2008 |                              |                         | 746                              | 0.5                       |
| 2009 | 4081                         | 1                       | 766                              | 0.6                       |

Sources: USDOT (2004a, 2010a), USDOT (1980–2000, 2009, 2010a)

#### 4.2 The Chicago DIVVY Infrastructure

The whole community area of Chicago city was considered in this study. There are about 840 census tracts in the Chicago city. The census tracts were divided into five economic hardship categories by the demographics and economic data namely highest, high, moderate, low, and lowest zone. Table 2 showed the number of census tracts for each economic hardship category.

Table 2

Number of census tracts of Chicago by Economic Hardship Category according to 2013 ACS

| Economic Hardship Category | Number of Census Tracts |
|----------------------------|-------------------------|
| HIGHEST                    | 167                     |
| HIGH                       | 171                     |
| MODERATE                   | 167                     |
| LOW                        | 167                     |
| LOWEST                     | 168                     |
| Grand Total                | 840                     |

#### 4.3 Initial and Expanded DIVVY Stations

At present, about 300 bike-share stations are fully functioning at Chicago city.

Figure 2 showed the spatial distribution of initial bike-share stations to the economic hardship category zones.

## Spatial distribution of Initial DIVVY Stations based on Economic Hardship Categories for Chicago City

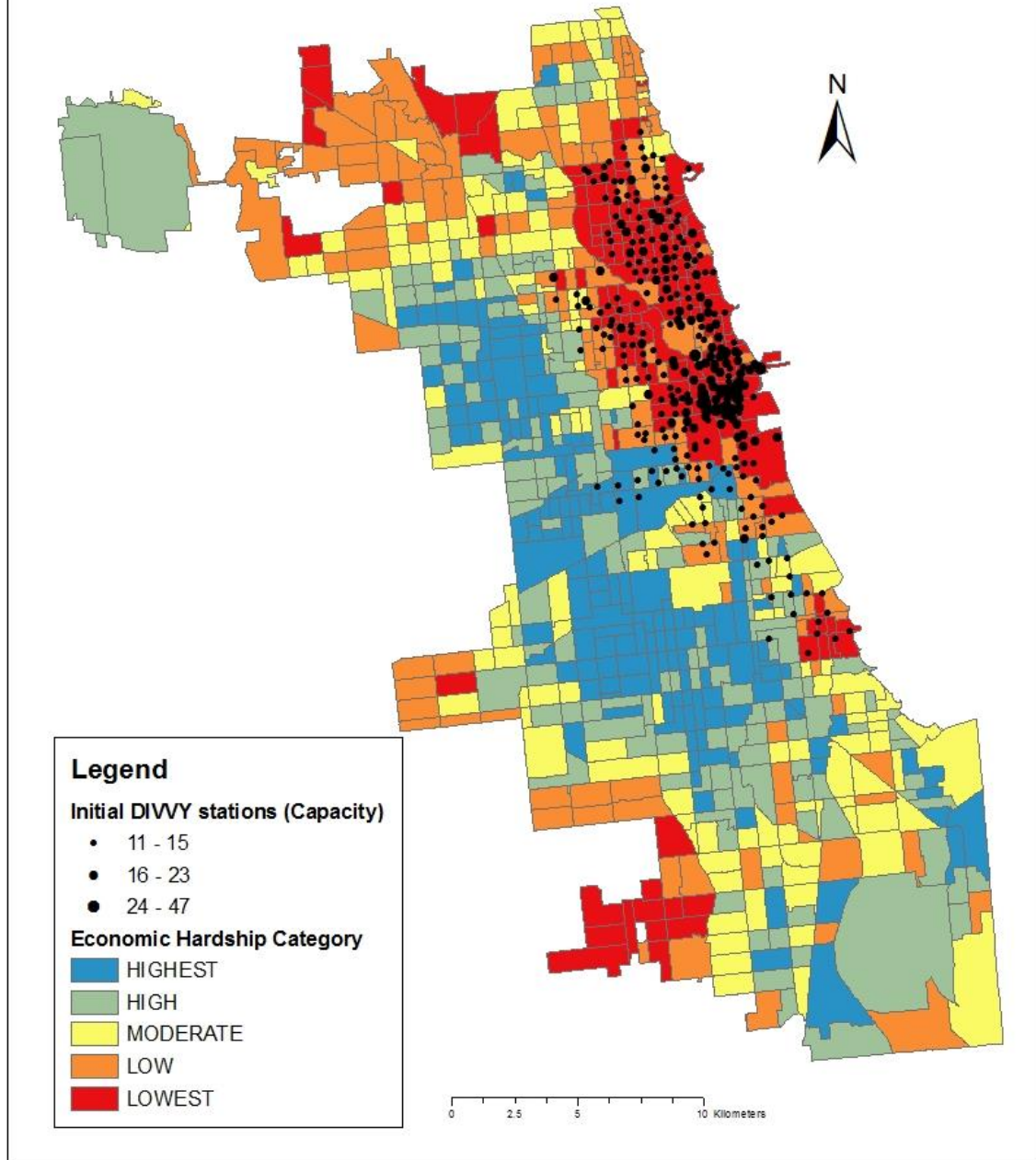
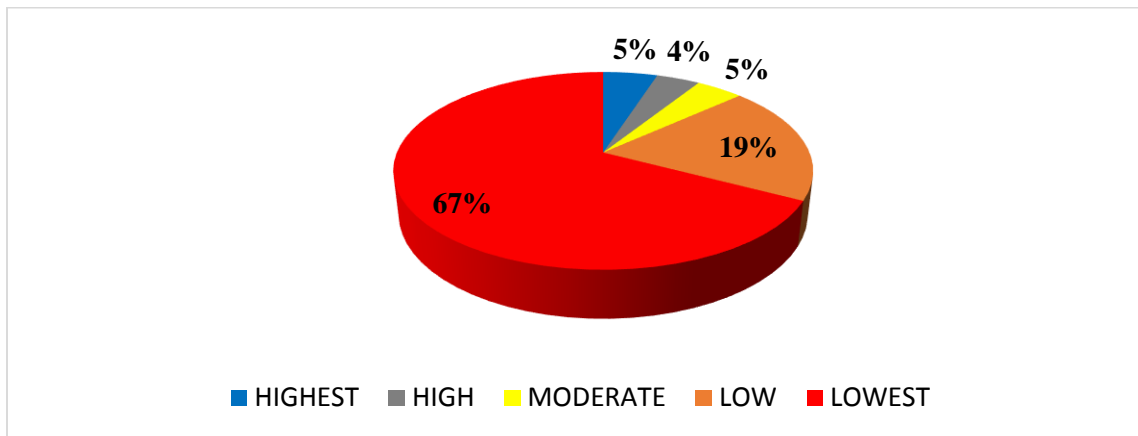


Figure 2 Map showing spatial distribution of initial DIVVY stations based on Economic Hardship Categories for the city of Chicago

For the existing scenario (Figure 3), almost two-third DIVVY stations are located under the area of lowest economic hardship category. About 9 percent in total of DIVVY stations are located in the area of high and highest category of economic hardship. A very few number of bike share stations are located in the moderate zone. So, it is assumed that the existing distribution of DIVVY stations are fairly unequal on the basis of economic hardship category for the city of Chicago. The census tracts under the category of low and lowest economic hardship zone are benefited more with the bike-share stations than the other areas. But, the DIVVY stations are more mandatory for the people of the highest economic hardship zone as they rarely own private cars (Sanchez, Shen, and Peng, 2004).



*Figure 3* Existing distribution of DIVVY stations based on Economic Hardship Categories for the city of Chicago

About 477 in total of DIVVY stations were proposed in 2015 for the expanded allocation of bike-share infrastructure at city of Chicago. Spatial distribution of expanded bike-share stations across the different economic zones were shown in Figure 4.

### Spatial distribution of Expanded DIVVY Stations based on Economic Hardship Categories for Chicago City

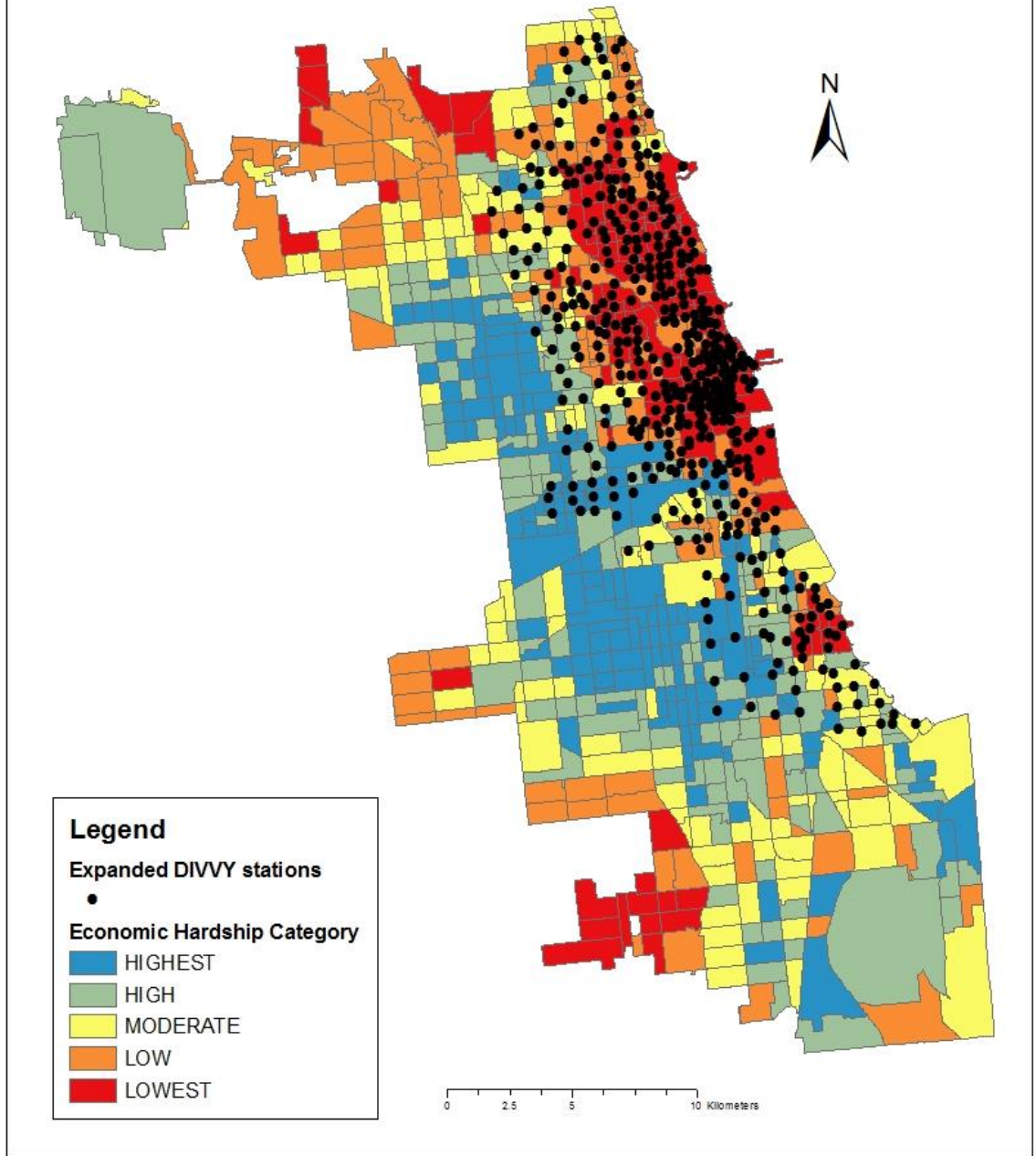
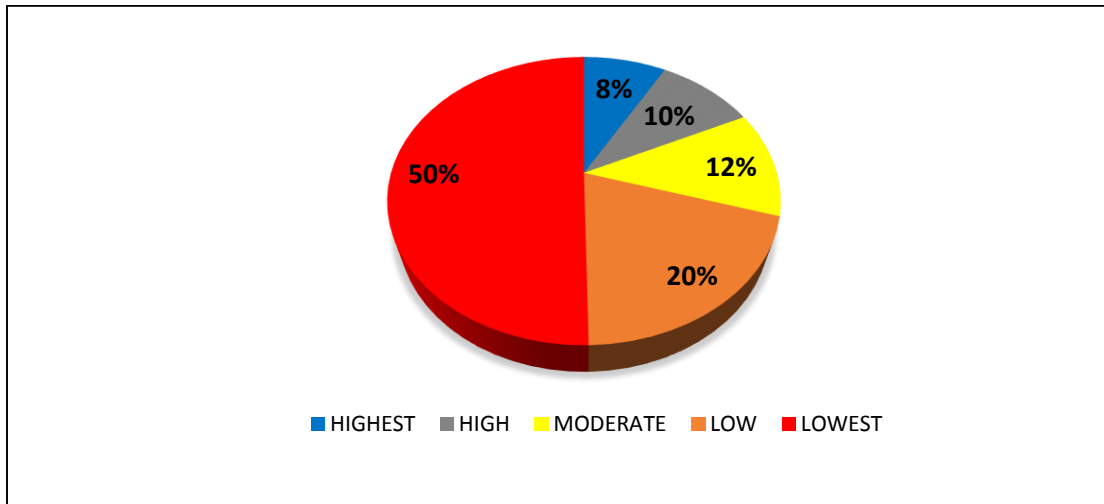


Figure 4 Map showing spatial distribution of expanded DIVVY stations based on Economic Hardship Categories for the city of Chicago

For the expanded scenario of DIVVY stations (Figure 5), the percentage of stations for high and highest economic hardship zone has increased by almost double from the initial one. But, still there is a huge inequality for distributing the DIVVY stations among the various economic hardship zones within equity perspective.



*Figure 5* Expanded (Total) DIVVY stations based on Economic Hardship Categories for the city of Chicago

About half of the total stations were located in lowest economic hardship zone according to the planning of expanded DIVVY stations. Almost one tenth of the total DIVVY stations were planned to set up in the moderate economic hardship zone. Therefore, still it is mandatory to update the distribution of DIVVY stations according to the transportation equity perspective on the basis of economic hardship category.

After reviewing the existing scenario, the detail analysis for the outcome of the first and second objectives were presented at the following chapter.

## CHAPTER V

### COMPARISON OF ACCESSIBILITY INDICES FOR INITIAL AND EXPANDED BIKE SHARE STATIONS ON THE BASIS OF ECONOMIC HARDSHIP CATEGORY

The accessibility value for each of the census tract to the initial and expanded DIVVY stations was examined to assess the distribution of bike-share stations in the view of equity perspective. In this study, accessibility was computed initially within two broad categories as Count Index and Network Distance Index. Count Index was subdivided into Count, Buffer from Centroid, and Buffer from Tracts indices. Quarter mile, half mile, and one mile cut-off values were considered for computing the indices for both of the Buffer from Centroid and Buffer from Tracts index. No cut-off and cut-off with quarter mile, half mile, and one mile were considered to compute the indices by measuring network distance.

So, in total of 11 different indices were calculated to measure the accessibility from the census tracts for both of initial and expanding (total) distribution of DIVVY stations. Table-3 showed the designation of the corresponding 11 accessibility indices. The accessibility indices were categorized by economic hardship zones and calculated by counts and network distance. These accessibility values literally indicate the degree of access from the census tract to the bike-share stations. In this chapter, a general comparison was shown for initial and expanded distribution of bike-share stations in terms of different accessibility indices across the economic hardship zones.

Table 3

Designation of the corresponding 11 accessibility indices that is used to examine the accessibility for existing and expanded distribution

| Count Index    |                                     |                                  |                                 |                                   |                                |                               | Network Distance Index         |                                      |                                   |                            |
|----------------|-------------------------------------|----------------------------------|---------------------------------|-----------------------------------|--------------------------------|-------------------------------|--------------------------------|--------------------------------------|-----------------------------------|----------------------------|
| Count          | Buffer from Centroid                |                                  |                                 | Buffer from Tracts                |                                |                               | Cut-off values                 |                                      |                                   | No Cut-off                 |
| Index 1        | Index 2                             | Index 3                          | Index 4                         | Index 5                           | Index 6                        | Index 7                       | Index 8                        | Index 9                              | Index 10                          | Index 11                   |
| COUNT ANALYSIS | BUFFER FROM CENTROID (QUARTER MILE) | BUFFER FROM CENTROID (HALF MILE) | BUFFER FROM CENTROID (ONE MILE) | BUFFER FROM TRACTS (QUARTER MILE) | BUFFER FROM TRACTS (HALF MILE) | BUFFER FROM TRACTS (ONE MILE) | ACCESSIBILITY (1 MILE CUT-OFF) | ACCESSIBILITY (QUARTER MILE CUT-OFF) | ACCESSIBILITY (HALF MILE CUT-OFF) | ACCESSIBILITY (NO CUT-OFF) |

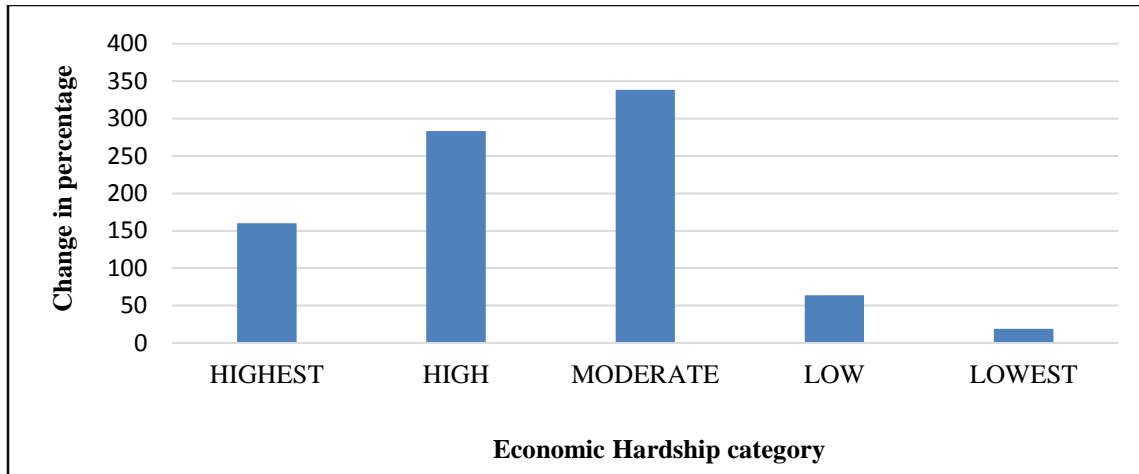
### 5.1 Accessibility Indices Based on Count Index

The accessibility value of this index were calculated by applying counting method for the DIVVY stations under the 840 census tracts for the City of Chicago. Similar method was also applied for calculating quarter, half, and one mile index for both of the buffer from centroid and tracts indices.

#### 5.1.1 Accessibility Index for Count Analysis within Census Tracts Boundary (COUNT ANALYSIS INDEX)

Overall change (from initial distribution to expanded distribution) in percentage for the accessibility values across different economic hardship zones was shown in Figure 6 for the Count Analysis index. Maximum change in percentage (338 percent) was observed for moderate economic hardship zone (Figure 6) and it was about 40 percent of total increase.





*Figure 6* Change in percentage for accessibility index of counts analysis for initial and expanded DIVVY distribution within census tracts boundary

The second highest gain in percentage of accessibility was observed for high category; which is about 283 percent. The percentage change for lowest category was lowest and it was about 19 percent. Since the percentage of accessibility was gained for different economic hardship zones from initial for expanded distribution, it was not adequate in the view of equity perspective.

#### 5.1.2 Accessibility Index for BUFFER FROM CENTROID (QUARTER MILE, HALF MILE and ONE MILE)

The change of accessibility against individual economic hardship category from initial to expanded distribution was almost similar and positive for the three accessibility indices under BUFFER FROM CENTROID INDEX (Table 4). The maximum amount of change in accessibility was gained by the highest and high economic hardship zones.

Table 4

Change in accessibility values from initial to expanded DIVVY distribution in terms of accessibility index of BUFFER FROM CENTROID (QUARTER MILE, HALF MILE and ONE MILE)

| Economic hardship Categories | BUFFER FROM CENTROID INDEX                |                       |                |  |                       |                |                                       |                       |                |
|------------------------------|---|-----------------------|----------------|--|-----------------------|----------------|---------------------------------------|-----------------------|----------------|
|                              | Accessibility value of Quarter Mile Index |                       |                | Accessibility value of Half Mile Index |                       |                | Accessibility value of One Mile Index |                       |                |
|                              | Initial distribution                      | Expanded distribution | Percent Change | Initial distribution                   | Expanded distribution | Percent Change | Initial distribution                  | Expanded distribution | Percent Change |
| HIGHEST                      | 7   | 29                    | <b>314</b>     | 41                                     | 139                   | <b>239</b>     | 192                                   | 584                   | <b>204</b>     |
| HIGH                         | 14  | 44                    | <b>214</b>     | 62                                     | 220                   | <b>254</b>     | 279                                   | 831                   | <b>197</b>     |
| MODERATE                     | 17  | 54                    | <b>217</b>     | 76                                     | 237                   | <b>211</b>     | 296                                   | 894                   | <b>202</b>     |
| LOW                          | 74  | 107                   | <b>44</b>      | 286                                    | 443                   | <b>54</b>      | 1045                                  | 1635                  | <b>56</b>      |
| LOWEST                       | 254                                       | 297                   | <b>16</b>      | 983                                    | 1149                  | <b>16</b>      | 3413                                  | 4030                  | <b>18</b>      |

For the BUFFER FROM CENTROID (QUARTER MILE) index, high and highest economic hardship zones gained almost 530 percent accessibility in together (Table 4) and it was about 65 percent of the total change. A little amount of change in accessibility was observed from Table 4 for low and lowest zones over the initial to expanded distribution. But, noticeable increase (about 217 percent) of accessibility was observed for the moderate economic zone; which was about 27 percent of the total increase.

About 254 percent of increase in accessibility is shown (Table 4) only for the high category under the BUFFER FROM CENTROID (HALF MILE) index. Highest and Moderate zones also gained a noticeable amount of accessibility from initial to expanded distribution under this index. Overall change in accessibility for lowest category for the index is almost similar to the BUFFER FROM CENTROID (QUARTER MILE) index. About 54 percent change in accessibility is observed by Table 4 for low economic hardship

category under BUFFER FROM CENTROID (HALF MILE) index, which was about 7 percent of total change for initial to expanded distribution.

Almost 400 percent of accessibility was gained for highest and moderate zones in together under the BUFFER FROM CENTROID (ONE MILE) index. The overall change in percentage of accessibility is increased slightly for low and lowest zones (Table 4) under the BUFFER FROM CENTROID (ONE MILE) index in comparison to other Buffer from Centroid indices. But, the change in accessibility is reduced for high category under this index in comparison to other indices under BUFFER FROM CENTROID index.

#### 5.1.3 Accessibility Index for BUFFER FROM TRACTS (QUARTER MILE, HALF MILE and ONE MILE)

The change of accessibility for low and lowest category zone from initial distribution to expanded distribution remained same for the three indices under BUFFER FROM TRACTS index according to Table 5.

The change in percentage of accessibility for high and moderate category occupied a lion share of about 60 percent of the total change from initial to expanded distribution according to BUFFER FROM TRACTS (QUARTER MILE) index. The accessibility for highest category zone was increased by 173 percent, which is about 20 percent of the total change for this index. From Table 5, less than 10 percent in total increase of accessibility was observed for the low and lowest category zone under the BUFFER FROM TRACTS (QUARTER MILE) accessibility index.

Table 5

Change in percentage for initial and expanded DIVVY distribution in terms of accessibility index of BUFFER FROM TRACTS (QUARTER MILE, HALF MILE and ONE MILE)

| Categories | BUFFER FROM TRACTS INDEX                  |                       |                |  |                       |                |                                       |                       |                |
|------------|---|-----------------------|----------------|--|-----------------------|----------------|---------------------------------------|-----------------------|----------------|
|            | Accessibility value of Quarter Mile Index |                       |                | Accessibility value of Half Mile Index |                       |                | Accessibility value of One Mile Index |                       |                |
|            | Initial Distribution                      | Expanded Distribution | Percent Change | Initial Distribution                   | Expanded Distribution | Percent Change | Initial Distribution                  | Expanded Distribution | Percent Change |
| HIGHEST    | 64  | 175                   | <b>173</b>     | 129                                    | 353                   | <b>173</b>     | 335                                   | 988                   | <b>194</b>     |
| HIGH       | 58  | 204                   | <b>251</b>     | 138                                    | 466                   | <b>237</b>     | 478                                   | 1313                  | <b>174</b>     |
| MODERATE   | 67  | 243                   | <b>262</b>     | 153                                    | 491                   | <b>220</b>     | 490                                   | 1394                  | <b>184</b>     |
| LOW        | 274                                       | 445                   | <b>62</b>      | 613                                    | 957                   | <b>56</b>      | 1621                                  | 2516                  | <b>55</b>      |
| LOWEST     | 922                                       | 1101                  | <b>19</b>      | 2048                                   | 2416                  | <b>17</b>      | 5012                                  | 6009                  | <b>19</b>      |

According to Table 5, change in accessibility for highest, high, and moderate zones was almost similar to the quarter and half mile indices under the BUFFER FROM TRACTS index. The census tracts under the economic categories of high, highest and moderate zone has occupied almost 90 percent of the total gain of accessibility by BUFFER FROM TRACTS (HALF MILE) index. The percentage change for lowest category is observed at Table-5 with less than 5 percent of total change for this index.

The accessibility is gained by almost 194 percent for the highest category under the BUFFER FROM TRACTS (ONE MILE) index and it is almost 30 percent of the total increase from initial to expanded distribution. The accessibility is decreased by almost 10 percent for high and moderate categories under the BUFFER FROM TRACTS (ONE MILE) index in comparison to other two indices about the BUFFER FROM TRACTS index.

## 5.2 Accessibility Indices Based on Network Distance

Accessibility was calculated based on network distance by considering the centroid of census tracts as the origin and the bike share stations as the destination. Straight line or crow-fly distance was considered for computing network distance. Distance decay function was used to convert the network distance into accessibility values for the census tracts by the economic hardship categories. Both of cut-off values and no cut-off values of network distance were calculated to get the accessibility from the census tracts to the DIVVY stations.

### 5.2.1 Analysis of Accessibility Indices for Network Distance (QUARTER MILE CUT-OFF, HALF MILE CUT-OFF and ONE MILE CUT-OFF)

A comparative analysis (from initial to expanded distribution) of network distance index with different cut-off values were discussed in this section. The overall change in accessibility values for different economic hardship categories were shown at Table 6.

Table 6

Change in percentage for initial and expanded DIVVY distribution in terms of accessibility indices for network distance (QUARTER MILE CUT-OFF, HALF MILE CUT-OFF and ONE MILE CUT-OFF)

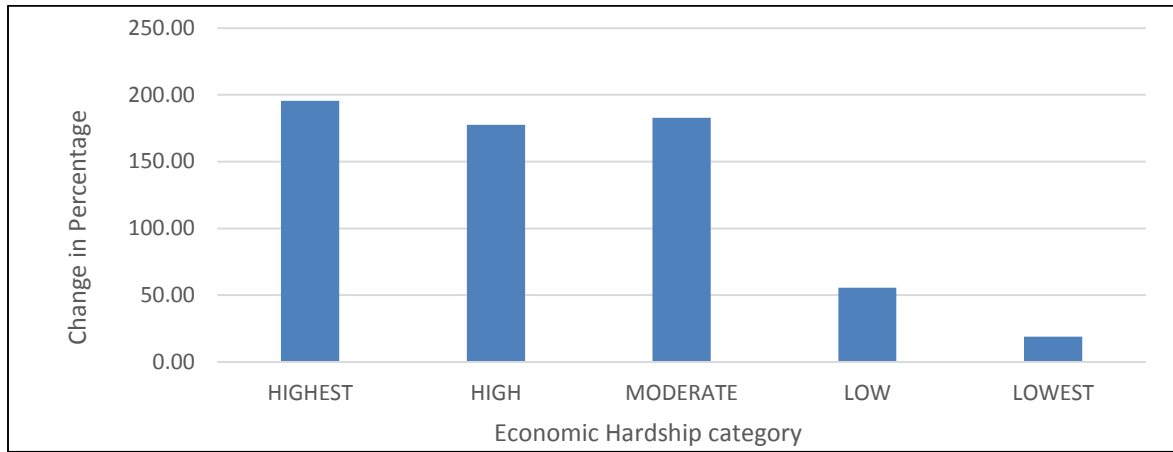
| Categories | NETWORK DISTANCE INDEX                    |                       |                |  |                       |                |                                       |                       |                |
|------------|---|-----------------------|----------------|--|-----------------------|----------------|---------------------------------------|-----------------------|----------------|
|            | Accessibility value of Quarter Mile Index |                       |                | Accessibility value of Half Mile Index |                       |                | Accessibility value of One Mile Index |                       |                |
|            | Initial Distribution                      | Expanded Distribution | Percent Change | Initial Distribution                   | Expanded Distribution | Percent Change | Initial Distribution                  | Expanded Distribution | Percent Change |
| HIGHEST    | 3.1                                       | 12.8                  | <b>308.5</b>   | 13.3                                   | 47.5                  | <b>256</b>     | 32.5                                  | 106.9                 | <b>228.6</b>   |
| HIGH       | 5.6                                       | 19.3                  | <b>243.6</b>   | 18.6                                   | 66.4                  | <b>256.9</b>   | 46                                    | 153.3                 | <b>233.1</b>   |
| MODERATE   | 2.1                                       | 15.3                  | <b>612.8</b>   | 18.2                                   | 69.5                  | <b>280.6</b>   | 48.7                                  | 164.5                 | <b>237.7</b>   |
| LOW        | 24  | 39.8                  | <b>65.3</b>    | 81.6                                   | 125.7                 | <b>53.8</b>    | 192.4                                 | 298.4                 | <b>55.2</b>    |
| LOWEST     | 103                                       | 119                   | <b>15.1</b>    | 325.7                                  | 378.2                 | <b>16.2</b>    | 706.8                                 | 824.2                 | <b>16.6</b>    |

On the basis of ACCESSIBILITY (QUARTER MILE CUT-OFF) index, about 613 percent of accessibility was gained only for moderate economic hardship category and it is about 50 percent of the total change. From Table 6, accessibility was gained for more than 250 percent for both of the highest and high zones. But, the accessibility of lowest category was slightly (about 15 percent) increase from initial to expanded distribution by ACCESSIBILITY (QUARTER MILE CUT-OFF) index.

Almost similar percent of accessibility was gained for high and highest categories under the accessibility index based on network distance for HALF MILE CUTOFF (Table 6). Each of the above categories has gained the accessibility by almost 30 percent of the total increase from initial to expanded distribution. The accessibility for moderate zone was also increased by highest percentage (about 280 percent) by this index; which was similar to quarter mile cut-off index. But, Only 8 percent of total change in accessibility was observed for low and lowest zones by ACCESSIBILITY (QUARTER MILE CUT-OFF) index (Shown in Table 6).

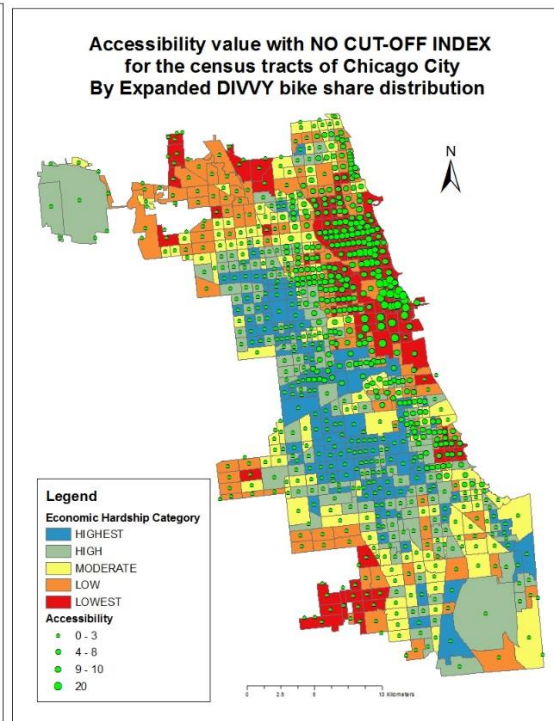
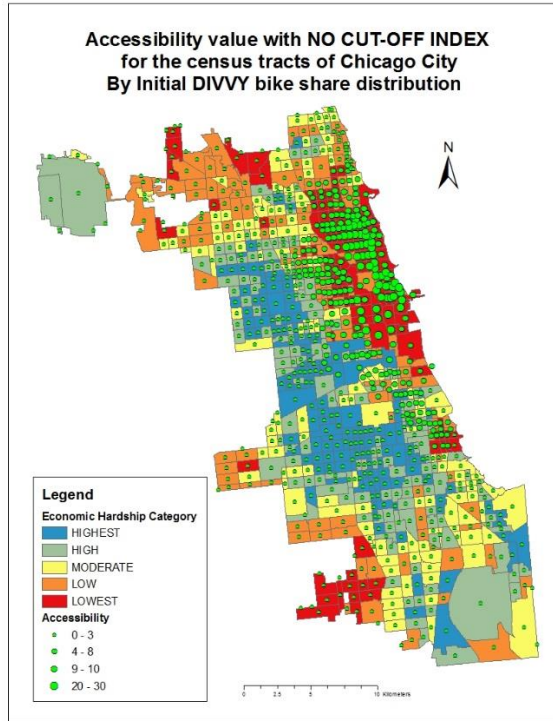
The total change (60 percent) in accessibility for high and highest category was remained same under the ACCESSIBILITY (HALF MILE CUT-OFF) index and ACCESSIBILITY (ONE MILE CUT-OFF) index.

### 5.2.2 Analysis of Accessibility Index for Network Distance (NO CUT-OFF)



*Figure 7* Change in percentage for initial and expanded DIVVY stations in terms of accessibility index for network distance (NO CUT-OFF)

Maximum accessibility was gained by high, highest and moderate categorical zones from initial to expanded scenario under the measurement of ACCESSIBILITY (NO CUT-OFF) index (Figure 7). Almost 200 percent of accessibility was gained by each of the highest, high and moderate zone from initial to expanded distribution of DIVVY stations. But, the total percentage in accessibility was barely increased for low and lowest zones under the ACCESSIBILITY (NO CUT-OFF) index. Only 3 percent change of total accessibility was observed for lowest economic hardship zone. The spatial distribution of accessibility across the various economic zones for initial and expanded DIVVY stations are shown at Figure 8 and Figure 9 consecutively.



*Figure 8* Map showing Accessibility Value (NO CUT-OFF) of initial DIVVY stations for different Economic Hardship zones for the city of Chicago

*Figure 9* Map showing Accessibility Value (NO CUT-OFF) of expanded DIVVY stations for different Economic Hardship zones for the city of Chicago

From the above analysis by exploring various accessibility indices, it is clear that accessibility was increased mostly for moderate, high, and highest zone consecutively from initial to expanded distribution. But, the increase in accessibility for expanded distribution could not meet the equitable distribution of bike-share stations for different economic hardship categories for the city of Chicago. Therefore, there is the need to re-distribute the expanded bike share stations to gain the equity for different economic hardship zones by maximizing the composite accessibility value.

In the following chapter, the outcome of the linear optimization technique was analyzed in terms of re-distributing (third objective) the DIVVY bike-share stations.



## CHAPTER VI

### RE-DISTRIBUTION OF DIVVY BIKE-SHARE STATIONS USING LINER OPTIMIZATION MODEL

In this chapter, linear optimization model was computed by considering a new composite accessibility to optimize the expanded DIVVY stations across the 840 census tracts in Chicago City. The new composite accessibility was calculated based on seven suitability indices for siting the expanded DIVVY stations across the census tracts of Chicago city.

Table 7

List of suitability indices that forming the new composite accessibility

| Suitability Index-1  | Suitability Index-2 | Suitability Index-3               | Suitability Index-4 | Suitability Index-5 | Suitability Index-6 | Suitability Index-7                    |
|----------------------|---------------------|-----------------------------------|---------------------|---------------------|---------------------|--|
| Historical Landmarks | L-Train Stations    | Recreational Destinations (Parks) | Bus Stations        | Population Density  | Job Density         | Percentage Commute by bike and walking |

The suitability indices were considered based on the literatures to site the bike-share stations in a particular location. Table-7 showed the seven suitability indices that form the composite accessibility for each of the census tract.

Two Linear Programming (LP) models were calibrated to maximize the composite accessibility in terms of re-distributing the expanded DIVVY bike-share stations. One of the models was calibrated to maximize the composite accessibility without constraining the values of economic hardship categories and it was called Model-1 (Table 8). Another

model was calibrated by considering the economic hardship values as the constraint of the LP function. It was called Model-2 in this study and showed in Table 8. Both of the models were calibrated for maximizing the composite accessibility for all of the 840 census tracts with optimizing the DIVVY bike-share stations. The total of 477 expanded DIVVY stations were considered in the LP models for optimizing the re-distribution process.

Table 8

Designation of the models that were calibrated by LP maximization

|         |  |
|---------|--|
| Model 1 | maximize the composite accessibility without constraining the values of economic hardship categories |
| Model 2 | Maximizing the composite accessibility by constraining the economic hardship categorical values      |

#### 6.1: Re-distribution of DIVVY Bike-share Stations by Maximizing the Composite Accessibility with Model-1 (Without Constraining the Economic Hardship Categories by Census Tracts)

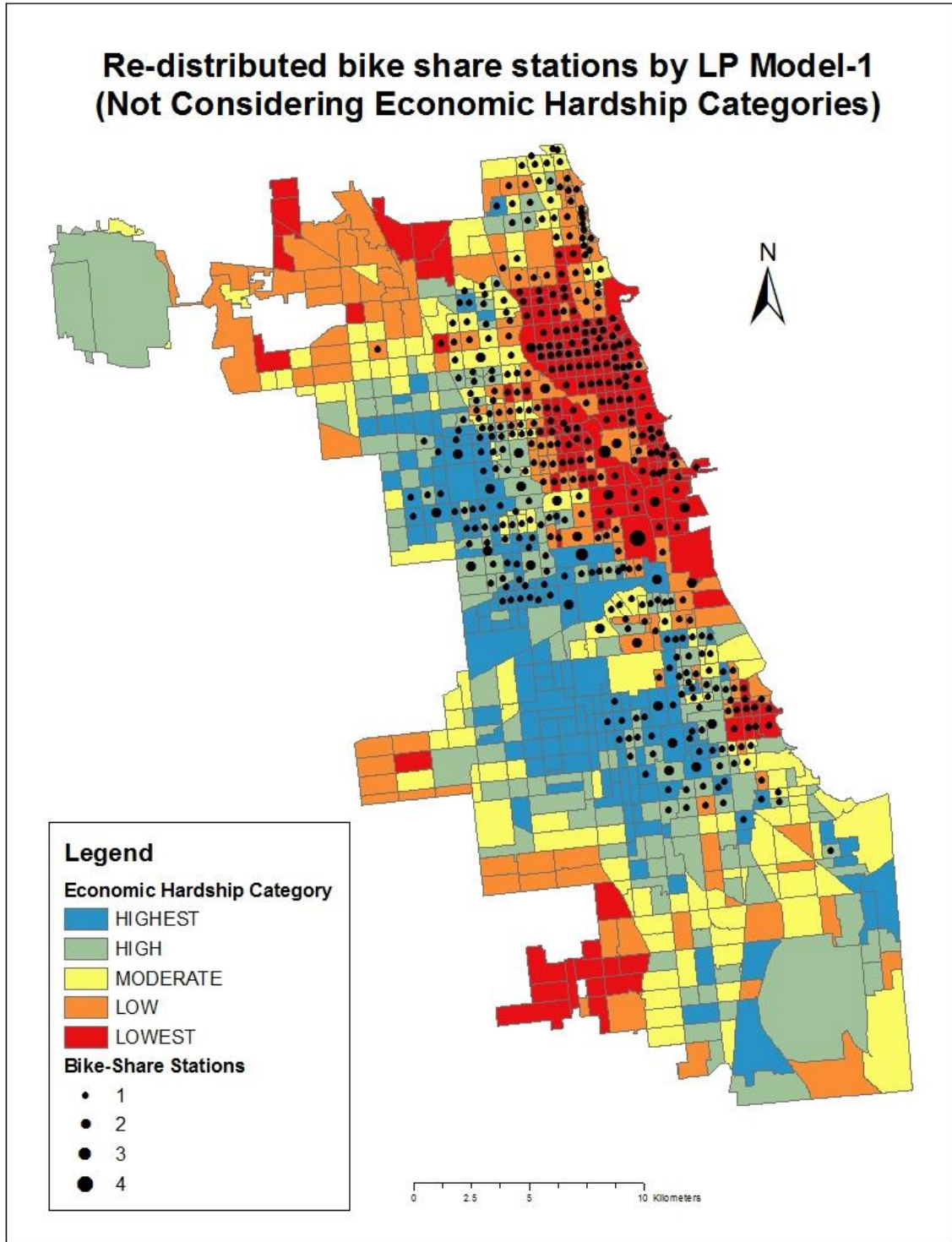
Table-9 showed the frequency distribution and the overall percentage of the total number of re-distributed DIVVY bike-share stations across the economic hardship categories based on LP Model-1.

Table 9

Re-distributed DIVVY bike-share stations with percentage by economic hardship categories for LP model-1

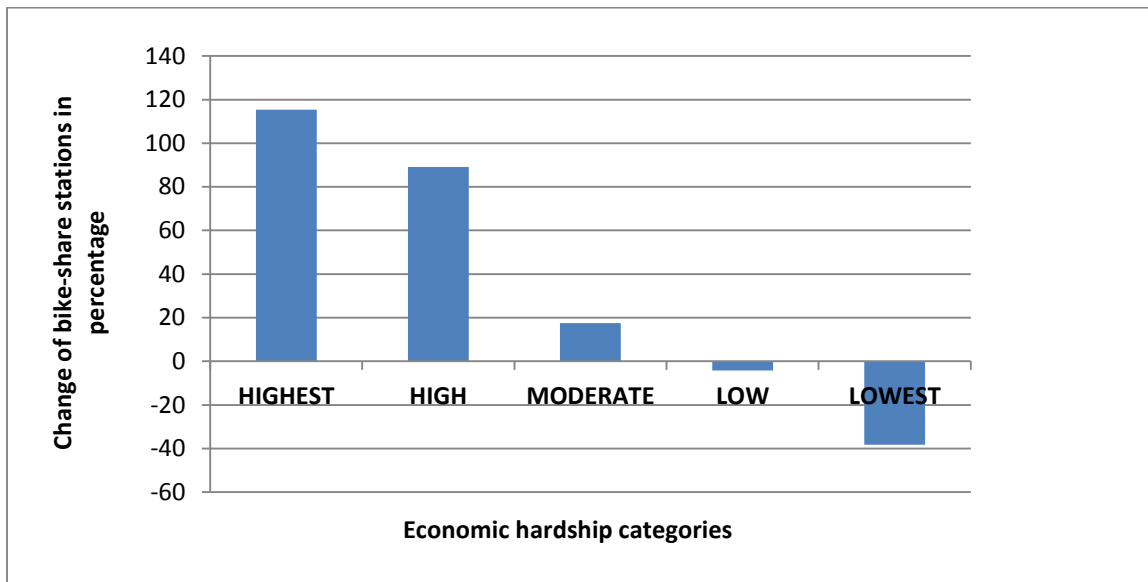
| <b>Economic Hardship categories</b> | <b>Number of re-distributed DIVVY stations</b> | <b>Percentage of re-distributed stations</b> |
|-------------------------------------|--|--|
| HIGHEST                             | 84   | 17.6   |
| HIGH                                | 87   | 18.2   |
| MODERATE                            | 67   | 14.1   |
| LOW                                 | 91   | 19.1   |
| LOWEST                              | 148  | 31.0   |
| <b>Total</b>                        | <b>477</b>                                     | <b>100</b>                                   |

It is noticeable from Table 9, that about 50 percent of the total bike share stations were re-distributed for low and lowest economic hardship zones by Model-1. Since the composite accessibility was much higher for the entire census tracts under these two zones (low and lowest), comparatively higher frequency of DIVVY stations were allocated by LP Model-1. As the model-1 was calibrated without considering the constraints value for economic hardship zones, the unrestricted optimized value was assigned for the re-distribution process. Figure 10 showed the spatial distribution for the bike share stations by LP Model-1.



*Figure 10* Map showing spatial distribution of re-distributed DIVVY stations based on LP Model-1 for the city of Chicago

From the frequency distribution of bike-share stations in Table 9, the lowest amount (about 14 percent) of stations were re-distributed for moderate economic hardship zone. Model-1 showed an interesting distribution of bike share stations for highest and high economic hardship zones. About 35 percent of total bike-share stations were re-allocated to the high and highest economic hardship zones, which is remarkable for those areas.



*Figure 11* Change in percentage of DIVVY stations for different economic hardship zones from expanded distribution to the re-distribution by LP Model-1

Figure 11 showed the change in percentage of the DIVVY stations from the expanded allocation to the re-distributed LP allocation for Model-1. Overall percentage was gained by highest, high, and moderate economic hardship zones based on the re-distribution of DIVVY station by LP model-1 (without considering the constraints of economic hardship categories). About 115 percent bike share stations were gained by highest economic hardship zone. Besides, overall loss in DIVVY stations for low and

lowest economic hardship zone was about 40 percent (Figure 11) in together by LP model-1 in comparison to expanded distribution.

#### 6.1.1 Correlation between Composite Accessibility and Re-distributed DIVVY Stations Based on LP Model-1

A correlation matrix was calculated for showing the relationship between the composite accessibility and the optimized bike-share station in terms of different economic hardship zones in Chicago city. From Table 10, the Pearson's correlation value was 0.74 which showed a moderately high positive correlation between the composite accessibility values and the resulted DIVVY stations by LP model-1.

Table 10

Correlation between the composite accessibility and the re-distributed bike share stations by LP model-1

|                               |                     | <b>Correlations</b> |                               |
|-------------------------------|---------------------|---------------------|-------------------------------|
|                               |                     | Bike-share stations | Composite accessibility value |
| Bike-share stations           | Pearson Correlation | 1                   | .74                           |
|                               | Sig. (1-tailed)     |                     | .118                          |
|                               | N                   | 5                   | 5                             |
| Composite accessibility value | Pearson Correlation | .74                 | 1                             |
|                               | Sig. (1-tailed)     | .118                |                               |
|                               | N                   | 5                   | 5                             |

The positive correlation proved the reliability of the data model and its associated outcome of DIVVY stations based on the maximization of composite accessibility values. Since the LP model was calibrated based on the maximization of composite accessibility, the positive correlation helped to maximize the optimization of DIVVY stations across the

census tracts. LP Model-1 was basically calibrated without considering the constraints value for economic hardship categories and therefore, the correlation value tends to be higher between accessibility and resulted bike share stations. Figure 12 showed the spatial relationship between the composite accessibility and Model-1.

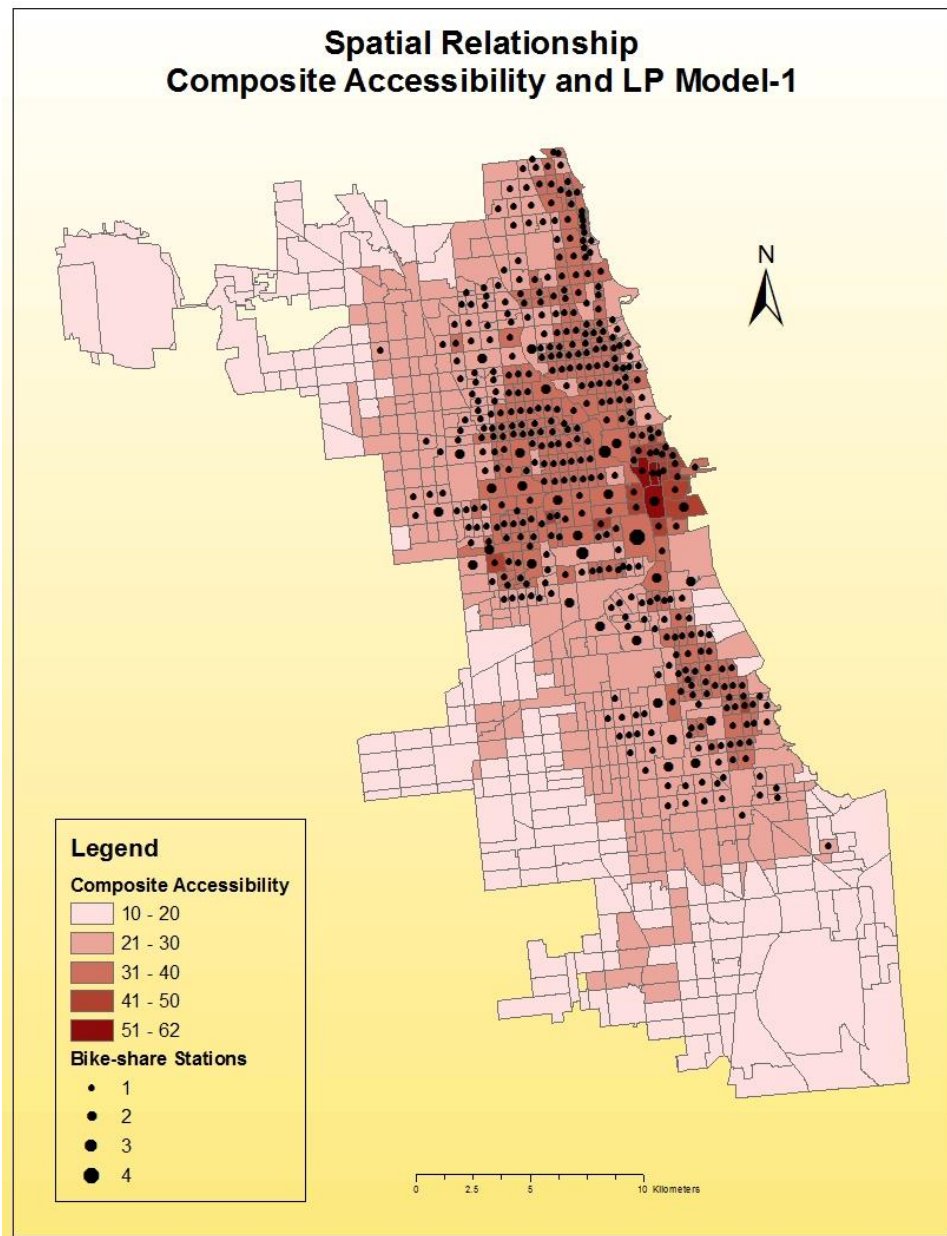
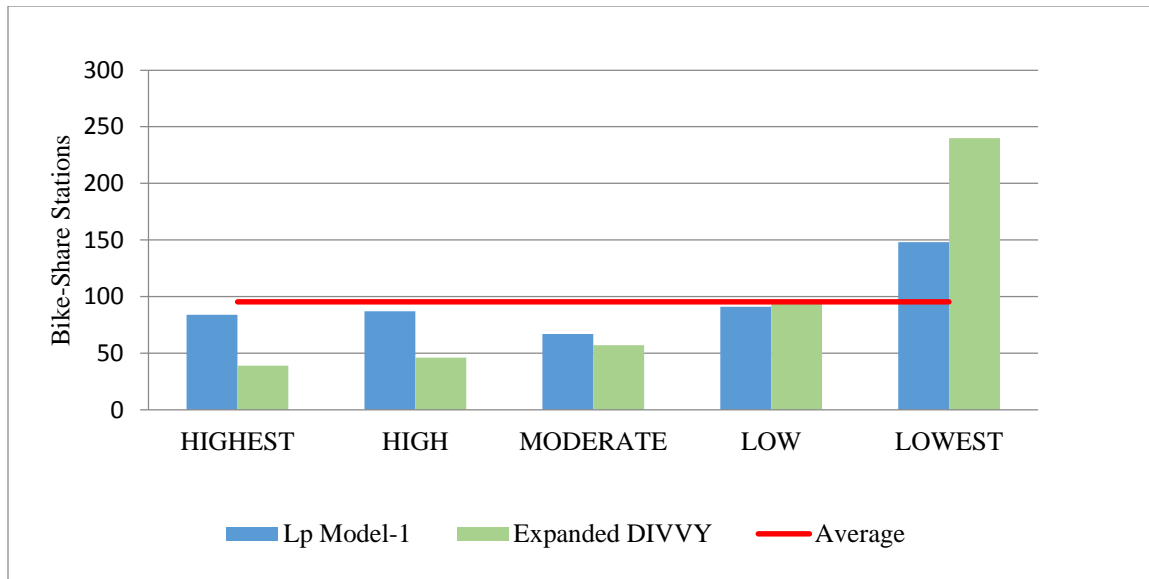


Figure 12 Map showing relationship between composite accessibility and re-distributed DIVVY stations based on LP model-1 for the city of Chicago

### 6.1.2 Comparison of Expanded Distribution and LP Model-1 with Respect to Categorical Deviation from Mean Bike-share Station Value

The categorical average value was about 95 bike-share stations across the economic hardship categories for the city of Chicago. In this sub-section, a general comparison with categorical mean value was discussed for both the expanded allocation and re-distribution based on LP model-1.



*Figure 13* Comparison from mean value for the expanded bike-share distribution and the re-distribution by LP model-1

It is noticeable from Figure 13 that most of the economic hardship zones did not meet the average value for the expanded allocation of DIVVY stations. Highest, high, and moderate economic hardship zones were below the mean value for the expanded allocation of bike-share stations. Only the low category met the average value for the equal allocation of DIVVY stations. But, the average value for the bike-share stations was exceeded by almost 150 percent for the lowest categorical zone.



On the other hand, only low category met the average value for the re-distributed bike share stations by LP model-1. The deviation of bike-share stations from mean value was lower for most of the categories by LP re-distribution, in comparison to expanded DIVVY distribution. Almost 40 percent of positive deviation from mean value was shown in Figure 13 for lowest zone according to LP Model-1. Besides, very low (10 percent) negative deviation from mean value was examined for highest and lowest zones by LP Model-1.

#### 6.2: Re-distribution of DIVVY Bike-share Stations by Maximizing the Composite Accessibility with Model-2 (Constraining the Economic Hardship Categories by Census Tracts)

LP model-2 was calibrated to optimize the bike-share stations by maximizing the composite accessibility with considering the constraint value of economic hardship categories. An average value of 100 bike-share stations were considered as the constraint for each of the five economic hardship categories to maximize the LP model based on equal opportunity. The total of 477 stations were also considered as a constraint for the LP model-2. Table-11 showed the frequency distribution with percentage for the re-distributed DIVVY stations based on LP model-2.

Table 11

Re-distributed DIVVY bike-share stations with percentage by economic hardship categories for LP model-2

| <b>Economic Hardship categories</b> | <b>Number of re-distributed bike-share stations</b> | <b>Percentage of Re-distributed stations</b> |
|-------------------------------------|---|--|
| HIGHEST                             | 100   | 20.96  |
| HIGH                                | 100   | 20.96  |
| MODERATE                            | 77  | 16.14  |
| LOW                                 | 100   | 20.96  |
| LOWEST                              | 100   | 20.96  |
| <b>Total</b>                        | <b>477</b>  | <b>100</b>                                   |

The DIVVY bike share stations were re-distributed almost equally across the different economic hardship zones based on LP model-2. About 100 stations (20 percent of total stations) were equally re-distributed for each of highest, high, low, and lowest economic hardship zones by maximizing the composite accessibility (Table 11). The moderate economic hardship zone was considered for the least number of bike-share stations and it was about 17 percent of total distribution. Figure 14 showed the spatial re-distribution for the bike share stations by LP Model-2.

### Re-distributed Bike share stations by LP Model-2 (Considering Economic Hardship Categories)

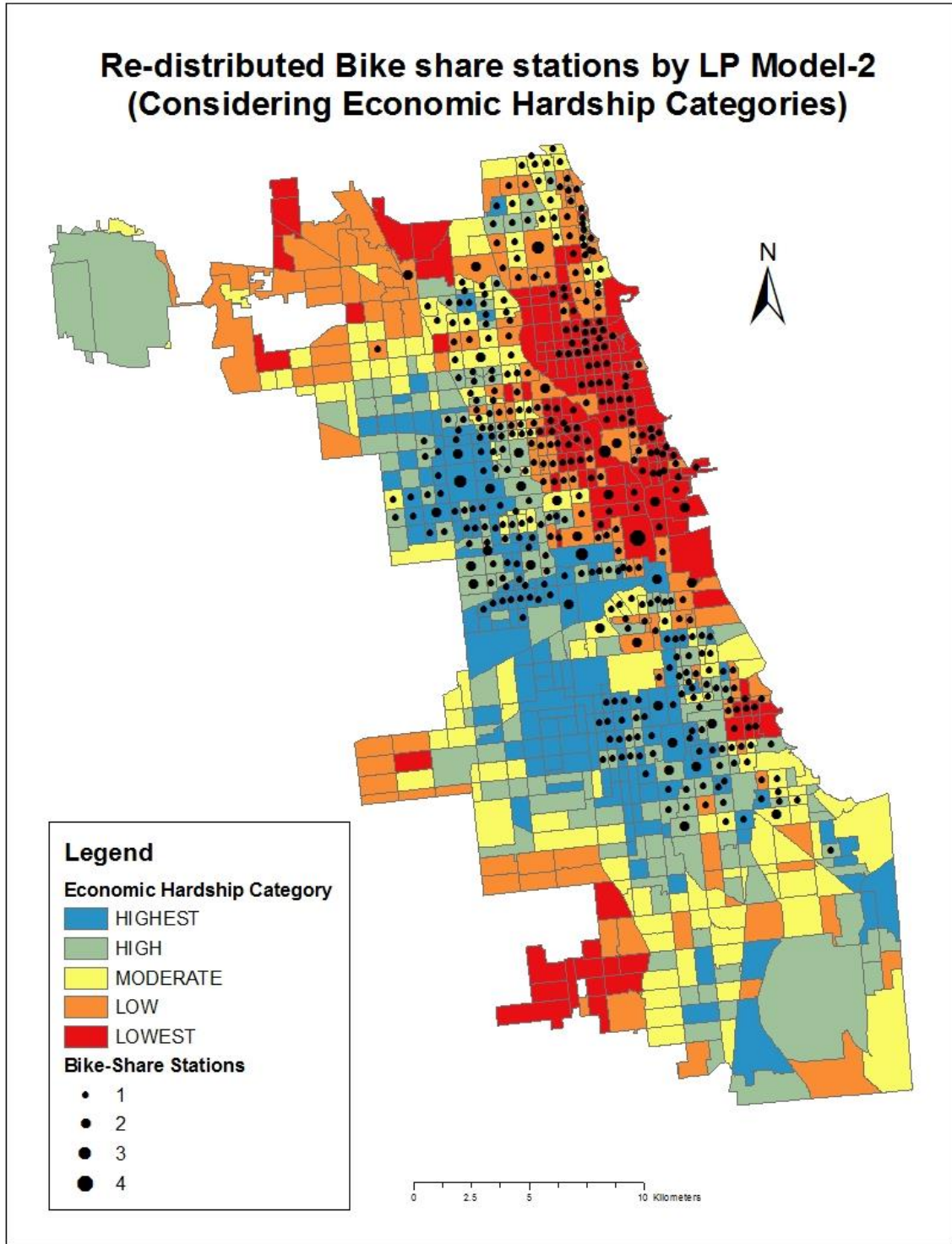
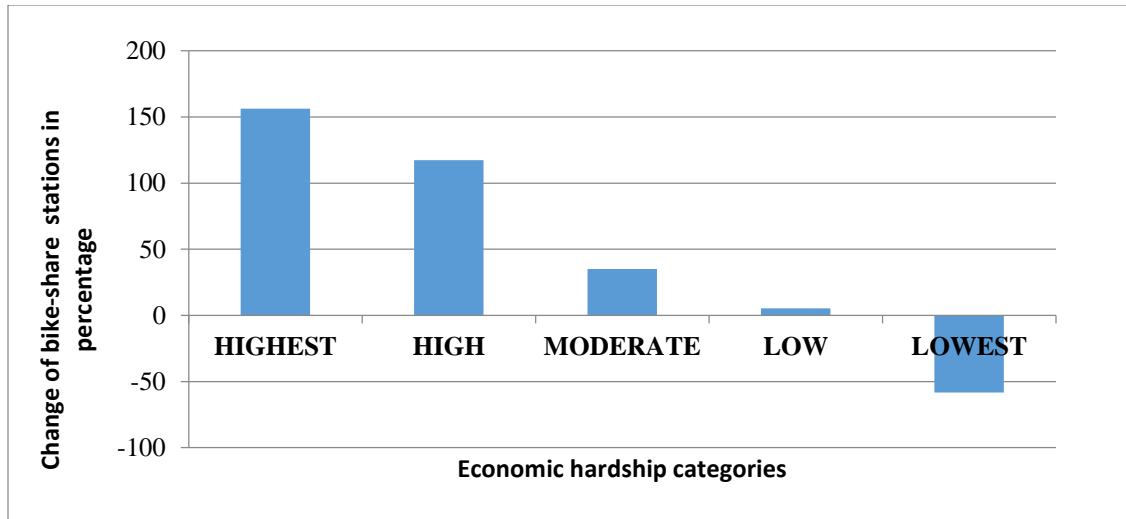


Figure 14 Map showing spatial distribution of re-distributed DIVVY stations based on LP model-2 for the city of Chicago



*Figure 15* Change in percentage of DIVVY stations for different economic hardship zones from expanded distribution to the re-distribution by LP model-2

According to Figure 15, overall number of bike share stations was increased by the re-distribution of LP model-2, in comparison to expanded distribution of DIVVY stations. A sequential percentage gain of about 40 percent, 120 percent and 150 percent was noticed for the moderate, high, and highest economic zones respectively. Total percentage of bike share stations for low category was slightly increased (about 5 percent) to LP model-2 in comparison to expanded distribution of DIVVY stations. Only the bike-share stations for lowest category was negatively changed (about 70 percent) by re-distribution of LP model-2, in respect to expanded distribution (Figure 15).

#### 6.2.1 Correlation between Composite Accessibility and Re-distributed DIVVY Stations Based on LP Model-2

A correlation matrix was computed with the composite accessibility and the resulted bike share stations by LP Model-2 across the different economic hardship categories. From Table 12, the Pearson's correlation value was about 0.65 and it presented

a moderately positive value. Since there is a positive correlation between the composite accessibility and re-distributed DIVVY stations, the re-allocation process was truly acceptable for the LP model-2.

Table 12

Correlation between the composite accessibility and the re-distributed bike share stations by LP model with considering economic hardship constraints

|                               |                     | Bike-share stations | Composite accessibility value |
|-------------------------------|---------------------|---------------------|-------------------------------|
| Bike-share stations           | Pearson Correlation | 1                   | .645                          |
|                               | Sig. (1-tailed)     |                     | .229                          |
|                               | N                   | 5                   | 5                             |
| Composite accessibility value | Pearson Correlation | .645                | 1                             |
|                               | Sig. (1-tailed)     | .229                |                               |
|                               | N                   | 5                   | 5                             |

The correlation value was lower for the re-distributed DIVVY stations by LP model-2 in comparison to LP model-1. Since the LP Model-2 was calibrated based on the constraints value of economic hardship categories, it held more limit to run the data model for LP Model-2 than Model-1. Figure 16 showed the spatial relationship with the composite accessibility and Model-2.

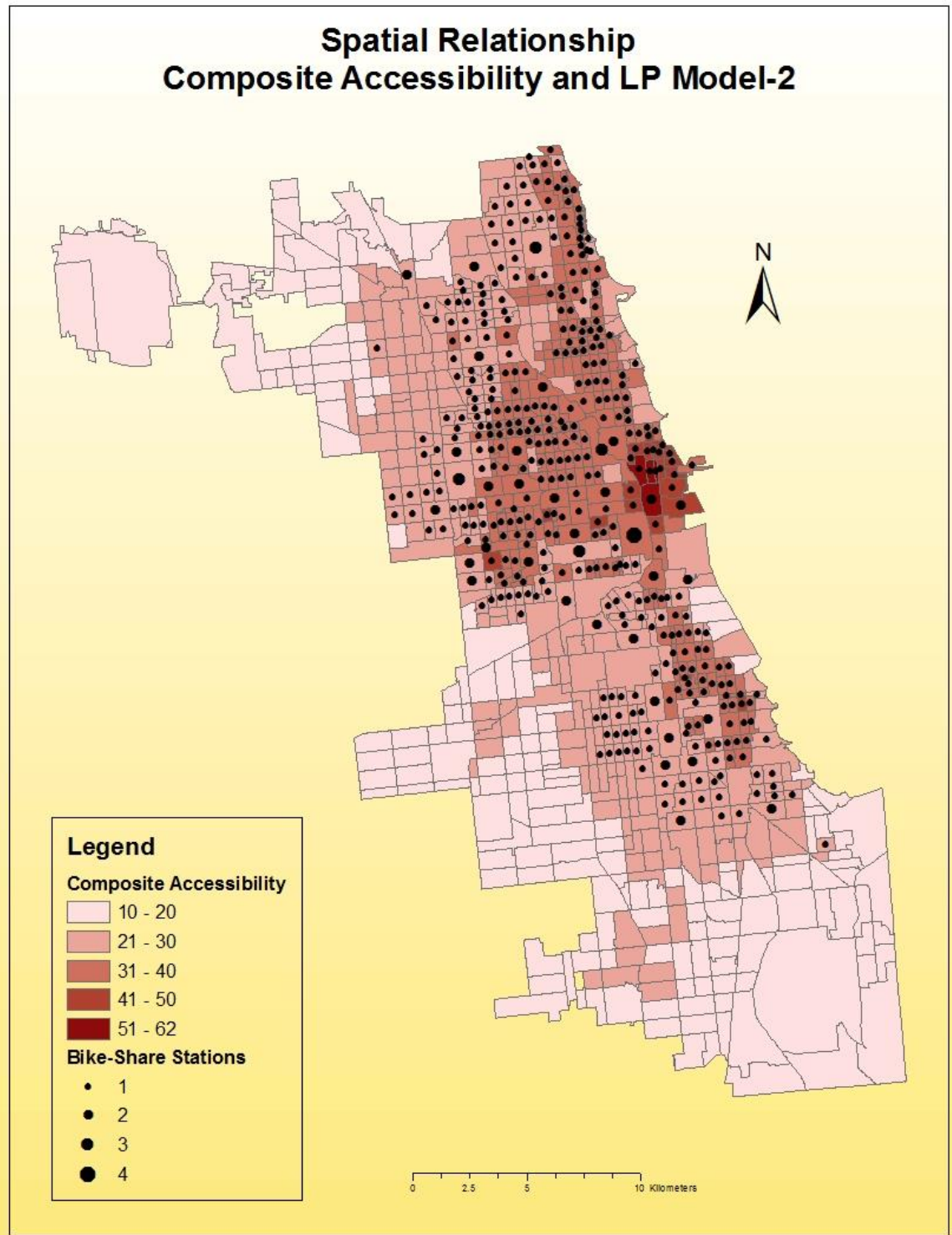


Figure 16 Map showing relationship between composite accessibility and re-distributed DIVVY stations based on LP model-2 for the city of Chicago

### 6.2.2 Comparison of Expanded Distribution and LP Model-2 in Respect to Categorical Deviation from Mean Bike-share Station Value

A comparative distribution against the average bike share stations were presented in Figure 17. The expanded distribution and the re-distributed bike share stations by LP Model-2 were examined in this sub-section to observe the deviation from the mean bike-share station's value.

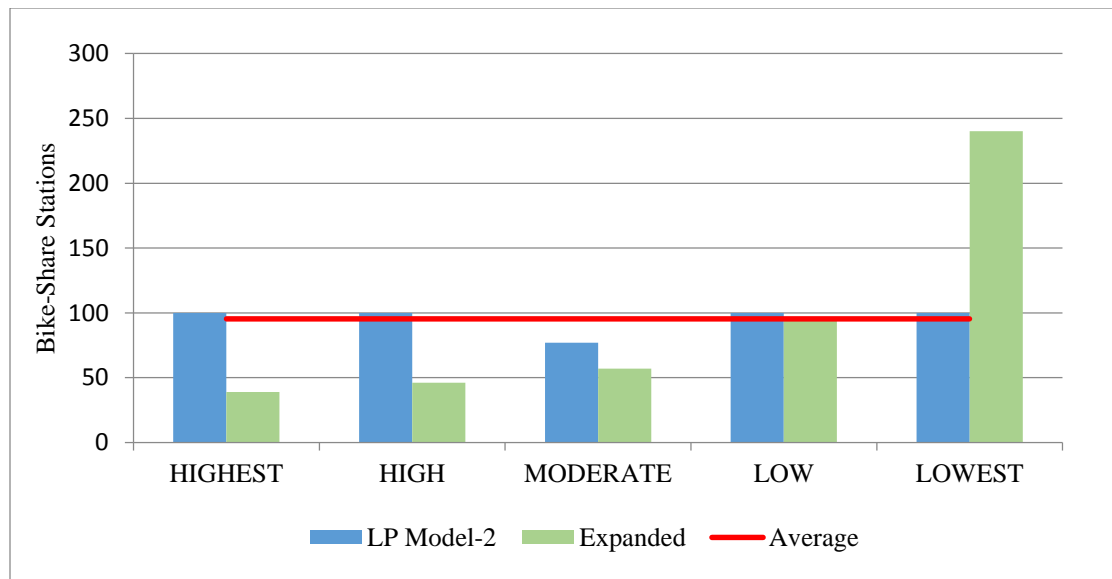


Figure 17 Comparison from mean value for the expanded bike-share distribution and the re-distributed DIVVY stations by LP model-2

Almost all of the economic hardship categories met the average value of the bike-share stations according to the re-distribution by LP Model-2 (Figure 17). Only the moderate economic hardship zone was negatively deviated (about 20 percent) from the average value.

But, Figure 17 showed a huge deviation from the mean station number value for the distribution based on expanded bike share stations. Highest, high, and moderate

categories were negatively deviated from the mean bike station value, while lowest category was positively deviated for the distribution based on expanded bike share stations.



## CHAPTER VII

### EXPLORING THE DIFFERENT ALLOCATED MODEL IN IMPROVING EQUITABLE DISTRIBUTION OF BIKE SHARE INFRASTRUCTURE

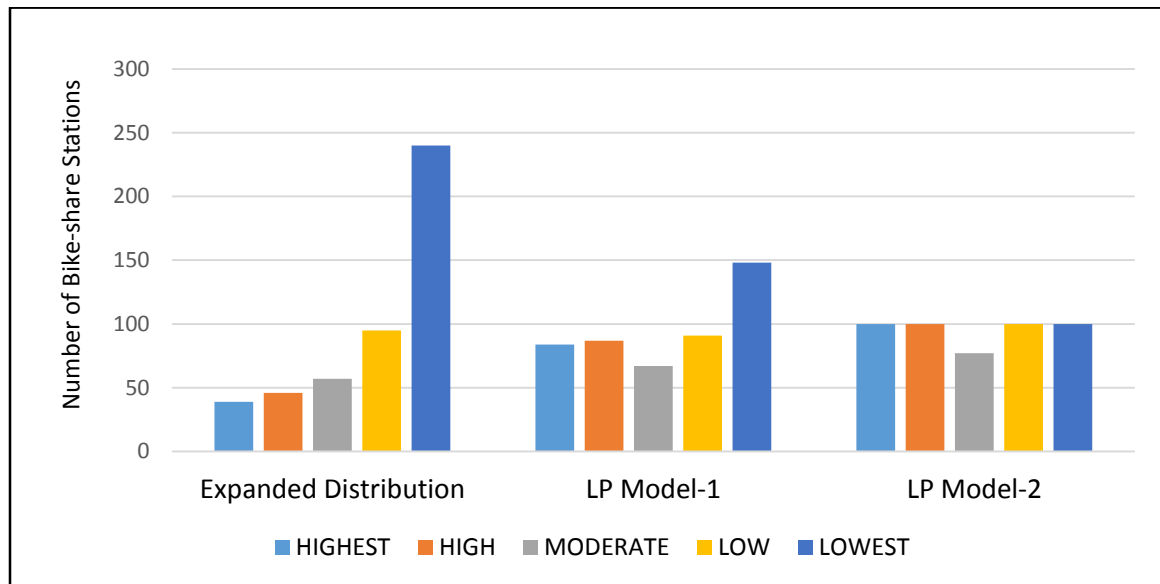
In this chapter, an overall comparison was presented to select the best model in improving the equitable distribution of bike-share infrastructure for the city of Chicago. A comparative analysis was performed between the allocation of expanded DIVVY distribution, re-distributed DIVVY stations by LP Model-1 and re-distribution by LP Model-2. Some descriptive statistics of these three types of allocation were shown in Table 13. The range was very high with extreme low and high value of bike-share stations for expanded distribution across the five (N=5) economic hardship categories. Standard deviation value was also high (about 84 stations) based on expanded allocation of DIVVY stations, in comparison to LP Model-1 and LP Model-2.

Table 13

Descriptive statistics of three types of allocation of DIVVY stations based on expanded distribution, LP Model-1, and LP Model-2

| Descriptive Statistics |                                  |                  |                  |                       |                            |
|------------------------|----------------------------------|------------------|------------------|-----------------------|----------------------------|
|                        | Economic Hardship categories (N) | Minimum Stations | Maximum Stations | Range of the stations | Std. Deviation of stations |
| Expanded Distribution  | 5                                | 39               | 240              | 201                   | 83.6                       |
| LP model-1             | 5                                | 67               | 148              | 81                    | 30.7                       |
| LP model -2            | 5                                | 77               | 100              | 23                    | 10.2                       |
| Valid N (list wise)    | 5                                |                  |                  |                       |                            |

The range (81 stations) and standard deviation (30 stations) were lower for the re-distributed allocation of bike share stations according to LP model-1 compared to the expanded distribution. The most efficient re-distribution of DIVVY stations was explored in Table-13 for the LP model-2 (with constraining the economic hardship categories). The range and standard deviation of bike-share stations were also lowest for the LP model-2, compared to other two allocations of bike-share stations.



*Figure 18* Comparison between Expanded distribution of DIVVY stations, LP model with and without constraints by economic hardship categories

The comparison in Figure 18 showed the allocated percentage of bike share stations in different models with respect to economic hardship categories. The expanded distribution showed an unequal allocation of bike-share stations to the different economic hardship zones. Almost 50 percent of total DIVVY stations were allocated only for the lowest economic hardship zone. Besides, a very few percentage of total stations were

allocated for highest and high economic hardship zones according to expanded distribution of DIVVY stations.

Alternatively, LP model-1 showed a less percentage of bike-share stations for the moderate category zone. But, the best equal distribution of DIVVY stations over the different economic hardship categories were examined by the LP model-2.

Table 14

Chi-square test for independence to examine the three allocation of expanded distribution of DIVVY stations, LP model with, and without constraints by economic hardship categories

| Chi-Square Tests             |                      |    |                       |
|------------------------------|----------------------|----|-----------------------|
|                              | Value                | df | Asymp. Sig. (2-sided) |
| Pearson Chi-Square           | 260.354 <sup>a</sup> | 8  | .000                  |
| Likelihood Ratio             | 254.159              | 8  | .000                  |
| Linear-by-Linear Association | 125.564              | 1  | .000                  |
| N of Valid Cases             | 1431                 |    |                       |

A. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 68.33.

A chi-square association test was performed with 95% confidence level to examine the relationship between the three allocations across the economic hardship categories in terms of distributing DIVVY stations. From Table 14, it was noticeable that the test significant value was less than (0.05) and it was significant. It means that there was a statistically significant association between three allocation methods and economic hardship categories. Therefore, all of the three allocation methods were not equally preferable to re-distribute the DIVVY bike-share stations across the census tracts by economic hardship categories.

Since there was a statistically significant difference among the three allocations of DIVVY stations, one of the model should be preferred finally to re-distribute the stations. Considering all of the analysis, the LP model-2 proved the satisfactory result for equal re-distribution of bike share stations across different economic hardship zones for Chicago.

## CHAPTER VIII

### CONCLUSION

#### 8.1 Summary

Transportation accessibility with equity perspective is considered as a vital indicator for sustainable urban development. Bicycle as a transport mode has become popular with city dwellers. This has led to the establishment of bike-sharing systems in many cities. However, many of these bike-sharing systems are not equitably distributed especially from the point of view of different economic hardship groups in the city. This study examined how bike-sharing system could be equitably redistributed using the Chicago DIVVY bike-sharing system as a case study.

In this study, bike-sharing stations of Chicago city were re-distributed on the basis of transportation equity perspective among the different economic hardship categories. Initially, eleven accessibility indices were computed by using the ArcGIS software for initial and expanded (total) DIVVY stations of Chicago city. Accessibility indices were calculated based on counts and network distance for different economic hardship categories. It was noticeable that the poor economic zones were facilitated with less opportunity to access the bike-share stations, in comparison to rich economic zones according to the existing scenario of bike-share infrastructure of Chicago city. Although the disparity in accessibility has tried to overcome from initial to expanded distribution, still there was a huge disparity exists between the different economic zones.

After analyzing the current disparity, linear optimization models were calibrated to re-distribute the expanded bike-share stations in an equal manner to all of the economic zones. About seven suitability indices were calculated and combined for making the composite accessibility to site the bike-share stations. Two models were calibrated by maximizing the suitability indices for the optimal allocation of bike share stations. Model-2 showed a satisfactory re-distribution of the bike-share stations for different economic hardship categories in comparison to other models and distributions. Therefore, the LP model-2 (constraints the economic hardship categories) was recommended to re-distribute the bike share stations for different economic hardship zones across the city of Chicago.

## 8.2 Major Findings

The number of DIVVY stations for Low and Lowest zone categories were replaced by High, Highest, and Moderate zone categories from initial to Expanded (Total) bike share station. For COUNT INDEX, almost two-third of the total gain in percentage was observed only for the High and Moderate categorical zone. Gaining the accessibility for high, highest, and moderate zone was extremely regulatory for all of the BUFFER FROM CENTROID INDICES (QUARTER MILE, HALF MILE, and ONE MILE). Almost similar percentage (10 percent) was gained combinely by low and lowest categories for all of the indices about BUFFER FROM TRACTS INDEX (QUARTER MILE, HALF MILE, and ONE MILE). The increase in accessibility was prominent at Moderate zone for all of the accessibility indices based on network distances. The percentage change at Moderate zone for ACCESSIBILITY (QUARTER MILE) INDEX was 15 percent and 13 percent more than ACCESSIBILITY (HALF MILE) INDEX and ACCESSIBILITY (ONE MILE)

INDEX consecutively. According to ACCESSIBILITY (No CUT-OFF) INDEX, the gain in percentage was more than three times for High, Highest and Moderate zone than the percentage gain for Low and Lowest zone. The range and standard deviation value was too high for expanded allocation of bike share stations across the 840 census tracts in comparison to other two LP models. More than 50 percent of the bike share stations were re-distributed for low and lowest economic hardship zones according to LP maximization without constraining Economic hardship categories (Model -1). An equal distribution of bike-share stations were notified for all of the economic hardship categories except the moderate zone for the LP model with considering the constraints (Model-2).

### 8.3 Recommendations

The re-distributed bike-share stations by LP Model-2 could be a good alternative for the bike planners and policy makers to ensure the equitable distribution of DIVVY bike-share stations across the city of Chicago. The proposed method by linear optimization technique could be a viable option to introduce or re-distribution of equitable bike-share stations for different communities of the cities around the world.

However, only economic hardship categories does not cover the full scenario in evaluating the transportation equity. The further work could be continued with considering the other factors in addition to economic hardship criteria for re-distributing the DIVVY stations in the view of equity perspective. The user's demand could be incorporated for siting the re-distributed bike-share stations for further transportation planning purposes. The most used bike-stations also could be considerable for the re-distribution process.

In this study, the individual spatial location of the re-distributed bike-share stations across the different economic zones was not shown due to the lack of XY coordinate data. Further studies could be continued in detail analysis with the individual location of each bike-share station for a particular zone by using composite suitability.



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