

An optimization approach for equitable bicycle share station siting

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ABSTRACT

Bicycle share systems are becoming an increasingly popular feature of many urban areas across the United States. While these systems aim to increase transit mode options as well as overall bicycle ridership, bike share programs also face challenges and criticisms related to density and inequitable distribution of services. Key factors in the success of bicycle share include high station density as well as services that reach a variety of neighborhoods, though many current systems do not reach low-income areas. Equitable station distribution therefore appears to be a complex problem to address. We propose utilizing spatial analytics, including GIS and spatial optimization, to help site bicycle share stations across an urban region. Specifically we seek to apply a covering model to assess how many bicycle stations are needed, and where they should be located, so no user would have to travel too far for access. The city of Phoenix, Arizona, is used as a case study to illustrate the coverage and access tradeoffs possible through different investment strategies. Accordingly, for a given investment level, the set of stations is identified that provides the best access to the designated bike path network for the greatest number of potential users. Further, tradeoff options that differentially favor either network or population coverage are possible, and can be identified and evaluated through the proposed analytical framework.

1. Introduction

Cycling is associated with a range of individual and population-level benefits, including decreased risk of adverse health outcomes as well as reduction in carbon emissions typically associated with motorized traffic (Kuzmyak and Dill, 2014). Despite benefits, cycling rates remain low in the United States, representing around 1% of all trips (Kuzmyak and Dill, 2014). One avenue for increasing rates of cycling is for cities to adopt public bicycle share programs, providing on-demand access without the responsibility of ownership, eliminating the need for storage, and reducing risk of theft (Smith et al., 2015). In a typical community-based bicycle share model, users check out a bicycle from a kiosk or station for short-term rental and return it to another station (or the same station) after a short period of use (Fishman et al., 2013; DeMaio and Gifford, 2004). Contemporary versions of these programs require payment via credit card or smartphone application, and the bicycles themselves are equipped with tracking technologies that allow program operators to follow bicycle movement between stations (Fishman et al., 2013). If a user returns a bicycle outside the time allotted by the program, additional charges may be incurred (DeMaio and Gifford, 2004). Both of these features allow users and bicycles to be tracked and provide incentive against theft of equipment. Bicycle

sharing programs have become increasingly popular in recent years, with over 600 cities worldwide currently in operation (Smith et al., 2015). Within the United States, adoption of bicycle share systems has been steady, with > 60 cities now having active programs.

1.1. Benefits of bicycle share programs

Incorporating bicycle share systems into the mode choices available to urban commuters has several potential benefits including increased active transport, a reduction in negative environmental impacts associated with motorized travel, and providing connection to other transit modes (Shaheen et al., 2010; DeMaio, 2009). Cities with low levels of cycling as a travel mode may have as much as a 1.5% increase in cycling activity after bicycle share programs are introduced (DeMaio, 2009). Further, cities with bicycle sharing have increased rates of transit use as connectivity to other modes increases. Commuters who already use public transit may opt to use a bicycle share program over transfers or walking to save time (Shaheen et al., 2010; DeMaio and Gifford, 2004). Connection to other public transit modes has the potential to aid the “last mile problem” (Shaheen et al., 2010) where commuters can arrive relatively close to a destination via transit, but might still be in need of additional transit support for distances that are

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too far to walk. Bicycle share activity is higher around public transit links, especially during peak hours, and many riders may use the bicycles to reduce overall travel times associated with transfers and backtracking that are necessary in some transit systems (Ricci, 2015; Fishman et al., 2013). Bicycle share stations with high activity are also associated with areas lacking public transport accessibility, suggesting that bicycle share can fill gaps in public transport along with the positive interaction potential with existing transport options (Fishman et al., 2014; Ricci, 2015).

A reduction in personal vehicle trips associated with increased bicycle trips has the potential to reduce greenhouse gas production, though overall modal shift in areas with bicycle share programs is necessary to realize this benefit (Shaheen et al., 2010; DeMaio, 2009). Specifically, the greatest benefit in terms of emissions would come from those bicycle share users who would otherwise use a personal vehicle and total motor vehicle miles travelled has been reduced with adoption of bicycle share (Ricci, 2015). Cycling as a transport mode is also associated with reduced risk of obesity, hypertension, and overall lower mortality (Buehler et al., 2016; Saunders et al., 2013). Those living near bicycle share stations tend to have increased cycling activity, with bicycle share use associated with lower body mass and reduced stress (Ricci, 2015).

1.2. Factors influencing bicycle share use

While there are clear benefits to integrating bicycle share within an overall public transport design, there are user-level factors that may determine whether systems are successful. Station location and density are among the most important factors in bicycle share system success; stations should be located close together so that users are not taxed with walking far distances to access the system while also giving riders increased options to connect with stations. Uniformly high density within bicycle share systems, or stations located approximately 1000 ft. apart or at a density of 28 stations per square mile, is associated with higher ridership overall (NACTO (National Association of City Transportation Officials), 2015). “Convenience” is often stated as a motivator for taking advantage of bicycle share; living in close proximity to a bicycle share station results in higher utilization, with walking as the most common mode that people use to connect to stations (Fishman et al., 2013, 2014; Fuller et al., 2011).

Density and distribution across different types of neighborhood types is also key in fostering bicycle share ridership, though equity in spatial distribution has been criticized in many North American systems (NACTO (National Association of City Transportation Officials), 2015). Bicycle share and other “active living” programs have targeted communities with higher socioeconomic status (Smith et al., 2015). There is risk of further marginalizing traditionally underserved populations if station distribution is not equitable across a region. Lower-income communities may be more likely to experience difficulties related to mobility and accessibility overall and tend to be underserved by bicycle share systems (Smith et al., 2015). Bicycle share is often not a convenient or accessible transport option in low-income neighborhoods as station density does not make it a practical choice among transport options (NACTO (National Association of City Transportation Officials), 2015). Despite lower bicycle station density in areas with lower socioeconomic status, users in those areas make a higher number of trips after controlling for station density and expanding systems into lower-income areas has led to increased ridership among low-income users (Ogilvie and Goodman, 2012; Goodman and Cheshire, 2014). This suggests that convenient access and visibility in low-income areas is crucial in developing both equity and increased ridership within bicycle share systems (Goodman and Cheshire, 2014).

One factor contributing to inequitable station distribution is that urban downtown development areas are ideal for short bicycle trips because of the density of transport destinations. Though it makes some sense to establish systems in areas where users are more likely to

quickly adopt due to proximity and concentrated activity/attractions, such an arrangement will contribute to social inequity (Ricci, 2015). Distribution of stations among urban cores as well as throughout residential neighborhoods has the potential to resolve issues related to public transit linking as well as bicycle share system inefficiencies.

1.3. Bicycle share system design

There is a need for bicycle share system design approaches that ensure sufficient density and equitable distribution across a region to foster bicycle share success in terms of access, ridership, and efficiency. One approach is to optimize system design focused on impedance and coverage (García-Palomares et al., 2012). Minimizing impedance aims to locate stations across a study area so distance between stations is minimized, and maximizing coverage aims to locate stations where the most potential demand (population) is served. While such a modeling approach identifies good locations for stations within the study area based on specific model objectives and parameters, it has notable limitations. Coverage optimization ensures that the greatest amount of benefit is provided by the system in terms of serving demand, but does not account for social equity within that population in terms of income or other factors. In a similar vein, features of the study area such as parks neighboring areas of low population density will likely be underserved by approaches that focus solely on where people live, yet are still popular destinations for bicycle share users (García-Palomares et al., 2012). Another approach focuses on projected user demand and budgetary constraints to locate stations within travel zones (Frade and Ribeiro, 2015). While such approaches consider the fiscal realities of investing in and implementing bicycle share, the results do not identify the specific locations for the stations and consider only initial investment budgets. Both approaches rely on a priori knowledge of the number of stations to be installed or a budget that restricts the number of stations. Restricting the analysis of station location to a particular number of stations (or budget) may offer insight for the initial phase of bicycle share system installation, but system expansion would require subsequent analyses, lacking integration and would likely introduce system inefficiency (Church and Murray, 2009). An effective approach for system design would consider the optimal number and location of stations at a given service standard, and would identify how best to install these stations given a particular configuration.

The purpose of this paper is to develop a framework for locating bicycle share stations that are equitably distributed throughout a region in order to meet a given service standard for access. To this end, the specific objective was to identify a configuration of bicycle share stations that provide the best network and population coverage at a one-mile service standard for a given level of investment. **If the desire is to ensure that no user would have to travel more than a half-mile to reach a station, and no more than one mile between stations, how many stations would we need and where should they be located?** Starting from a plan of equal distribution across an area ensures that the level of density is achieved and that all areas receive service, regardless of neighborhood make up. **Finally, there is a critical need for approaches with capabilities to assess and compare service provision in existing systems; in this way we improve on prior models by including assessment of tradeoff solutions for alternative station configurations.** We outline our approach and results utilizing coverage modeling. Implementation and application for bike sharing in the City of Phoenix is reported, wherein we evaluate and characterize the current system and use our modeling approach to develop a reconfigured station arrangement with greater coverage.

2. Methods

2.1. Study area

Phoenix, Arizona is relied upon as a case study in our analysis.

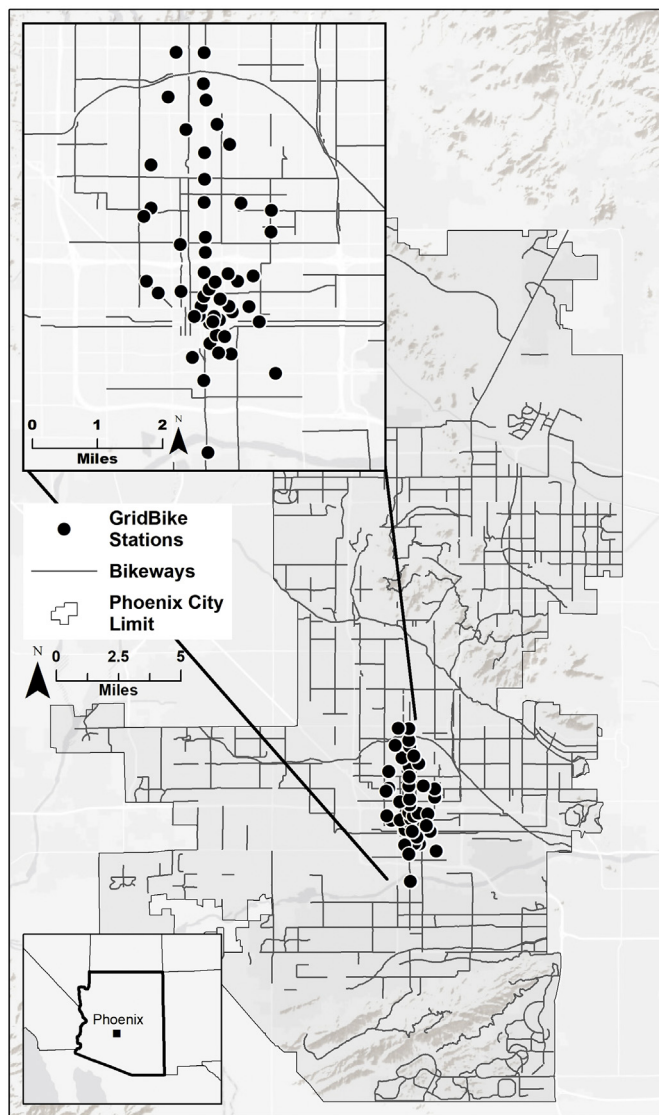


Fig. 1. Current Grid Bike station configuration in Phoenix, AZ.

Phoenix's bicycle share program, Grid Bike, launched in 2014 and plans to operate 500 bicycles throughout the region (City of Phoenix, 2014). Currently, the system has 62 stations in the Phoenix metro area, with 51 stations generally distributed around the city's downtown and midtown cores (Fig. 1). To site stations in Phoenix, Grid considers factors like ridership, traffic, visibility, and safety; most locations are also preferred to be near stop signs and ADA compliant sidewalks (minimum 4 ft. width) (Hash, 2017). The residential population in this region is 1,319,587 people.

Considering that people tend to show preference for dedicated infrastructure (e.g., bicycle lanes, separated bicycle paths) and that areas with cycling infrastructure are more likely to have higher numbers of cyclists and increased safety (Broach et al., 2012; Winters et al., 2013), we restricted our analysis to specifically designated bicycle infrastructure. While we use the bicycle network in our model, the full street network and sidewalks can be used to traverse between stations. The associated bicycle network consists of approximately 744 miles of roadway and canal paths within the Phoenix city limits and includes bicycle lanes, separated paths, and routes marked for shared use by cycling traffic. We chose a half-mile service standard as a distance that most people are willing to walk for a daily trip or errands (see Southworth, 2005). Most users are willing to travel up to a half-mile on foot to access a bicycle share station (Bachand-Marleau et al., 2012).

This service standard generally ensures a spatial separation between stations of at most one mile, representing a relatively short cycling trip and a high degree of access to other stations. Given this service standard, the current configuration of bicycle share stations in Phoenix provides coverage access to 48.9 miles of existing bicycle network infrastructure, measured as a half-mile radius from each station, and provides service coverage to 55,913 people. In percentage terms, this equates to access coverage of < 6.6% of the bike network system and approximately 4.2% of the total population of census blocks located within a half-mile radius of a bicycle share station.

2.2. Approach

A location coverage model is structured and solved to site bike sharing stations in order to provide an equitable spatial distribution across the study area. Location coverage aims to determine where to locate facilities to best serve demand, where service is defined relative to suitable access (i.e., within a certain distance or travel time) (Church and Murray, 2009). The significance of coverage standards and goals is that they reflect an aspect of equity, where users are ensured a minimal level of service (Tolegas et al., 1971; Church and ReVelle, 1974).

One aspect of demand to cover is service demand, or the bicycle infrastructure network; the facilities that cover this demand are the bicycle share stations. Since a cyclist could ride, or wish to ride, a bicycle anywhere along the network, service demand exists along the entire network, rather than at discrete locations. The network, however, is represented as discrete line segments, relatively small in size. We measure coverage herein as a half-mile radius extending in all directions from a station location. Euclidean distance was used as people walking to access bicycles on the network are not necessarily limited to the street network itself. Considering the local conditions of the study area it is possible to cut through parks, schools, or shopping centers to access station locations (Berke et al., 2007). Pedestrians are not restricted to the street network and sidewalks; since users walk rather than drive to bike stations, Euclidean distance better matches their movement patterns as users will attempt to minimize distance by taking the straightest path while walking to stations. Related, the street network in Phoenix is largely gridded, with long blocks- with up to 1 mile between major arterial streets in the downtown area-, so a half-mile distance restricted to the street network does not present many options in terms of turning or network travel choice. A second aspect of demand to be covered is residential population, which also is essentially continuously distributed throughout the region, reflecting that a user may originate almost anywhere. However, population based information is only available at the Census block level, so is assumed to originate from these discrete spatial units.

While bicycle share can theoretically be sited almost anywhere in the region, analysis was undertaken to derive a feasible set of potential sites. Research by Wei et al. (2014) outlines the way in which continuous space coverage goals can be achieved through the use of discrete optimization approaches, and serves as a basis for identifying potential sites (see also Murray and Tong, 2007). Suitability analysis is used to reduce the infinite number of potential station locations to a finite and manageable set. To assist, we used a continuous arc covering model to determine the minimum number and location of bicycle stations that would be needed to cover the bicycle network infrastructure at a one-mile service standard. The main assumption of the continuous arc covering problem is that facilities, bicycle share stations, can be sited at any point along the network. Potential facility sites, therefore, are not known a priori. The objective function of the model minimizes the number of facilities sited while the constraints specify that the entirety of the network (arcs) must be fully covered by the set of selected facilities, with facilities sited along the network. The practical solution approach for this analysis was to generate and iteratively modify a point representation of the bicycle network until full coverage of the network was achieved. At each iteration, coverage was determined, the

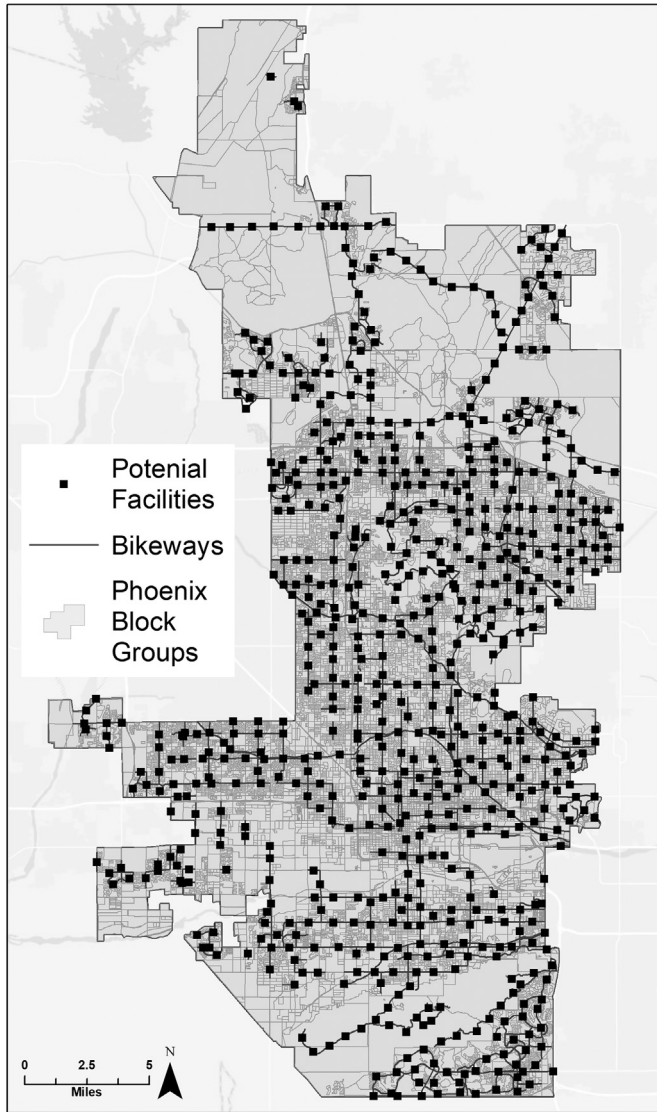


Fig. 2. Potential bicycle share station locations (693) and potential user demand (14,600 census blocks).

point representation was modified, and an optimal solution for that point set was found. Fig. 2 shows the optimal solution that was used for potential bicycle station sites.

Collectively, there are two types of demand: service demand, or line segments that represent the bicycle network, and population demand, or census block polygons that report the total number of potential users. The demand then is combined with discrete potential bicycling share station sites, which are conceived to be reasonably accessible at a half mile. This distance, 0.5 miles, therefore represents a suitable service access standard. The modeling goal is to site bicycle share facilities such that the greatest demand, both service and population, possible is served. Doing so ensures user equity in terms of access combined with budgetary limitations that would restrict the number of stations installed at any given time.

A biobjective coverage optimization model is proposed based on extending the work of Church and ReVelle (1974). The objectives are to (1) maximize total bicycle network coverage, and (2) maximize potential user demand coverage. Supporting mathematical notation is as follows:

- k = index of bicycle network segments
- i = index of population blocks (user demand)
- j = index of potential bike share facilities

Ω_k = set of potential bike share facilities, j , capable of serving/covering network segment k

Ψ_i = set of potential bike share facilities, j , capable of serving/covering user demand i

β_k = value or length of network segment k

α_i = number of potential users in demand area i

w = importance weight for bicycle network coverage, [0, 1]

p = number of bike share stations to site (budgetary limit)

$$X_j = \begin{cases} 1 & \text{if share facility sited at location } j \\ 0 & \text{otherwise} \end{cases}$$

$$Y_k = \begin{cases} 1 & \text{if network segment } k \text{ is covered by sited bike facility} \\ 0 & \text{otherwise} \end{cases}$$

$$Z_i = \begin{cases} 1 & \text{if user demand } i \text{ is covered by sited bike facility} \\ 0 & \text{otherwise} \end{cases}$$

This notation is now utilized to structure the associated coverage model relied upon. The formulation is as follows:

$$\text{Maximize } \sum_k \beta_k Y_k \quad (1)$$

$$\text{Maximize } \sum_i \alpha_i Z_i \quad (2)$$

Subject to

$$\sum_{j \in \Psi_k} X_j - Y_k \leq 0 \quad \forall k \quad (3)$$

$$\sum_{j \in \Omega_i} X_j - Z_i \leq 0 \quad \forall i \quad (4)$$

$$\sum_j X_j = p \quad (5)$$

$$X_j = \{0, 1\} \quad \forall j \quad (6)$$

$$Y_k = \{0, 1\} \quad \forall k$$

$$Z_i = \{0, 1\} \quad \forall i$$

The objectives, (1) and (2), seek to maximize potential service demand associated with the bicycle network and residential population, respectively. Constraints (3) and (4) link bicycle sharing station siting decisions to the coverage they provide to the bicycle network and to the associated user demand polygon units, respectively. Constraint (5) stipulates the number of bicycle sharing stations to be sited. This is equivalent to a budgetary limitation. Binary integer decision variables are specified in constraints (6).

The two objectives complicate application and solution of this location coverage optimization model because the decision to locate a station will not necessarily be equally beneficial for network coverage and user demand coverage. In fact, they may be conflicting. A common approach to integrating bi-objectives is through the weighting method (see Cohon, 1978). This involves the introduction of a priority weight, w . This weight, typically ranging in value between 0 and 1, then enables the integration of the two objectives as one weighted objective as follows:

$$\text{Maximize } w \sum_k \beta_k Y_k + (1 - w) \sum_i \alpha_i Z_i \quad (7)$$

Solution of this objective therefore requires a priori specification of w , reflecting decision-makers' preference for one objective over the other. In practice a range of weights are generally considered, enabling the generation of a tradeoff curve that can subsequently be evaluated for decision making and analysis purposes.

3. Application

The demand and potential station sites are shown in Fig. 2. The bicycle network consisted of 744 miles of roadway and canal paths within the Phoenix city limits that constitute bicycle lanes, separated paths, and routes designated for cycling traffic along with roads that provide interconnection. The network was represented by 4668 discrete line segments. Potential users were derived based on the 2010 Census Block population. There were 14,600 blocks with non-zero population, with a total population of 1,319,587 within the study area. Depending on specific planning goals, other measures of demand, such as proximity to public transport links or low-income areas, could also be used. Share station sites consisted of 693 potential locations, and are illustrated in Fig. 2.

Data processing and determination of coverage provided were carried out in ArcGIS using Arcpy. The bi-objective model was solved using FICO Xpress-IVE. All analysis was done on desktop personal computer (Intel Xeon E5 CPU, 2.30 GHz with 96 GB RAM). Investment level p and objective priority weights w were varied to obtain a range of decision making alternatives. Values of p ranged from 1 to 693, and 12 different objective weights were examined (1, 0.9999999, 0.999999, 0.99999, 0.9999, 0.999, 0.9, 0.8, 0.5, 0.1, 0.0001, 0). In total, 8316 different optimization problems were solved requiring approximately 4.09 s of computing per problem.

Varying weights and re-solving the model produces likely non-dominated solutions, if a unique solution is identified. The solutions obtained enable a number of potentially interesting tradeoffs to be considered, such as: Objective (1) vs. Objective (2) for a given value of p ; Objective (1) vs. p ; and Objective (2) vs. p .

4. Findings

The overarching aim of our analysis is to demonstrate that bicycle share stations can be distributed in a way that is both spatially and socially equitable, while at the same time being sensitive to budgetary realities. Complete coverage of the entire region is possible if all 693 potential station sites are selected; the network is completely covered, and voids of coverage in the study area are restricted to the interior of parks without road access, topographic barriers such as mountains, and sparsely developed areas of the city with few roads. Subsequent proximity analysis indicates that the overall mean distance between sited bicycle stations and their nearest bus stop is under one mile. Over 100 of the sited stations would be outside regions of the city that do not have any public transit access at all. The mean distance to bus stops falls to approximately 0.25 miles when stations located in the transit-sparse regions are excluded. Approximately 25% of the census tracts within Phoenix had a low to low-middle median household income (under \$32,500) in 2014, and 14.5% of the sited bicycle share stations fall within those tracts.

The bicycle network and population coverage achieved when the dual objectives of network and population coverage are weighted $w = 0.5$ is shown in Fig. 3 for the entire range of investment levels. The number of bicycle share stations to install is given along the x-axis ($p = 1$ to 693). The y-axis indicates the percentage of coverage associated with the particular number of stations installed, with a curve for both network and population service. The network coverage rises steadily as the number of stations increases while population coverage increases rapidly but begins to taper beyond 300 stations.

Fig. 4 shows the biobjective tradeoff for $p = 51$ stations with w ranging between 0 and 1. Network coverage is favored when w equals 1, whereas population coverage is favored for a value of 0. Intermediate values, therefore, represent trading off the favoring of these two extremes. The coverage provided by the current 51 existing station arrangement is also shown. That the existing coverage lies below the curve highlights that the existing station configuration is comparatively inferior to all of the tradeoff solutions. That is, one can always do better

than the existing system in terms of covering the network or serving the user population.

It is possible to more closely evaluate several of these tradeoff solutions ($w = 0.999$, $w = 0.5$, and $w = 0.99999$). In the first case, network coverage is favored, but as depicted in the tradeoff curve is capable of suitably serving 200,000 people within the half-mile standard. In addition, approximately 200 miles of network coverage is provided by the 51 stations sited. This configuration is shown in Fig. 5a. The stations selected using the location coverage model in this case are fairly evenly distributed across Phoenix, rather than being tightly clustered in the city's downtown core. In percentage terms, coverage is provided by this configuration of share stations to some 27% of the bike network and 15% of the population, greatly exceeding the capabilities of the existing configuration of stations. The $w = 0.5$ solution shown in Fig. 5b accounts for both network and population coverage; as is shown, the configuration is quite similar to the $w = 0.999$ solution with even distribution across the city and without clustering in the downtown core. Finally, the $w = 0.99999$ solution in Fig. 5c weights network coverage even more favorably and shows a more varied distribution of stations across the study area, including many in the downtown core.

5. Discussion and conclusions

The objective of this paper was to demonstrate how bicycle share stations could be spatially distributed to enhance station accessibility while also attaining spatial and social equity. Reconfiguring the current 51 station alignment would make considerable sense to this end and fiscal realities suggest that complete system coverage using 693 stations is likely unrealistic, at least in the short-term, in Phoenix. The proposed framework and approach outlines a method for first determining how many stations are needed for a given level of service, and then selecting stations based on investment level in order to best cover the region. As shown by Figs. 3 and 4, there are many options for enhancing both network and population coverage. The current station configuration (Fig. 1) and the proposed reconfigurations of station locations (Fig. 5) differ greatly, demonstrating that conventional system design might be at odds with a simultaneous goal of network coverage and spatial equity.

That 693 stations would be needed to cover the city of Phoenix highlights some key considerations within the current dialogue around system design. Two of the largest bicycle share programs in the United States serve the New York City and Washington, DC metro areas with over 600 and 400 stations respectively. While these regions differ from Phoenix in population density and size, they demonstrate that even where bicycle share systems deploy large number of stations, issues related to spatial and social distribution of those stations persist (Smith et al., 2015). The assessment that effective system design involves spatially dense station configuration across large areas that include low-income neighborhoods presents seemingly incompatible goals for programs that are relatively new or lacking in capital for initial investments. The 693 stations needed to cover the study area in this example would represent about one station per square mile, which is a density that is much less than the recommended 28 stations per square mile. While high station density is one of the ultimate goals among bicycle share systems, the recommended density is unlikely to achieve an even spatial distribution that is also socially equitable. Our analysis highlights the need for system developers and stakeholders to anticipate the need for a very high number of stations to achieve the density and equity necessary for success in terms of ridership and integration into an overall transport system. Though it is possible to identify a solution that covers the entire network at a distance standard that is both bikeable and walkable, it is likely that a denser system with stations spaced even more closely together would require many more stations to be located. Increased numbers of stations satisfies more demand and provides more accessibility within the system, though there are diminishing returns in terms of the tradeoff between costs and

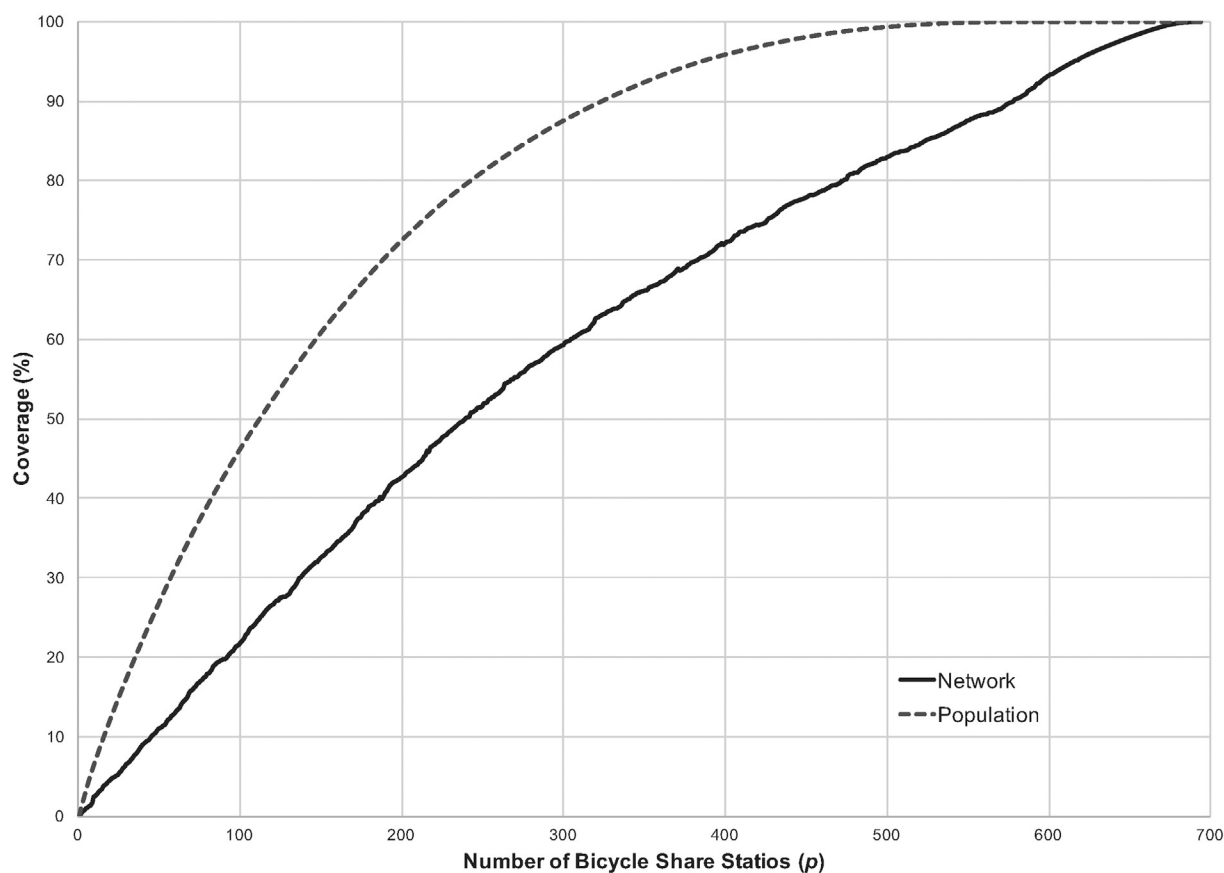


Fig. 3. Coverage for network and population for a given p ($w = 0.5$).

improvement in demand served, as demonstrated in Fig. 2 (see also García-Palomares et al., 2012). One can note as well that the approach also sited stations that increased access to public transport as well as filling gaps in areas with reduced access to any public transport; these factors are associated with increased use of bicycle share systems and may contribute to overall success of the system (Fishman et al., 2014).

Despite the need for balance between system costs and station distribution, the need for equity within the system, and particularly the

need to refrain from further marginalizing disadvantaged portions of urban populations, must also be considered. The value of the developed modeling approach is that tradeoff options between population and network coverage and the number of stations installed can be generated and evaluated to realize particular goals in terms of coverage and equity. A further benefit of the proposed approach is that it avoids a priori limits to where and whom can be served by the bicycle share system by first generating a set of station locations that evenly covers

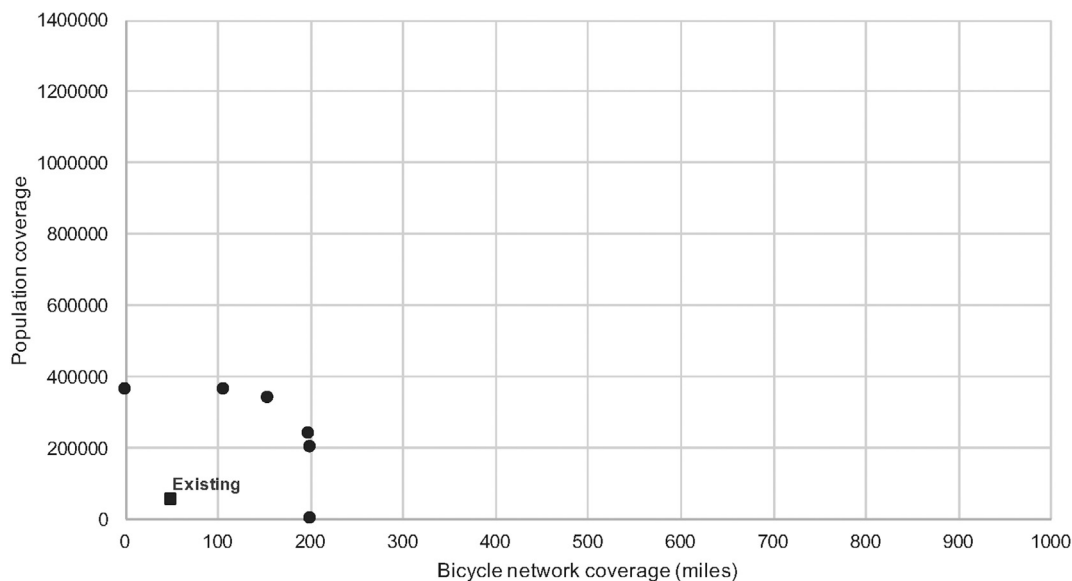


Fig. 4. Tradeoff solutions for $p = 51$.

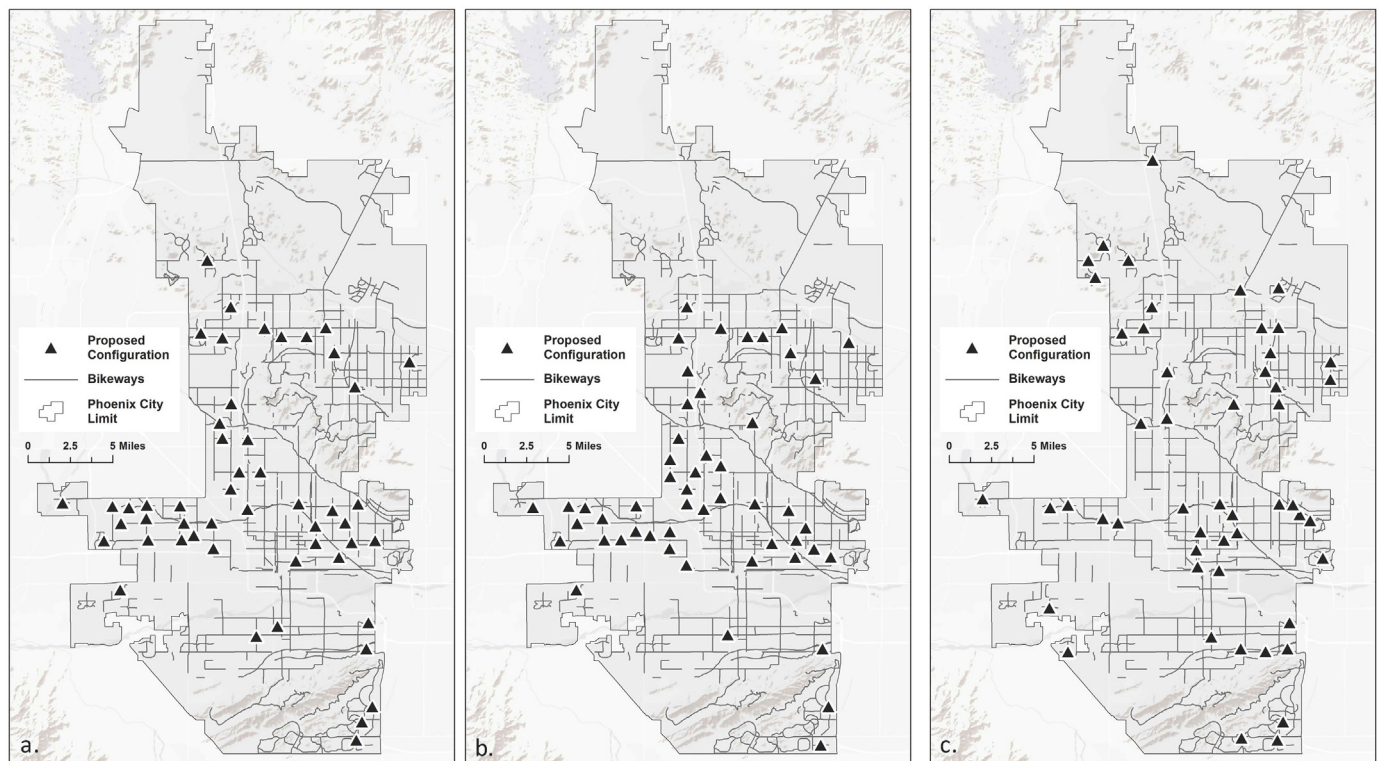


Fig. 5. Proposed bicycle share configuration a, ($p=51$ & $w = 0.999$); b, ($p=51$ & $w = 0.50$); c, ($p=51$ & $w = 0.99999$).

the service area. In comparing the current bicycle share configuration (Fig. 1) with the proposed reconfigurations in Fig. 5, it is notable that none of the current station locations appear to be selected when using weights equal to 0.999 or 0.5; it is only when the weight very heavily favors the network ($w = 0.99999$) that stations in the downtown core appear. The $w = 0.999$ configuration more than triples the population coverage and provides four times more network coverage than the current arrangement, despite not being congruent with any current station locations. In fact, it shows that in assessing and prioritizing network and population coverage it is possible that one can do much better by distributing stations outside the downtown core. Our model confirms this notion where at $w = 0.99999$ the network is heavily favored and stations are placed downtown at a detriment to population coverage (Fig. 5c). The divergence in station distribution between these configurations aligns with previous notions that a focus on locating stations in areas of higher economic and social activity likely results in social inequity and uneven patterns of use among differing socioeconomic groups (Ricci, 2015). This finding also substantiates the assertion that high station density and ensuring distribution across a variety of neighborhoods to provide social equity are somewhat incompatible goals without design approaches that account for both. While initial system design may prioritize urban cores, the developed framework provides a means to assess service provision. Current system coverage can be evaluated in terms of the level of service, and different coverage scenarios (e.g., prioritizing population coverage) can be compared to generate more effective system designs.

One limitation of the current analysis is that we chose to site bicycle share stations only where bicycle infrastructure of some kind was present. While we made this choice under the assumption that bicycle share users would likely feel more comfortable riding in those areas, it is possible that access to bicycle infrastructure itself may not be equitable across the study region. Rather than planning along existing infrastructure, the entire street network could be used as the demand to avoid potential bias related to current inequitable distribution of bicycle facilities. Again, it is likely that an increasingly high number of

stations would be needed to cover the entire street network rather than the bicycle network alone. A further limitation related to the use of installed bicycling infrastructure as the study area is that the model and our analyses do not ensure that the system is bikeable between stations. Areas of the network may not be contiguous and require a user to leave the bicycle infrastructure and access portions of the road infrastructure not marked as bicycle facilities. While we have explored tradeoffs and discover that the basic findings remain consistent, there are more comparisons that could be examined. For example, service coverage could be relaxed or more flexible with variable coverage levels for population and network (e.g., 1 mile coverage for population and 2 mile coverage for the network).

Density and equity of station distribution is just one part of making bicycling share succeed in the United States. There are also concerns related to costs for rentals and system use. Expansion into lower-income or overall broader geographic space may require that fees on the user-end increase; this could result in reduced trips overall for lower-income users despite neighborhood access (Goodman and Cheshire, 2014). Some systems have used subsidies or discounts for low-income residents so that bicycle share use is a financially feasible option for them (Smith et al., 2015). In a similar vein, potential users on the lower end of the income spectrum may not have credit or debit cards, or access to smartphones which are often required to provide payment to access the system (Goodman and Cheshire, 2014). Bicycle share must be a feasible and attractive transport option to ensure its success in the United States. Despite potential benefits of bicycle share systems, it is clear that station location and spatial distribution are a key factor in fostering success. Stations tend to be located among areas with the lowest rates of economic hardship, which leads to less access for low-income users and overall lower rates of use from those users. Equitable station distribution that also achieves a level of density that makes distances between stations walkable or bikeable is one way that systems could reduce inequities while fostering increased rates of overall ridership.

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