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by

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A GEOGRAPHICAL ANALYSIS OF BICYCLE SHARING SYSTEMS

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Vélib' jeté dans le canal Saint-Martin qui réapparait
lors du vidage du canal

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Contrast and colour modified from original

"C'est vraiment bien [mobi, le système de vélo en libre service de Vancouver]. Il faudrait maintenant plus de pistes cyclables. . . "

Pascale de Rotrou

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Contents

Chapter 1

Introduction

Transport is a fundamental necessity of individuals to access goods, services, recreation and employment. Within the last century the rise and domination of motorized vehicles has modified the distances travelled to access destinations and in the process dramatically reshaped urban form and land use to meet demand (Docherty, Giuliano, and Houston, 2008). Motorized travel has however come with many negative consequences: the rapid urbanization of arable land and wilderness, social inequality, environmental degradation, increased energy consumption, automotive, cyclist and pedestrian fatalities and other outcomes from a sedentary lifestyle (Knowles, Shaw, and Docherty, 2008; Stradling, Meadows, and Beatty, 2000).

Within the context of conventional private car dominated transportation, technological developments have recently introduced bicycle sharing systems, a form of shared transport, into many of Europe's, North America's and Asia's larger cities to address some of the ills of existing urban transportation (DeMaio, 2009). Bicycle sharing systems (BSS) are autonomous systems of accessible bicycles that can be easily used for one way trips between stations or points within an area. This thesis evaluates whether BSS initiatives are effective at beneficially transforming urban transportation socially, environmentally or economically.

The historic reshaping of cities to accommodate car travel and parking has been at the expense of other travel modes. Where a little over a century ago streets were shared spaces for pedestrians, cyclists, horse carriages and trams, they have been replaced almost completely by private cars. With the increased speed of cars, equivalent travel times allowed travel of much greater distance and access to existing arable land or wilderness for residential development (Potter and Bailey, 2008). This increase in travel distance also necessitated the development of roads, further consuming land. Over the following decades the spread of populations required the creation of a network of roads to connect services, employment and recreation where parking became ubiquitous (Jakle and Sculle, 2004). Fundamentally cars require more space to travel and, at their destinations, park. This has caused some urban residential cores, especially in North America, to be demolished in exchange for highways to accommodate access to urban cores by suburban car commuters (Benesh, 2014). Private cars, independently of their emissions, are bound by geometric limitations that monopolize space and reducing alternative land use possibilities (Handy, 2005). Public and shared transportation options, conversely, with their more efficient use of space, can reduce the need for large roads and parking, shifting land-use back to more productive uses. Bicycle sharing systems, by their nature, allow first and last-mile connections to other modes of transport, providing a possible partial solution to existing car dependence.

Aside from the geometric constrains of car dependent transport, such urban societies are unjust (Hine, 2008). Existing roads and urban structure prioritizing and facilitating car access is based on demand. Demand, however, is largely determined by wealthier individuals who can afford to travel and have cars (Martens, 2006). Additionally perceived need for travel infrastructure is largely decided by elected or business elites less aware to the requirements and realities of poorer individuals and areas (Benesh, 2014; Mercier, 2009). This can perhaps be best illustrated by the example of urban highway construction in North America, once again, that displaced lower income, typically non-white, residents. Social injustice affects lower income residents through the reallocation of land to exclusive use types, such as roads, highways and parking but also due to contrasting level of access to goods, services, employment and recreation. Households with one or two cars make two to three more journeys than those without (Stradling, Meadows, and Beatty, 2000). These additional journeys increase access to a larger selection of goods and services that may provide economic, health (better food) and recreation alternatives not as easily available to those without cars. An important promotion of BSS then, especially in North America, is the increased accessibility these systems provide. Bicycle sharing systems, more economically accessible than cars, provide bicycles to residents so that they can potentially reach destinations previously unattainable in the time or cost an alternative transport method requires.

Car dominant cultures have global environment and social impacts as well. Globally, transport is responsible for a seventh of global $C0_2$ emissions and the fastest growing emissions sector (IPCC, 2014b). Beyond transportation, the construction of cars and roads have significant energy and resource dependencies that further exacerbate their environmental impacts (Potter and Bailey, 2008). In regards to social justice, the effects of climate change will affect lower-income countries and individuals the most (IPCC, 2014a). Climate change impacts weather, temperature and fresh water supplies (among others) modifying habitats with harmful or fatal consequences for species, and species and societies dependent upon them, who cannot migrate or migrate sufficiently rapidly. With existing globalization dependencies and linkages, climate change impacts will likely be severe for all societies and individuals. Bicycle sharing systems provide an additional alternative to motorized travel, thereby helping to reduce CO_2 emissions. Additionally, the availability of bicycles in a BSS, typically promoted by municipalities, help to normalize the image of cycling for everyone, rather than for elitist recreational racers or risk taking commuters, while potentially also decreasing the barrier to individuals simply trying to cycle.

Cars have negative local impacts as well. Their exhaust can alter environments, such as soil composition through acid rain, and harm human respiratory and cardiovascular systems, among others (Cox, 2010; Schindler and Caruso, 2014). More explicit however are the socially accepted fatalities and injuries to car passengers and other more vulnerable street users such as pedestrians and cyclists. Alternatively, an insidious side affect of car dependence is the sedentary life style it promotes, increasing likelihood of drivers and passengers become overweight or obese and experiencing cardiovascular diseases. As part of a feedback loop, some pedestrians and cyclists fearing for their safety or their children's, drive as a result, further increasing the number of cars, congestion, emissions and other negative aspects. So while BSS can provide an opportunity to exercise, with many physical, sociological and mental health benefits (Garrard, Handy, and Dill, 2012), other infrastructure changes may be required to provide a sense of safety to cyclists.

Clearly cars have many advantageous as well, accessibility, comfort, convenience, among others, but as we have presented, at a large scale, some of the benefits are reduced, such as speed due to congestion, and the many other social, environmental and economic externalities. Bicycle sharing systems, in this context, are brandished by advertisers, cycling advocates and municipalities as tools to promote change in urban transportation existing unjust and unsustainable practices. Although the rise in popularity and deployment of BSS is recent, within the last decade, the idea was conceived 50 years ago. Previously BSS had been limited due to the anonymity between bicycle providers and users, relying on trust for the return of the bicycle. New IT solutions linking credit cards to bicycles ensure user accountability and the return of bicycles. In the last ten years perception of BSS have shifted from novelty to requirement for any city desiring to appear modern (Ó Tuama, 2015).

Decision makers and BSS operators, with very few exceptions, pronounce their systems as successful. With little access to data it is difficult to evaluate glowing reports quoting abstract statistics of distances travelled, CO_2 emissions reduced, members registered, number of trips over arbitrary time periods or less verifiable claims, such as social equity or congestion reduction. In addition, BSS deployments have been consistently absent of clear purpose or goals (Fishman, Washington, and Haworth, 2013; Ricci, 2015) while repeatedly stating the many supposed benefits. Creating an objective measure of success requires data, something that is typically unavailable. A typical component of conventional BSS are public web maps providing the location and number of bicycles. In aiming to determine the effectiveness of BSS, this thesis, using publicly available data, develops a methodology to estimate BSS trips in order to create a comparable metric of performance.

While there exists lots of work describing how BSS are used (Ahillen, Mateo-Babiano, and Corcoran, 2015; Beecham, Wood, and Bowerman, 2014; Borgnat et al., 2011; Fishman, Washington, and Haworth, 2013; O'Brien, Cheshire, and Batty, 2014; Parkes et al., 2013; Ricci, 2015; Wood, Slingsby, and Dykes, 2011; Zhao, Deng, and Song, 2014), no literature has been found describing how they are operated. Formalization of BSS data to estimate trips exposes new data sets not previously studied, one of which is the moving of bicycles to adjust to demand, often called rebalancing (Ahillen, Mateo-Babiano, and Corcoran, 2015; Beecham, Wood, and Bowerman, 2014; Erdoğan, Battarra, and Calvo, 2015; Parkes et al., 2013; Regue and Recker, 2014; Wood, Slingsby, and Dykes, 2011;

Zhao, Deng, and Song, 2014). The theoretical perspective has been thoroughly analysed in a short time but not described in practice. This thesis explores BSS rebalancing operations in relation to system purpose through data analysis and operator interviews.

Using estimated trips per day normalized by bicycles in the system, provides an objective comparable measure of BSS performance, one measure of success, often reported by decision makers and media. Integrating this metric with BSS attributes and system compactness, urban structures, weather and transportation infrastructure allows regression analysis to determine which factors influence performance. This thesis reveals performance for a large number of BSS as well as reporting which attributes are effective and, perhaps more importantly and contrary to recommendations by influential practitioners, which are not.

This research was initiated by apparent use of BSS for 'urban greening' and to self promote associated decision makers and municipalities, among other outcomes typical of policy boosterism (McCann, 2013), rather than being part of a larger effective cycling initiative. Trip estimation and determinants of performance analysis show that many systems are in fact little used and therefore have little of the promoted benefits. Rebalancing analysis reveals how operations and the desired benefits of BSS by municipalities do not align. Combining these findings with interviews and media analysis, this work critically examines the many promoted positive aspects of BSS. The final objective of this research is to apply a critical urban sustainability perspective to the existential conflict surrounding BSS' multiple actors, of contrasting desires, operating under the pretence of environmental or social sustainability.

1.1 Research objectives

Contemporary media, politicians, advertisers, technology providers and some academic research discuss BSS within an established narrative of success. While these systems clearly have potential in transforming urban transportation from car dependence, BSS are still largely unproven to be effective. **The primary goal of this research is to evaluate BSS performance and determine whether these systems are successful and achieve promoted social and environmental outcomes.** This critical analysis of the status quo applies quantitative and qualitative methods through four finer research questions:

1. How can the number of daily trips be best estimated when no such public data is consistently available.

2. How are operators managing BSS, specifically rebalancing aspects.

3. How does performance compare between BSS and what are the determining factors.

4. What are the purposes of the diverse actors involved with BSS and how do these impact outcomes.

The balance of this chapter summarizes BSS history, technological aspects and the multitude of actors before describing the research methodology, applied research and findings.

1.2 Bicycle sharing systems

1.2.1 BSS evolution

The evolution of BSS technology can be classified into multiple generations (Beatley, 2000; DeMaio, 2009) based on technological, information and usability. The earliest generation, initiated by a Dutch counter-culture organization in Amsterdam opposing consumerism and car pollution, simply consisted of bicycles painted white for free public use. The system quickly collapsed from theft but also due to police confiscating unlocked bikes (Teun Voeten, 1990). The idea however spread to La Rochelle in 1974, Cambridge (UK) in 1994, Portland in 1994 and Boulder in 1995 (Beatley, 2000; DeMaio, 2009; Shaheen, Guzman, and Zhang, 2010). While La Rochelle had some success (Shaheen, Guzman, and Zhang, 2010) others were short lived due to vandalism or theft (Beroud and Anaya, 2012; DeMaio, 2009).

The second generation of BSS aimed to reduce theft by using custom bicycle components incompatible with general bicycles and coin operated locks. This generation expanded in the early 1990's in Europe and later in the decade in the United States (DeMaio, 2009; Shaheen, Guzman, and Zhang, 2010). Unlike the earlier generation, bicycles needed to be taken and returned at stations. Copenhagen's 1995 system stands out due to its size and duration of operation, only closing in 2012. Despite Copenhagen's system also experiencing theft and vandalism, it has been strongly used (Beatley, 2000). With 17 years of operations it is the longest running of any BSS to date.

The third generation largely solved bicycle theft and vandalism by removing anonymity due to linking users with credit cards. Early examples, such as Portsmouth's (UK) in 1996, did not yet have the physical and information usability that has become standard. Whereas earlier generations typically name their systems after a colour, branding became an important component of third generation BSS (Shaheen, Guzman, and Zhang, 2010). Rennes' (France) system, launched in 1998, was important as it was the first BSS provided and operated by an advertiser, Clear Channel, in exchange for billboard advertising rights. Something that became common in many European countries over the next decade. A few other municipalities deployed small systems, testing their potential (DeMaio and Gifford, 2004), but it was Lyon's and Paris' 2005 and 2007 launches that spurred a decade of rapid global BSS deployments. The number of BSS in the world grew from 11, all in Europe, in 2004 to 160 in 2009 (DeMaio, 2009; DeMaio and Gifford, 2004). Determining the current number of operating BSS has become burdensome, but as of 2016 there are likely more than a 1000, over a hundred of which are in the United States alone (Firestine, 2015).

The literature defines a fourth generation of BSS based on improved rebalancing, ease of station installation, power sources (e.g., solar, battery, underground), tracking, electric bicycles and integration with public transport (DeMaio, 2009; Shaheen, Guzman, and Zhang, 2010). Previous generational changes have greatly modified how residents interact with the bicycles, mainly in terms of ease of use. Definitions of a fourth generation of BSS are incremental, focusing on the operations and technology, rather than providing a new user experience. This research doesn't distinguish between third or fourth generation BSS, simply referring to them as conventional.

Not all BSS fit nicely into these generational categories. Germany was one of the earliest countries to have a large number of systems due to being operated by the semi-private national rail company. Their BSS didn't use stations. Bicycles were operated by calling an automated service, identifying yourself and getting the unlock code for the bicycle. Locking the bike required a similar process. Many of these services have now shifted to using stations as well as only requiring smart cards for the transactions, greatly simplifying usage.

Most conventional BSS have four main components: bicycles, docks, kiosks and information systems. Not all BSS have these components. We distinguish between three types of conventional BSS: station based, flex and station free. Station based BSS (Figure 1.1) are the most common in Europe and North America. These are produced by JCDecaux, PBSC, BCycle and Clear Channel, among others. A station based system has bicycles that lock into docks, controlled by electronics in the kiosk. These 'smart stations' differ from 'smart bikes'. Smart bikes provide all the interaction necessary to use a bike on-board the bicycle (Figure 1.2), providing resilience in case the kiosk is inoperable due to battery failure or connection issues.

Smart bikes are sometimes used with station systems, but always for flex and station free BSS. Flex systems provide stations as well but users are able, for a fee, to drop off their bicycle anywhere within a zone (Figure 1.3). Station free BSS simply do not have stations or docks, the bicycles lock their wheels or are locked using public bicycle racks. While the flexibility has advantages, allowing users to leave these 'public' bikes, that are exclusive and sometimes privately operated, has caused conflict due to blocking pedestrian sidewalk use (Nitschke, 2015) or cyclist access to public bicycle racks (CBS New York, 2016).

While kiosks are responsible for securing and releasing bicycles and communicating with the central service, they provide interactive displays for existing or new members to use the bicycles (Figure 1.4). New daily, weekly, monthly or annual memberships can often be purchased with a credit card. The ability and purpose of kiosks vary. Some BSS require memberships be requested by mail or online, others dispense access keys or cards directly at the kiosks. Kiosks often have maps showing the surrounding urban area and other station locations. For advertiser operated BSS, the backs of kiosks serve as advertising billboards (Figure 1.4).

Docks, for those systems using them have a variety of designs (Figure 1.2). Dock designs are a compromise between preventing theft and vandalism, size and perhaps existing patents. Docks can also be distinguished as 'smart' or not. Checking out a bicycle at a station in Luxembourg requires a relatively lengthy interaction with a kiosk to select and unlock a bicycle while in Paris simply placing a membership card on the

Figure 1.1: Components of Chicago's bicycle sharing system. (Photo by Julia Affolderbach)

Figure 1.2: Types of bicycle sharing system docks and locking mechanisms. Clockwise from left: Luxembourg's JCDecaux side mounted lock, Dijon's Clear Channel pins lock, Cologne's nextbike with stationless smart-bike, and London's BIXI pass through dock.

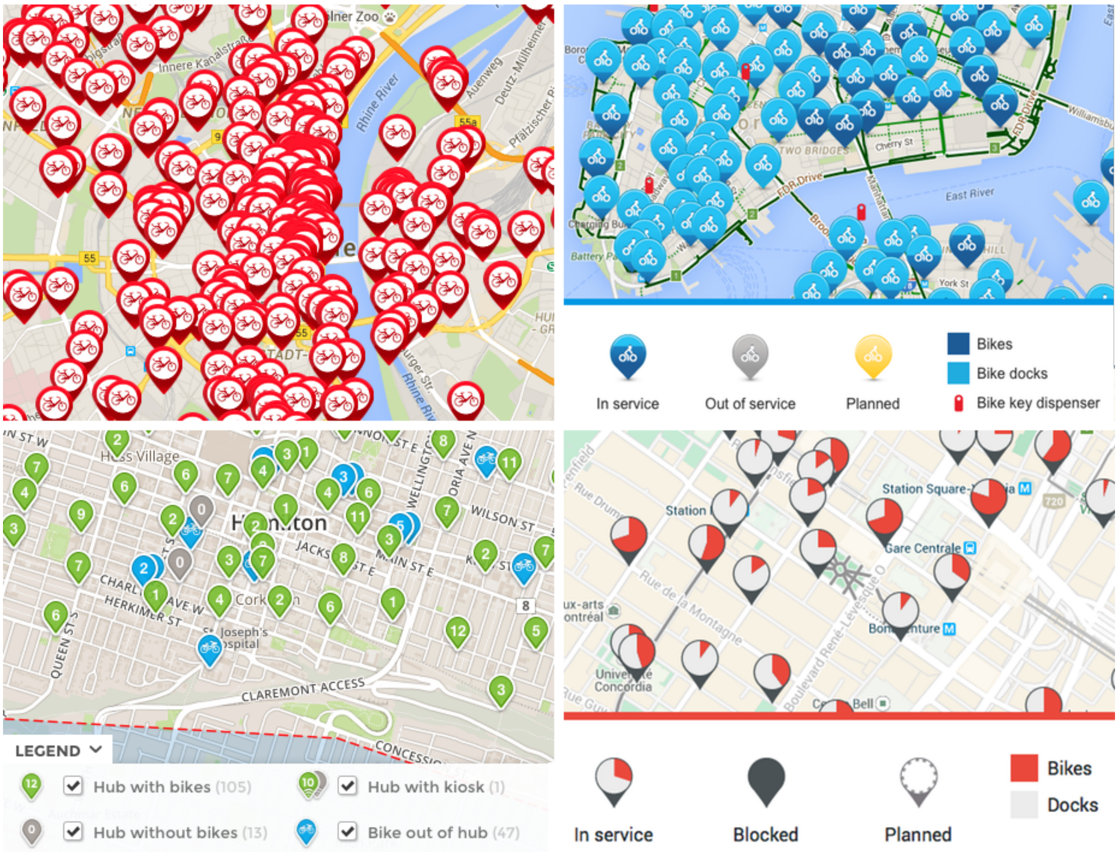

Figure 1.3: A variety of information systems displaying the location of stations or bicycles depending on the system type.

dock achieves the same outcome instantly (Figure 1.5). Some docks allow a variety of devices such as smart cards and fob keys (Figure 1.1). Smart bikes have dock like options implanted on the bicycle (Figure 1.2).

Information systems, accessible through smart phones or internet browser show the location of BSS stations, their number of available bicycles and docks. Some systems also allow the reservation of individual bicycles. Depending on the type of system, whether it is station based, flex or stationless, the maps are different. Figure 1.3 depicts Cologne's stationless system, NYC and Montreal's station systems and Hamilton's flex system.

Bicycles are the component with the least variability between systems. They all have sturdy heavier frames, thicker tires, lighting, large seats and adjustable seat heights. Bicylce components are typically abnormal sizes making theft fruitless due to incompatibility. Electric bicycles have begun to appear in the last few years but are still quite rare. Some systems have a mix of regular and electric bikes while others use electric bikes exclusively.

So within the context of conventional BSS, there still exists a wide variety of features affecting ease and manner of use. Many technology providers focus on the sophistication of their systems rather than its ease of use. Within the diversity of BSS technology some systems are much faster and easier to use, providing greater flow between modes of transportation. Perhaps technology providers believe cities and riders desire wielding status symbols above a more easily functional BSS.

1.2.2 Actors

There exists a variety of actors involved in the deployment of BSS, often with different desired outcomes. Technology manufacturers, such as PBSC and BCycle, produce all BSS components, others collaborate, such as 8D and Arcade Cycles. The municipality is always included in the process of locating stations on public land, but systems without stations sometimes omit their involvement. An operator, typically a private company but sometimes the local transport authority, takes care of day to day maintenance and customer service. The system owner and manager is often the same. In North America and the UK, sponsors play an important role in providing subsidy for the BSS.

Most BSS have actors play multiple roles. Seattle's system was owned by a non-profit, operated by Motivate, using technology from 8D and Arcade Cycles while working with the City of Seattle for station placement and securing a grant to help the non-profit purchase assets. Seattle's, Toronto's and Montreal's BSS are some of the ones purchased by their municipalities when they encountered financial difficulties. Boston owns its BIXI infrastructure, operated by Motivate. Finally, for any BSS owned by JCDecaux or Clear Channel, such as those in Antwerp, Dublin, Luxembourg City, Milan or Paris, the technology and operations are carried out by the advertiser.

Ownership of BSS infrastructure varies. In dealings with advertisers such as JCDecaux and Clear Channel, all the infrastructure belongs to them. In North America cities, non-profits and Universities often purchase the infrastructure but there are exceptions such as New York City where the operator, Motivate, owns it.

Figure 1.4: Bicycle sharing system kiosk in Luxembourg, front with terminal and map and back with advertisement.

Figure 1.5: JCDecaux docks in Paris, left, and Luxembourg, right, affording different usability.

The rise of BSS has created new opportunities but also instability and conflict between actors. Lawsuits have repeatedly occurred between advertisers and advertisers and cities regarding system contracts. In North America instability in rapidly growing businesses has led to bankruptcies of BSS, technology providers and operators.

1.3 Thesis outline and main results

Mayors, operators and advertisers evaluate their BSS as successful for varied reasons independent of a stated purpose. This thesis focuses on creating an objective success metric while also describing the political and business behaviours encouraging the promotion of BSS. Chapter 2 provides a technical description of BSS information systems, used to create our metric, and data collection methodology. A formalization of various BSS data sets and their relationships yields new potential for analysis and estimating trips from open data (Chapter 3). A deep analysis of how BSS are being used and how operators rebalance the system, dictating which trips can occur, follows (Chapter 4). Using extensive data collection we provide performance scores for 75 BSS and determine what factors are and are not responsible for system performance (Chapter 5). Finally we focus on the purpose of BSS and how politics and business sometimes use these systems for alternative, and sometimes contradictory outcomes to those promoted (Chapter 6).

Chapters 3 - 6 are written to stand independently with their own literature review and conclusions. Some repetition exists as a result. We provide an overall conclusion reiterating their findings in Chapter 7.

Chapter 2 - Data collection and analysis methods. This Chapter details the creation of four data gathering and organisational programs. The data to be gathered in large quantities was the availability of bicycles over time, specifically the change. A complex but resilient data collection system was developed to gather and clean data into a structured format every 10 minutes for all the case studies. Data collection was carried out for over a year on 80 BSS. Aside from this data, metadata and BSS attributes were organized into a wiki for documentation. Over time with the number of BSS growing this wiki became time consuming to extract information from and keep up to date. A collaborative and structured portal was developed to simplify analysis but also encourage broader participation in the documenting of BSS for research purposes. Another program was created to collect publicly submitted data for station suggestions of new and expanding systems. Finally we describe the tools used for general analysis as well as programming of the data gathering systems.

Chapter 3 - Trip estimation and data formalization. This methodological chapter describes the formalization of the different BSS data sets available and how their combination allows new insights into BSS operations. Station level data, the availability of bikes, is openly available for all conventional BSS. The number of trips, as well as origin and destination are not. A few select operators share trip data. This chapter describes how aggregating and merging these two data sets allows the extraction of rebalancing, the moving of bicycles to adjust to demand, as well as other interactions impacting station levels. This formalization allows a better comprehension of the factors differentiating station level data from number of trips. The second portion of this chapter focuses on the creation of three estimation models based on various temporal and spatial aggregations. Results show that trip estimates using one model are superior and sufficiently reliable for other purposes. Publicly available station level data can therefore be used to make estimates of BSS usage, something not typically available, for an objective evaluation of system performance or success.

Chapter 4 - Rebalancing strategies, patterns and purpose. Rebalancing, the moving of bicycles to or from stations to meet demand, is a necessary aspect of BSS operations to maintain system functionality. This chapter details rebalancing analysis through spatio-temporal data and operator interviews. Importantly, we relate rebalancing to the purpose of the BSS, stating that rebalancing behaviour alters outcomes. While extensive literature focuses on theoretical optimal rebalancing aspects, this analysis describes the practice, showing how intertwined BSS use and rebalancing are, requiring that both be analysed in concert otherwise leading to potentially incorrect conclusions. This chapter provides innovative methods of representing system and station usage before focusing on rebalancing. We describe the vehicles, facilities, labour, software and strategies used for rebalancing. Analysis allows the formalization of two types of rebalancing. Our findings show that disproportionate expenditures are allocated to the provisionment of BSS as a commuter service, in the process requiring intense rebalancing with associated CO_2 emissions. Many aspects of rebalancing impact BSS outcomes, we provide policy recommendations based on desired outcomes of environmental sustainability, equity, private utility cycling and profit. We conclude that municipalities expect BSS to bring benefits without considering how rebalancing and service level agreements shape outcomes.

Chapter 5 - Success determinants of bicycle sharing systems. By having a way of estimating BSS trips it is possible to use trips per day per bike as a comparable measure of success or performance. This chapter provides performance measures for 75 BSS. By gathering for each case study local attributes of the BSS, station density, geographic features, weather and transport infrastructure, we apply these independent variables to multiple regression models using performance as the dependent variable. Results show that a third of our sampled BSS are used less than once per day per bicycle. Operator type, station density, helmet requirement, population and cycling infrastructure are some of the variables found to influence performance, supporting existing findings. Alternatively results also show that larger systems with more stations are not related to higher performance. This finding contravenes best practices promoted by industry operators and BSS associations. Our performance estimates show that some systems are little used and therefore derive little of the, already contested, benefits intended. We use these findings to recommend that municipalities consider what purpose their BSS is meant to serve and whether alternatives may be more effective.

Chapter 6 - A critical perspective of bicycle sharing system politics, business and purpose. This chapter brings an alternative perspective, critical of success metrics such as those we present in the other chapters as being too narrow. We describe the less positive aspects of BSS history and development from a critical urban sustainability perspective. Initially conceived as a tool to fight against pollution and consumerism, BSS have been co-opted to increase urban outdoor advertising and promoting consumerism. Bicycle sharing systems are promoted as bringing social and environmental sustainability yet both can be contested as the demographic distribution of the benefits is skewed to the already privileged. While BSS as a new technology are promoted as solving urban problems, this chapter describes how they are used more as vehicles for advertisement and promotional tools to boost local pride, city image and policy makers while stimulating the economy through expenditures on technological solutions. Beyond sustainability, we describe how rapid adoption of BSS by decision makers has allowed private corporations to control the newest form of public transport while conflicts between technology providers and advertisers reduce the system efficacy.

Chapter 2

Data collection and analysis methods

Outline

This chapter describes the data collection and analysis performed for the quantitative sections of this work. Large amounts of data where collected at repeated and frequent intervals for over a year. This required a large data capacity and redundancy solution. In addition to raw data, large amounts of metadata were collected requiring different solutions. A total of four automated data collection or storage systems were created to facilitate this research. We detail their purpose, design and suggest alternatives for similar future work. We briefly describe software and programming languages used for analysis.

2.1 Introduction

Determining whether bicycle sharing systems (BSS) are successful or not depends on the goal. Using the number of trips or performance, such as the number of trips per day per bike, are objective measures to begin comparison. The problem, as of 2012 when this research began, was that such data was unavailable. Requests for data from operators such as JCDecaux were ignored. One successful method was to form a partnership with the municipality and request data through their BSS manager. This provided data but at great effort and after long delays. Alternative data sources existed however for those with some knowledge in web scraping.

One of the hallmarks of conventional BSS are web-based maps showing the locations of stations and the availability of bicycles and free docks to park a bicycle (Figure 2.1). Any data that is visible to the user can be repeatedly gathered at set intervals by a program. This is web scraping.

Data collection for this research started in 2011 with the gathering of Luxembourg's station levels, the number of bicycles and spaces available over time (Figure 2.1). Initially

Figure 2.1: Web map of stations for JCDecaux's Luxembourg BSS.

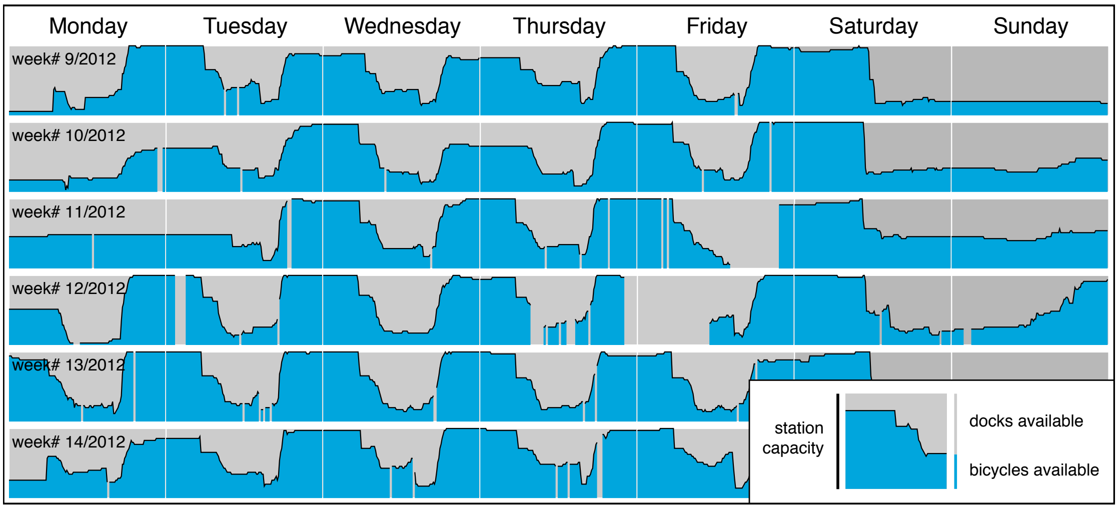

Figure 2.2: Station level data for one of Luxembourg's bicycle sharing system stations showing bicycles and docks available.

this was an intensive task as each station in a system required a request. So every ten minutes a simple script would individually request the state of Luxembourg's 70 or so stations. Initially companies such as JCDecaux resisted having people gather this data but in 2013 made the process much simpler by only requiring one request per system.

Data collection for most case studies began in early 2013. Only the 50 or so larger BSS (25 stations or more) in Europe, North America and Australia were tracked. At the time most of these were in Europe. The number of system has since grown at a rate making it difficult to track new systems let alone gather their data. The evolution of the number and types of BSS required adapting how these were tracked. This chapter begins by documenting the four methods of data collection (Section 2.2) followed by programming languages and software used (Section 2.3) for the quantitative analysis of Chapters 3, 4 and 5.

2.2 Data collection systems

2.2.1 DokuWiki

Due to qualitative nature of this research, in addition to the quantitative, we needed a method to gather and organize links to reports, media articles, BSS operator pages, corporate pages, press releases, quoted statistics and contact information for the case studies. The variety of information and cross linkages between BSS' multiple actors (technology provider, municipality, operator, cycling organizations, among others) required flexible organization. The DokuWiki program, a similar but lighter version of the software used by Wikipedia, was used to build richly intertwined connections simply.

The wiki was crucial in managing interview contacts to track the individual state of conversations between email, telephone and interview exchanges. Quantitatively, early data scraping was complex, requiring the discovery of the source and protocol necessary to gather the data, all of which was documented in the wiki.

Over time the quantity of information, while regularly structured, became time consuming to compare between the many and growing case studies. The system was replaced in 2015 with an open and participatory but structured system where individual attributes could be requested for all case studies (Section 2.2.4).

2.2.2 Hub and Spoke

Station level data was gathered from early 2013 to the summer of 2014, for over a hundred case studies, is the backbone of this thesis research. Our data collection system consisted of five servers (spokes) connected to a dispatch hub (Figure 2.2.2). The hub distributes different parts of the list to the five servers every 10 minutes. The servers where located in five separate locations. Servers individually completed their data collection tasks, parsed the relevant data and passed it back to the two redundant storage servers. Servers would then communicate with the hub to indicate if any errors occurred or whether the server was down. This design of the data collection system addresses multiple issues.

Rather than collecting data roughly every ten minutes our system aimed to collect data exactly every ten minutes on the hour. This meant that a large number of requests had to be made in a very short period of time. The problem with this is the quantity of data requested but also the number of requests. One server was not sufficient. By using five servers more data request could be initiated closer to the desired time and take the remaining time, before the next requests in 10 minutes, to parse the data and send it to the two main data storage servers.

Some operators did not appreciate the toll on their systems of systematic data collection. While we requested station states every 10 minutes, some BSS data enthusiasts and researchers have done so at higher frequency. This resulted in some operators blocking requests from servers repeatedly requesting data. To prevent this from happening, using five servers at different locations gave the appearance of our individual servers requesting data every 50 minutes rather than 10, reducing the likelihood of the requests being blocked.

As servers occasionally fail for periods of various duration, sometimes requiring manual intervention, each server communicates its status with the hub. In the case a server is not responsive the task list is redistributed equally among the remaining servers. This insured a more complete data set with fewer gaps.

Originally collected data for JCDecaux's systems was extremely burdensome. A separate request was required for each station, meaning the individual request of over a 1000 small files for Paris alone. As many of our case studies were operated by JCDecaux this meant data collection was quite burdensome. In the summer of 2013 JCDecaux provided a friendlier application programming interface (API) that allowed all the data for each BSS to be retrieved in one request, reducing much of the burden. Other case studies continued to have the same requirements however.

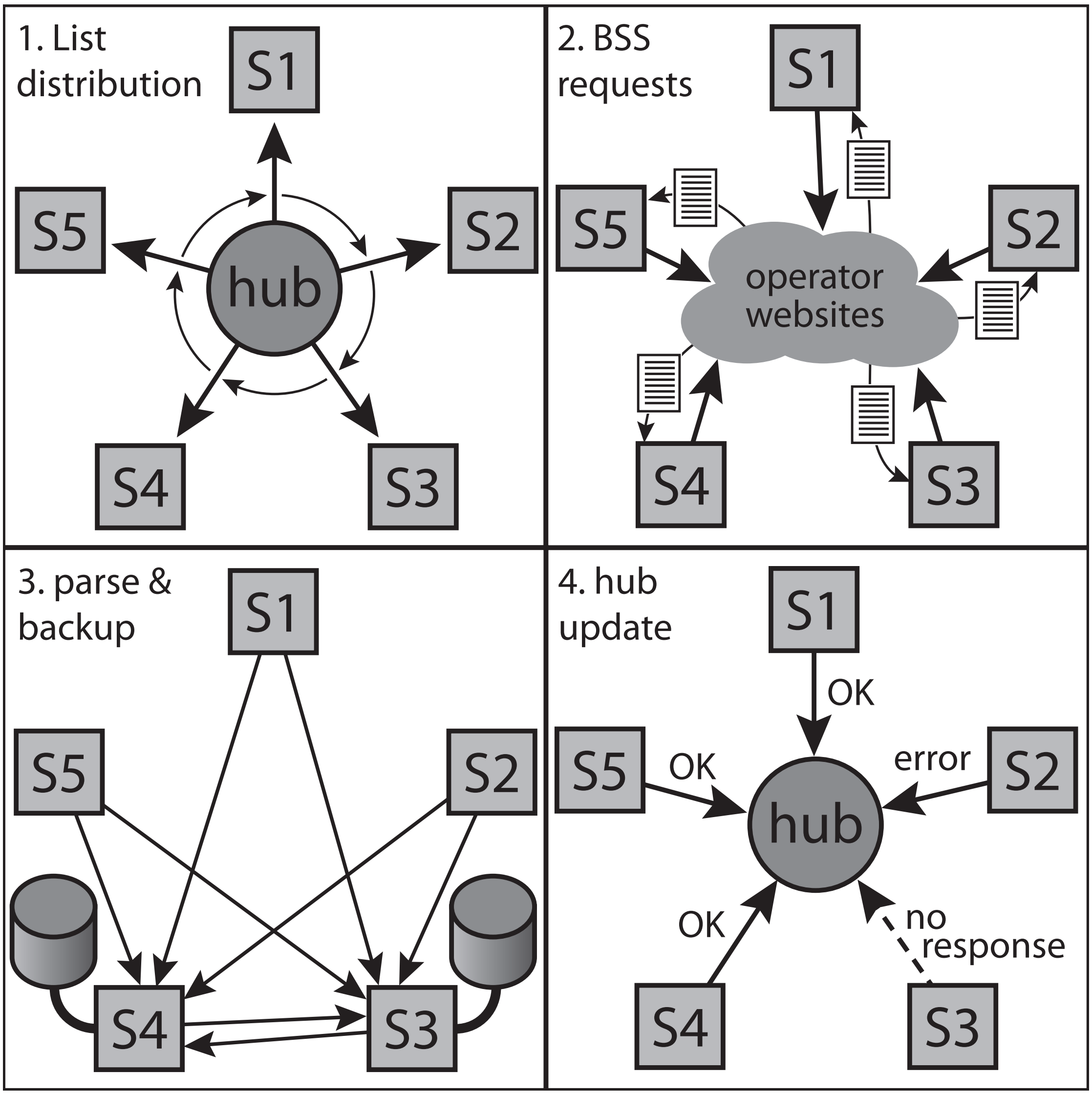

Figure 2.3: Hub and Spoke data collection server system.

Each operator has its own data syntax to provide data for their web maps. For some systems it is heavily embedded and difficult to extract and for other much simpler. For each syntax we had to customize distinct data collection and parsing protocols.

The central hub design provided a useful feature of summarizing any errors that occurred within the spokes. Data syntax for some systems changed over time requiring rapid response to reduce data loss. A central status page presented any errors to facilitate monitoring and sent emails in the case of serious errors. The technology has evolved since and in 2016 the standard syntax called the General Bikeshare Feed Specification (GBFS) was formalized. Adoption has slowly spread in North America, greatly simplifying data collection for future researchers.

The creation of a similar data collection system today would be much simpler due to the simpler collection and parsing of data. The evolution in cloud computing has also reduced costs and complexity in hosting multiple servers if they are still required. The use of four different types of servers (multiple Linux distributions and Windows server) for our Hub and Spoke system created additional complexities relating to multiprocessing and data transmission protocols.

This data collection system was also used to gather data that was not used in the thesis. Many German systems, that do not have stations, were also tracked to compare station and non-station based system performance. Car sharing car locations were also gather for multiple cities where BSS were also present in order to analyse how it contrasted in direction and distance. Neither of these data sets were used due to lack of time.

2.2.3 Public participation

A separate but much simpler data collection system has been ongoing since 2013, gathering station suggestions. Many North American BSS before launch or when pondering an expansion, deploy web-based public participation GIS (PPGIS) to allow submission of station location suggestions as well as comments and votes on other's suggestions.

Data was collected repeatedly for Austin, Chicago, Los Angeles, New York City, Philadelphia, Portland, San Francisco, Washington and Vancouver between 2013 and 2016. Again due to time constraints analysis was not completed.

2.2.4 Collaborative API

During successive analyses, with the growing number of case studies, having unstructured or non-queryable data within the DokuWiki system became burdensome. There exists limited BSS research spanning multiple case studies likely because of the effort required to primarily find the data source and then gather the data. In order to facilitate this research, but also future research, a structured, open and participatory BSS database was created (bikeshare-research.org) allowing anyone to submit, edit and download data.

The ability to download data in a structured format facilitated the organization of success determinants in chapter 5. An API was created allowing researchers to directly download the locations of BSS station level data feeds as well as metadata such as when the system launched, the type, the number of bikes and stations, the operator. The site also provides a historical record of changes to BSS. As they rapidly evolve the number of bicycles, stations and their location rapidly disappear preventing longitudinal studies. In addition to these quantitative metrics, links to news articles, reports and other resources are also available.

The comprehension of how BSS are being used requires a large and diverse set of data which is a barrier to research. This site aims to facilitate future BSS comparative research.

2.3 Quantitative analysis

While individual chapters describe the theoretical methodology, we present in this section the applied methods used for statistical, spatial and data analysis.

The hub and spoke and PPGIS data collections system were entirely programmed using Python. Python was imperative (especially the Python Data Analysis Library - pandas) for memory intensive processing tasks, particularly those involved in trip estimation (Chapter 3). The R programming language (R Core Team, 2015) was the dominant tool for most data and statistical analysis. While ArcGIS and QGIS were used for some minor analysis, R quickly proved to be the easiest and most efficient for spatial analysis and cartographic production of multiple case studies in a regular manner. The collaborative API was developed using PHP and Javascript as well as the Bootstrap framework.

2.3.1 Rebalancing geovisualization application

A comprehensive geovisualization system was developed for rebalancing analysis of the nine case studies analysed in Chapter 4. Stations, trips and rebalancing quantities were overlaid on a variety of web-based maps showing transit, cycling infrastructure, roads and satellite imagery. For each station further analysis was displayable showing temporal tendencies in trip and rebalancing types and outage (full or empty stations) frequency. The application, and other analysis, can be viewed online (https://bikeshare-research.org/rebalancing/).

2.4 Methodological conclusions

In the span of this research the number of BSS has dramatically increased and the types of systems has diversified. Data and metadata collection, as can be seen by the evolution of our data collections strategies, has had to evolve accordingly. While in 2014 it may have still been possible to compare most existing BSS, the number of systems, thought to be above a 1000 has now become burdensome to track and update as they evolve. The diversity of BSS types also makes comparison more difficult. A rise in the number of BSS being station free, allowed to float within areas, as has the number of electric systems. The durations of usage time has more variation, with some systems allowing

60 minute usage or even multiple hours, greatly modifying expected usage compared to the typical 30 minute free use period. Finally, some systems do not meet the strict definition of BSS of allowing deposit at a separate destination than the origin or not being automated.

As BSS research continues, comparative work will become selective rather than expansive, as was attempted with this data collection, due to the expanding number and types of systems. The intent of the participatory BSS API (bikeshare-research.org), developed as part of this work, is that it provides necessary resources to facilitate and encourage future comparative research.

Chapter 3

Trip estimation and data formalization

Outline

Bicycle sharing systems (BSS) have increased in number rapidly since 2007. The potential benefits of BSS, mainly sustainability, health and equity, have encouraged their adoption through support and promotion by mayors in Europe and North America alike. In most cases municipal governments desire their BSS to be successful and, with few exceptions, state them as being so. New technological improvements have dramatically simplified the use and enforcement of bicycle return, resulting in the widespread adoption of BSS. Unfortunately little evaluation of the effectiveness of differently distributed and managed BSS has taken place. Comparing BSS systems quantitatively is challenging due to the limited data made available. The metrics of success presented by municipalities are often too general or incomparable to others making relative evaluations of BSS success arduous. This chapter presents multiple methodologies allowing the estimation of the number of daily trips, the most significant measure of BSS usage, based on data that is commonly available, the number of bicycles available at a station over time. Results provide model coefficients as well as trip count estimates for select cities. Of four spatial and temporal aggregate models the day level aggregation is found to be most effective for estimation. In addition to trip estimation this work provides a rigorous formalization of station level data and the ability to distinguish spatio-temporal rebalancing quantities as well as new characteristics of BSS station use.[1]

3.1 Introduction

Bicycle sharing systems (BSS) are the first new form of public transportation in over a hundred years to be widely adopted. The earliest growth of conventional BSS occurred in Europe (DeMaio, 2009). Paris' celebrated and highly used BSS eclipsed attention of

[1]This chapter is based on (Médard de Chardon and Caruso, 2015)

the development of the many systems in Europe, even those that were costly failures (e.g., Aix-en-Provence). Australian BSS adoption in 2010 has experienced much lower usage due to safety concerns, system accessibility, limited infrastructure and mandatory helmet legislation (Fishman, 2015; Fishman, Washington, and Haworth, 2012; Fishman et al., 2014; Fishman et al., 2015). The expansion of BSS in China in terms of number of systems and bicycles largely outnumbers other countries (Fishman, 2015). Only since 2010, late relative to Europe, have BSS expanded in North America (Fishman, 2015; Parkes et al., 2013). In 2013 New York City, Chicago, San Francisco, and Columbus deployed BSS. As of early 2015, nineteen of the 25 most populous cities in the United States have a BSS with the remaining six planning to launch soon or exploring the feasibility. The phenomenal growth of BSS in the US is attributed, in the popular media (Economist 2013) and literature (Fishman, Washington, and Haworth, 2013; Shaheen, Guzman, and Zhang, 2010), to the same benefits associated with cycling, namely flexibility, health, equity and sustainability. Bicycle sharing systems address many contemporary issues making its adoption politically justifiable. Throughout the literature and mass media, mayors figure prominently as supporters (DeMaio, 2009; Parkes et al., 2013; Tironi, 2014) in bike share discussions. This tight relationship between mayor and BSS creates the necessity for success of the BSS lest its failure and potential economic consequences be associated with its promoters. Determining the success of a BSS is difficult as the data necessary for such an evaluation is typically not publicly available. This chapter formalizes BSS data sources to create a method of estimating the number of trips a system experiences, one potential metric for measuring success.

Overstating the effectiveness and benefits of BSS can also be in the best interest of private corporations operating the BSS. In Europe, with its much larger ratio of advertisement provisioned BSS, corporations, such as JCDecaux and ClearChannel, often provide the infrastructure, maintenance and servicing in exchange for rights to commodify municipal public space through advertising billboards. These BSS mutually benefit contract holders and municipalities. Advertiser provide the municipality a new fashionable, environmentally and health conscious mode of public transport with little or no public investment, while winning the advertiser a lucrative contract and a green polish for their corporate image (Tironi, 2014).

Media regularly refer to specific BSS as being successful with little or no critical or quantitative comparison. Success reported from municipalities (Julien Kohnen et al., 2014; Ville de Luxembourg, 2014) or provisioners (JCDecaux, 2011) are being defined using overstated, arbitrary and incomparable measures such as number of members, trips completed over a period, carbon dioxide reductions (Fishman, Washington, and Haworth (2014) show that some BSS may increase overall emissions due to rebalancing vehicle operation), calories burned or distances travelled. The dearth of available trip data or comparable statistics between BSS does not allow effective comparisons, keeping statements of success safe from criticism.

A large proportion of the existing bicycle sharing literature can be grouped into two fields, the mathematical models focusing on rebalancing (Erdoğan, Laporte, and Calvo, 2014; Forma, Raviv, and Tzur, 2015; Kaspi, Raviv, and Tzur, 2014; Kloimüllner et al., 2014; Labadi et al., 2014; Pfrommer et al., 2014) and those characterizing BSS through analysis. Most of the latter focus on individual case studies (Basch et al., 2014a; Beecham, Wood, and Bowerman, 2014; Béland, 2014; Bordagaray et al., 2014; Borgnat et al., 2011; Chow and Sayarshad, 2014; Corcoran et al., 2014; Faghih-Imani et al., 2014; Fuller et al., 2011; Fuller et al., 2012; Gebhart and Noland, 2014; Jäppinen, Toivonen, and Salonen, 2013; Jensen et al., 2010; Kaltenbrunner et al., 2010; Lathia, Ahmed, and Capra, 2012; Molina-Garcia et al., 2013; Murphy and Usher, 2014; Nakamura and Abe, 2014; Ogilvie and Goodman, 2012; Vogel et al., 2014; Wood, Slingsby, and Dykes, 2011; Woodcock et al., 2014). While a few comparisons of the number of subscribers, stations, bicycles and modal share changes exist (DeMaio and Gifford, 2004; Jurdak and Samoilov, 2013; Martin and Shaheen, 2014; Midgley, 2009; Ravalet and Bussière, 2012; Shaheen, Guzman, and Zhang, 2010; Zhang et al., 2014; Zhao, Deng, and Song, 2014) only a few broader studies have been carried out (Fishman, 2015; Fishman, Washington, and Haworth, 2013; O'Brien, Cheshire, and Batty, 2014; Parkes et al., 2013; Zaltz Austwick et al., 2013) by making quantitative evaluations of a selection of BSS based on system size, connectivity, shape, flows and temporality of concurrent bicycle use as well as trips per day per bicycle. The difficulty in obtaining data and infrequency of publicly published equivalent metrics are the main causes making BSS comparison difficult (Corcoran et al., 2014; Fishman, Washington, and Haworth, 2013).

Municipalities having genuine desires to improve local sustainability, health and equity through the adoption of a BSS and improved infrastructure are challenged by a means of evaluating their systems due to the same lack of comparative measures. Parkes et al. (2013) and Fishman, Washington, and Haworth (2013) both recognize the need for better efficiency measures of BSS. The media, when data is available, uses the number of trips as a measure of BSS success (Bialick, 2013; Cripps, 2013; Goodyear, 2013; Paris.fr, 2013). This value is sometimes normalized by the population of the city or the number of bicycles in the system. Accessible daily values are only available for a few cities, most of which are in the United States. The number of trips for most BSS is sporadically available and using different scales of measurement. This chapter provides a model for estimating trips, based on publicly available data for all conventional BSS, thus allowing their comparison. The estimated number of trips would provide a meaningful measure for evaluation not presented in O'Brien, Cheshire, and Batty (2014) and at a wider BSS scale than Fishman, Washington, and Haworth (2013).

Conventional BSS, typically referred to as third generation BSS (DeMaio, 2009), consist of four components: i) sturdy bicycles with custom sized components to deter theft, ii) automated docks which secure bicycles, iii) stations, i.e., groups of docks, and iv) the information system (IS) which provides the location of stations and the current quantity of bicycles and free docks at each. The IS is typically accessible on-line or through mobile applications. We analyse in this chapter how one can use this data source, i.e., station levels, to estimate BSS number of trips per day and how robust the method is to temporal and spatial aggregations.

The availability of BSS data beyond that shown on IS is limited. A few cities provide trip data consisting of the date, time and duration of trips from an origin station to a destination station for certain periods or their complete history. These are very much the exception. Additionally some of these data sets are available by request to the provisioner. This chapter presents a methodology that allows the estimation of daily trip numbers for all conventional BSS with the wider aim of democratizing the evaluation and comparison of BSS. In order to do this we also formalize IS station level data, trip data, their relationship and the revealed rebalancing operations. This has useful applications for the extensive BSS rebalancing literature.

The remainder of this chapter will define the different data sets, formats and terminology used in our methods (Section 3.2). In the methods (Sections 3.3) we describe the models applied based on daily, time interval and station aggregations. Finally in the results (Section 3.4) we present how data collection interval durations impact estimation, the particularities of the case studies and the coefficients of our three models as well as their accuracy rate and validation testing outcome.

3.2 Definitions and Data

3.2.1 Definitions

There exists two types of data for BSS:

1. Trips: For each bicycle trip, T, from a departure station (origin) to an arrival station (destination) the date, time and duration are provided. This is only available for a few cities.
2. Station levels: The current number of bicycles (X) and its complement, the number of available docks at each station in the BSS. This is typically collected through consistent scraping or API calls at set time intervals (O'Brien, Cheshire, and Batty, 2014).

Corcoran et al. (2014) refer to these as $flows$ and *stocks* respectively. Access to the first item, trip origin-destination (OD) data[2] , allows the simple calculation of the daily number of trips, T_d, the value we seek to estimate in our methodology. Conventional BSS provide the second item, the station levels, through their information systems (IS). Our model aims to translate station levels, X, into daily trip sums, T_d. In an effort to do so, the OD trip data collected for a few BSS are extremely helpful in understanding differences and validating our transformation.

Observed station states and interactions

Conventional BSS with IS contain the current number of bicycles and spaces (docks) available at each station. In this analysis only the number of bikes available is of consequence, not the spaces or total number of docks. In fact our methodology simply uses

[2]The literature commonly refers to origin-destination as the journey between activity places. In the BSS context we use the terms to refer to a *portion* of a journey from the station of departure to the bicycle return. BSS trips with the same origin and destination do not capture a potential intermediary activity place visited.

changes to the number of bikes at a station to estimate T_d. The station state or level[3] can be collected for each station in a BSS synchronously and repeatedly at a set time interval, Δ, expressed in minutes. An interval of ten minutes, $\Delta = 10$, for example, requires 144 data collections per day. We denote by v each collection point per day and $V = \frac{60*24}{\Delta}$ the total number of collection points per day. BSS operators typically update the status of their IS data each minute explicitly (JCDecaux, 2014) or implicitly which can be observed by repeating requests more than once per minute. More frequent data collection insures greater accuracy but is encumbering due to the increased bandwidth and storage required.

We identify station states, X_{sdt}, based on the station, s, date, d, and time, t, the observation was taken. The changes in the number of bikes between sequential X_{sdt} observations is typically a bike being docked (returned to a station) or removed for use. However a change in value can also be due to technical issues (with the BSS operator system or our data collection), rebalancing operations or maintenance, which we will all refer to as *rebalancing* for simplicity. We call changes to X_{sdt} values over time *interactions*[4] and refer to the sum of interaction changes *between* temporally sequential X_{sdt} intervals as delta station states, $x_{\Delta sdt}$, where Δ is the interval duration in minutes.

$$x_{\Delta sdt} = X_{sdt} - X_{sd(t-\Delta)} \tag{3.1}$$

With a Δ of 10, a station with 7 bicycles at 5:00pm then 4 at 5:10pm will have a $x_{10sd(5:10pm)} = -3$. Applying this transformation to a complete BSS data set creates a matrix of $x_{\Delta sdt}$ for each station, s, for each time interval, t of each day, d.

Calculating $x_{\Delta sdt}$ from X_{sdt} can be done using Equation 3.1 with the understanding that not only trip interactions are being observed but also rebalancing.

Observed trips and synthetic interactions

Using OD trips data we can also directly calculate delta station states by looking at what time and station each trip's bicycle was removed and returned at. We use z to denote delta station states as they are based on OD trips, rather than station level states X, which do not contain rebalancing influence and are therefore not equivalent. We refer to $z_{\Delta sdt}$ as *synthetic* delta station states. The synthetic data is a cleaner source which provides a better data set to perform estimations of T_d and can also be used to reveal the rebalancing quantities when compared to $x_{\Delta sdt}$ data.

Trip data can be directly transformed to $z_{\Delta sdt}$ values. For each time interval and station, the trips that originate, O, are subtracted from those that arrive at their destination, D. This process clearly loses interactions when bike removals and returns coincide within the same time interval of the same station.

[3]We use state or level interchangeably to refer to the number of bikes available at a station.

[4]The term interactions is used to refer to the removal or return of a bicycle at a BSS station by a user for a trip or any other maintenance or rebalancing of the bicycle. This includes technical problems that may indicate that a bicycle has been added or removed from the station when in fact it may have not been moved. The term *interaction* is not to be confused with the term used in the spatial interaction literature where an interaction refers to a flow. In our analysis a trip comprises of two interactions.

$$z_{\Delta sdt} = \sum T_{(s=O)dt} - \sum T_{(s=D)dt} \tag{3.2}$$

Daily aggregates

The following equations define the aggregation of data from Equation 3.1 and 3.2. We use $z_{\Delta sdt}$ in the following equations but these are equally applicable to station level derived delta station states, $x_{\Delta sdt}$, as well as other forthcoming data types. Aggregating the daily observed interactions for each station is completed by summing across the V daily collection points.

$$z_{\Delta sd} = \sum_{v=1}^{V} |z_{\Delta sd(v\times\Delta)}| \tag{3.3}$$

Alternatively it is useful to sum the station interactions during each interval to identify variations along the day.

$$z_{\Delta dt} = \sum_{s=1}^{S} |z_{\Delta sdt}| \tag{3.4}$$

Where S is the total number of stations, s, in the BSS. To calculate daily interactions observed, we sum $z_{\Delta sd}$ (Equation 3.3) across stations or z_{dt} (Equation 3.4) across intervals per day:

$$z_{\Delta d} = \sum_{s=1}^{S} z_{\Delta sd} = \sum_{v=1}^{V} z_{\Delta d(v\times\Delta)} \tag{3.5}$$

In order to estimate the number of trips per day, T_d, based on a specified Δ, we converted interactions, which only account for half of a trip, into number of trips, $E_{\Delta d}$.

$$T_{z\Delta d} = \frac{z_{\Delta d}}{2} \tag{3.6}$$

And equivalently for station states:

$$T_{x\Delta d} = \frac{x_{\Delta d}}{2} \tag{3.7}$$

Calculating $z_{\Delta d}$, as Δ approaches 0, detects every bicycle removal and return. As we are currently focusing on synthetic delta station states with no rebalancing, dividing the number of interactions by two provides the exact number of daily trips, T_d.

$$T_d = \lim_{\Delta\to 0} T_{z\Delta d} = \lim_{\Delta\to 0} \sum_{s=1}^{S}\sum_{v=1}^{V} \frac{|z_{\Delta sd(v\times\Delta)}|}{2} \tag{3.8}$$

Which is not true using $x_{\Delta sdt}$ where we have:

$$T_d = \lim_{\Delta\to 0} T_{x\Delta d} - rebalancing \tag{3.9}$$

In which case $T_{x\Delta d}$ always overstates T_d as rebalancing is a positive value.

For positive durations of Δ, interactions begin to be lost. *Interaction collisions* are opposing interaction pairs, a removal and return, occurring between observations. Interaction collisions, as rebalancing, are positive values. The total effect, depending on rebalancing and interaction collision amounts, may be positive or negative. Hence $T_{x\Delta d}$ may over or underestimate T_d, depending on Δ, when using station level inputs.

$$T_d = T_{x\Delta d} + interaction\, collisons - rebalancing \tag{3.10}$$

Conversely, $T_{z\Delta d}$ contains no rebalancing, increasing Δ durations increases the number of interaction collisions resulting in the magnification of $T_{z\Delta d}$ underestimating T_d.

$$T_d = T_{z\Delta d} + interaction\, collisons \tag{3.11}$$

Longer time intervals effectively increase the potential number of interaction collisions, decreasing $z_{\Delta sdt}$ and $x_{\Delta sdt}$ values as well as the number of observed trips (Equation 3.6 and 3.7).

Disaggregated trips

While we wish to estimate the daily number of trips, our estimation models need not be specified at the arbitrary daily aggregate of trips. It is possible to operate models at a finer temporal resolution by knowing the number of interactions at finer resolution. To create interaction sums at the same temporal scale as the $z_{\Delta sdt}$ scale, we simply add the two terms of Equation 3.2 to count each bicycle removal and return (i.e., interactons, i).

$$i_{\Delta sdt} = \sum T_{(s=D)dt} + \sum T_{(s=O)dt} \tag{3.12}$$

Note that $i_{\Delta sdt}$, summed for each day across stations and time intervals, $i_{\Delta d}$, is equal to twice the number of daily trips, T_d, regardless of Δ. The aggregations $i_{\Delta sd}$, $i_{\Delta dt}$ and $i_{\Delta d}$ can be calculated following Equations 3.3, 3.4 and 3.5.

By comparing synthetic station states and interactions the quantity of interaction collisions, c, can be calculated at the Δ temporal resolution for each station.

$$c_{\Delta sdt} = i_{\Delta sdt} - |z_{\Delta sdt}| \tag{3.13}$$

Interaction collisions are the sole factor causing $T_{x\Delta d}$ to underestimate T_d. Rebalancing is the opposing factor causing $T_{x\Delta d}$ to overestimate T_d. Just as $c_{\Delta sdt}$ can be isolated so can rebalancing quantities, $r_{\Delta sdt}$. At this scale $r_{\Delta sdt}$ can indicate the source, through a negative value, and destination of rebalancing.

$$r_{\Delta sdt} = x_{\Delta sdt} - z_{\Delta sdt} \tag{3.14}$$

BSS attributes

As it is necessary to combine data sets from BSS of multiple sizes in our generalized model, we required a form of normalizing based on some related BSS attribute. The number of built stations in a BSS is an easily accessible attribute but does not account for the change in BSS usage throughout the day. This is desired as rebalancing and interaction collisions are more prevalent during high usage periods. The number of active stations, $A_{z\Delta dt}$ (or $A_{x\Delta dt}$ for station level data), which we define as the sum of stations that have had at least one interaction during the Δ interval, is an effective measure of the infrastructure size being used throughout the day.

$$A_{z\Delta dt} = \sum_{s=1}^{S} \begin{cases} 0, & if z_{\Delta sdt} = 0 \\ 1, & if z_{\Delta sdt} > 0 \end{cases} \tag{3.15}$$

This can also be evaluated for each day.

$$A_{z\Delta d} = \sum_{s=1}^{S} \begin{cases} 0, & if z_{\Delta sd} = 0 \\ 1, & if z_{\Delta sd} > 0 \end{cases} \tag{3.16}$$

We also use a similar parameter where rather than looking at how many stations are used concurrently we observe how often a station has been used throughout the day.

$$A_{z\Delta sd} = \sum_{v=1}^{V} \begin{cases} 0, & if z_{\Delta sd(v\times\Delta)} = 0 \\ 1, & if z_{\Delta sd(v\times\Delta)} > 0 \end{cases} \tag{3.17}$$

In this section we have shown that two data types exist for BSS and have formalized their relationship. Trip data provide the departure and arrival stations as well as the date and time at the start and end. Using these we have shown how synthetic delta station states, $z_{\Delta sdt}$, interactions, $i_{\Delta sdt}$, active stations, $A_{z\Delta dt}$, collisions, c_{sdt}, and trips per day, T_d, are related. Observed station states, X_{sdt}, the second form and more accessible form of data, allows the creation of delta station states, $x_{\Delta sdt}$, and rebalancing quantities, $r_{\Delta sdt}$. The relationships between all the above BSS data sets are clearly illustrated by:

$$T_d = \frac{i_{\Delta d}}{2} = \frac{|z_{\Delta d}| + c_{\Delta d}}{2} = \frac{|x_{\Delta d} - r_{\Delta d}| + c_{\Delta d}}{2} \tag{3.18}$$

We provide an abstract symbolic explanation of the overall process of combining the data sets and their derived data in Figure 3.1.

3.2.2 Data

For simplicity and clarity we refer to BSS by the most well known city (some span multiple municipalities) in which they operate.[5] We consider eight case studies (Table 3.1), chosen because both their trip data and station state data, X_{10sdt}, are accessible.

[5] An important part of BSS it seems are, with the exception of those named after sponsors, their quirky, upbeat names such as Divvy (Chicago), Nice Ride Minnesota (Minneapolis), and Hubway (Boston).

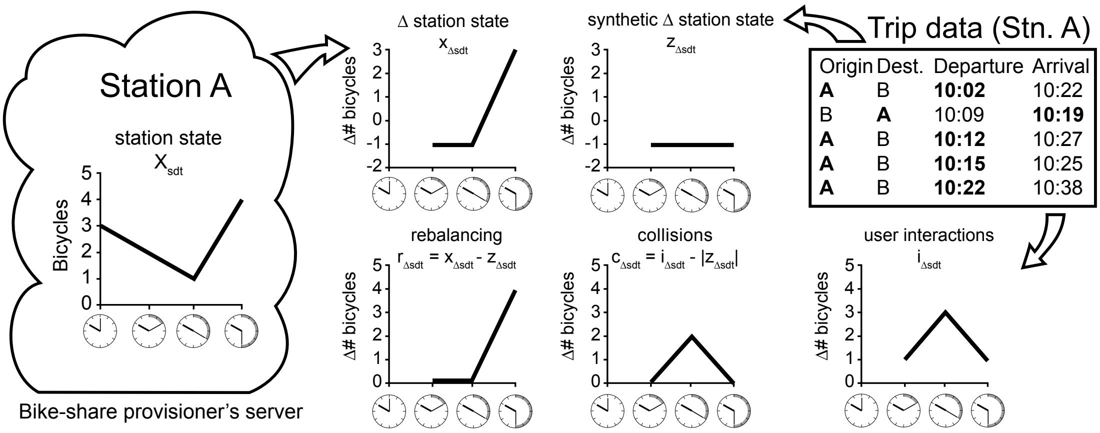

Figure 3.1: An abstract symbolic simplification of data derivatives and combinations.

	Boston	Chicago	London	Minn.	NYC	SF	Vienna	WDC
Stations	95	300	723	170	333	68	102	307
Bicycles[a]	767	2686	9250	1445	5687	606	1142	2590
$\overline{T}_d$	1688	4041	21493	1356	22890	782	1951	4822
Population[b]	4.6m	9.5m	8.4m	3.3m	11.7m	7.5m	1.7m	5.7m
Trip data period	2011-07 2012-10	2013-06 2013-12	2010-07 2013-12	2012-04 2013-11	2013-07 2014-02	2013-08 2014-02	2012-01 2012-12	2010-09 2013-12
Level data period	2011-08 2012-09	2013-06 2014-05	2013-03 2014-01	2013-03 2014-04	2013-05 2014-01	2013-07 2014-01	2012-01 2012-12	2013-03 2014-01

[a] Defined as B_{max} by O'Brien, Cheshire, and Batty (2014)
[b] Metropolitan area populations from Office for National Statistics (2013), U.S. Census Bureau (2011) and United Nations Statistics Division (2011)

Table 3.1: Case study attributes during data collection period.

While some of the largest BSS in the world are in China, no trip data or station level feed was found there or elsewhere. This causes our analysis to remain Europe and North America focused.

The number of bicycles actively usable for a BSS is typically ten percent less than that reported being present. This is due to a proportion of bicycles being maintained. To calculate the number of bicycles we refer to the maximum observed number of bicycles docked simultaneously, defined as B_{max} by O'Brien, Cheshire, and Batty (2014), over the studied time period. The mean trips per day, $\overline{T}_d$, in Table 3.1 is calculated using trip data over the data period that the BSS was operational.

Synthetic data derived from trip data

The selection of case studies (Figure 3.2) was determined by OD trip data being openly available through their respective websites or accessible by request (Vienna). Multiple requests for data were not responded to. The data periods are based on what was available or provided.

Station level data collected

As shown in Table 3.1, Boston and Vienna station states are accessible from the provisioners for the same period as the trip data available. For the other BSS, station state data, X_{sdt}, was gathered using a program that repeatedly, at ten minute interval, dispatched a data source list to multiple servers to concurrently retrieve the station levels. This system gathered data from March 2013 to July 2014. This data gathering system experienced occasional interruptions due to programming and connectivity issues as well as the BSS servers being down. As a result some data set days contain less than the desired number of 144 records per day.

Data cleaning was applied to x_{10sdt} values before use. Any values with interval durations which exceeded the Δ by ± 10 percent were removed. The same was done for days with fewer than 95 percent of the 144 desired x_{10sdt} values. While some BSS had very little data loss, non-standard intervals and insufficient records per day necessitated, in the worst cases, a removal of three percent and twenty percent of the records respectively.

As a trip consists of two interactions we expect the sum of all x_{10sdt} values to be zero. The sum of x_{10sdt} values for the full durations of the data sets is on average 1180 of over three million interactions. This indicates that there is no systematic loss or gain of interactions which would be caused by regular data gathering lapses.

Figure 3.2 shows weekly $\overline{T}_d$ normalized by the daily maximum number of bicycles, B_{max}, based on trip data available during the same span as the station level data collected. It is important to note that Chicago, NYC and SF all launched in 2013. This measure is a good indication of the utility a BSS provides and which is often reported by the media. One of the goals of this methodology is to provide the data in Figure 3.2 for all BSS. Station states, X_{sdt}, are democratic open data while T_d is typically closed. Using $z_{\Delta sdt}$ we try to bridge from x_{10sdt} to T_d.

3.3 Assumptions and Estimation Methods

Following our definitions and case study descriptions, we now present three models for estimating T_d, given $z_{\Delta sdt}$ or $x_{\Delta sdt}$ inputs, which aggregate data daily (DAM), by Δ interval (IAM) and station (SAM).

In theorizing what is required in to estimate trips for a daily aggregated model (DAM) we look at how we synthetically reconstructed $T_{z\Delta s}$ (Section 3.2). This methodology guarantees that $T_{z\Delta s}$ will be at most equal to T_d. Any difference is caused by collisions. It follows that stochastically with greater trips, a greater number of collisions will occur. Because BSS stations are located in a space of heterogeneous demand we expect to see an even greater collision rate and foresee the estimating of T_d for individual BSS to require an additional factor to compensate, non-linearly, for greater rates of lost trips due to collisions, $c_{\Delta d}$, as trips increase.

We assume that creating a generalized model applicable to multiple BSS of different sizes requires their differentiation through added characteristics. Collisions rates are the result of the intensity of trip interactions at origin and destination stations. Given two

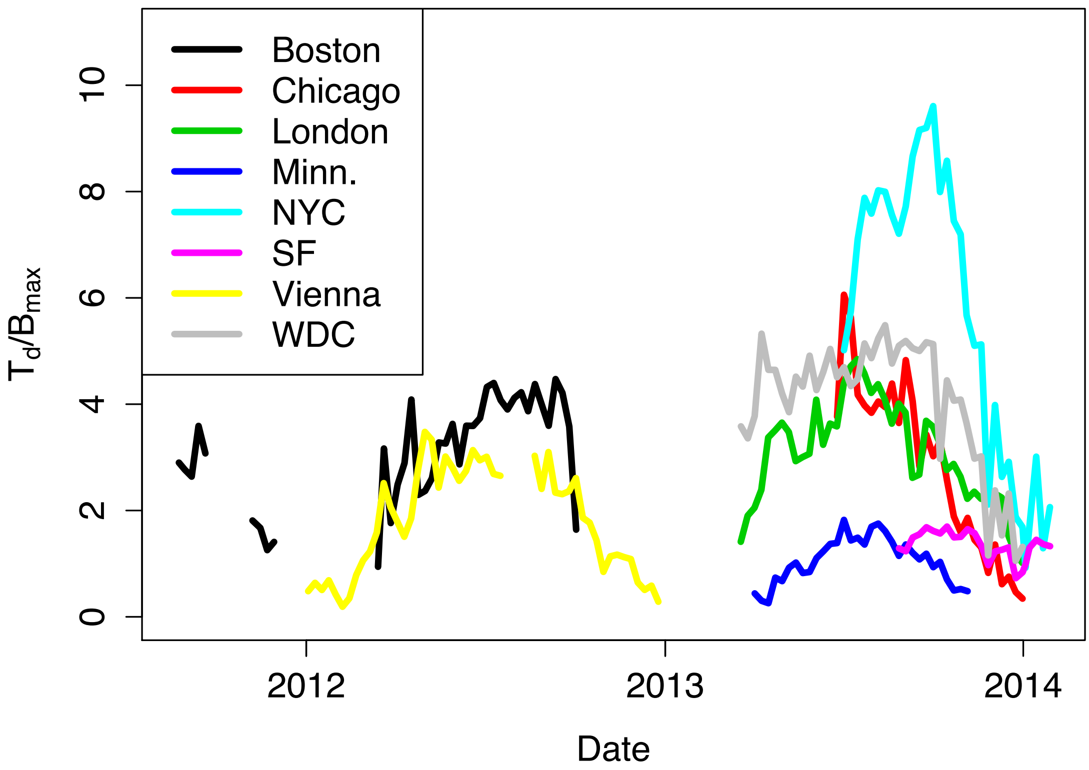

Figure 3.2: Weekly average number of daily trips normalized by daily maximum number of observed bicycles (B_{max}) for the eight case studies. Data is based on trip and T_d data available.

BSS with equal number of daily trips, a BSS with a greater number of stations will typically experience fewer interaction collisions, as the interactions are dispersed, than a BSS with fewer stations. To adjust for this we theorize that the number of active stations can help measure the intensity of activity.

By reducing the amount of aggregation to each *Delta* interval (IAM) or station (SAM) we still expect estimation to be influenced by collisions relative to activity density and therefore require a similar activity measurement, albeit at a different scale, to the daily aggregated estimations.

3.3.1 Model specifications

The following model is based on the hypothesized relationship between T_d and $T_{z\Delta sdt}$. We denote Equation 3.19 as the *individual* day aggregated model (DAM), specific to each BSS.

$$indivual\ DAM: \quad T_d = 0 + \beta_1 T_{z\Delta d} + \beta_2 T^2_{z\Delta d} + \epsilon \tag{3.19}$$

The quadratic factor $T^2_{z\Delta d}$ compensates for collisions for days of higher activity. Note that we lock the intercept to the origin. This prevents negative estimates, an undesired effect of a linear model on count data, in our application of individual BSS data sets to Equation 3.19 [6]. We expect β_1 to be close to one when DAM is applied to synthetic data, but less than one for T_{x10d} data to compensate for rebalancing.

The active stations parameter (Equation 3.16) is added in Equation 3.20 for the *combined* DAM model.[7] While $T^2_{z\Delta d}$ compensates for interaction collisions we use $A_{z\Delta d}$ to normalize the density of activity.

$$combined\ DAM: \quad T_d = 0 + \beta_1 T_{z\Delta d} + \beta_2 \frac{T^2_{z\Delta d}}{A_{z\Delta d}} + \epsilon \tag{3.20}$$

For the interval aggregation model (IAM) we modify Equation 3.20 to use the Δ temporal resolution data to estimate the number of interactions rather than daily trips. IAM sums interactions across all station in the BSS for each interval duration. The BSS normalization variable $A_{z\Delta dt}$ from Equation 3.15 is included as well as it's square to compensate for interaction collision losses.

$$IAM: \quad i_{\Delta dt} = 0 + \beta_1 z_{\Delta dt} + \beta_2 A_{z\Delta dt} + \beta_3 A^2_{z\Delta dt} + \epsilon \tag{3.21}$$

The final model sums interactions for each station throughout the day, $z_{\Delta sd}$, defined in Equation 3.3. Based on the assumption that stations with high usage experience more interaction collisions than those with lower usage, this method is designed to reduce the aggregation of values of differing variance. This station aggregation model (SAM) is BSS size agnostic and only uses the frequency of station use throughout the day (Equation 3.17) not the number of active stations in the system.

[6] As we aggregate count data there are few zero values and a normal, not Poisson, distribution.

[7] Other specifications were tested using different exponents and interactions for $T_{z\Delta d}$ and $A_{z\Delta d}$ but this yielded the best results.

$$SAM: \quad i_{\Delta sd} = 0 + \beta_1 z_{\Delta sd} + \beta_2 A_{z\Delta sd} + \beta_3 A^2_{z\Delta sd} + \epsilon \tag{3.22}$$

The individual DAM model (Equation 3.19) is applied to each BSS case study independently at each Δ to characterize the BSS. The model Equations 3.20, 3.21, 3.22 are then applied to the combined synthetic data sets for the eight case studies in Table 3.1.

3.3.2 Bootstrapping synthetic station levels

One thousand samples with replacement of each BSS data set the size of the smallest data set are applied to the combined data sets of the DAM, IAM and SAM models and regression results saved. The distributions of the thousand iterations are checked for normality and the mean coefficients, p-values and adjusted r-squared values reported.

The synthetic data, $T_{z\Delta sdt}$, contain no rebalancing, only interaction collisions, in terms of deviance from T_d. As $T_{z\Delta d}$ data are more directly related to T_d, compared to $T_{x\Delta d}$, we expect an almost perfect fit. For $T_{x\Delta d}$ however, which contains rebalancing effects in addition, we use cross-validation to prevent over specification of our models.

3.3.3 Cross validation of observed station levels

Applying the models to $x_{\Delta sdt}$ data requires additional steps due to the rebalancing effects, limited periods of data, imbalance in case study data sizes and few BSS case studies available. For the three models ten percent of the data, every tenth day of each BSS, is kept for validation and the remainder is allocated to coefficient estimation. Unlike in the synthetic analysis, only seven case studies are used. Chicago is saved as a validation set.

To measure the optimal achievable model we first apply DAM, IAM and SAM to each individual BSS. This serves for comparison with the BSS combined results. Across ten thousand iterations, each BSS data set is randomly divided into training (70%) and test sets (30%). The training sets use DAM, IAM, and SAM regression, Equations 3.20, 3.21 and 3.22 respectively, from which the coefficients are applied to the individual BSS test sets. The estimated number of trips, $\widehat{T}_{x10d}$, are evaluated against known T_d values using RMSE normalized by $\overline{T}_d$ for BSS comparison.

A similar cross-validation methodology is also used for the combined BSS data set. Ten thousand subsets of equal number of rows is taken, with replacement, from each BSS limited by the BSS with the least number of valid rows of data. The BSS data sets are randomly split 70% - 30% into training and test data sets. The training sets implement the DAM, IAM and SAM models and the iteration specific coefficient results are applied to the training sets from which the $\widehat{T}_{x10d}$, RMSE and model coefficients are saved for all ten thousand results. The resulting distributions are analysed for normality and the mean values reported.

Finally, the validation of DAM, IAM and SAM is performed using the ten percent of days of data put aside for this purpose. As these results are likely to over estimate the efficiency of our coefficients due to their being used for training, a separate BSS, Chicago, for which data recently became available, is also applied to the models for validation.

Δ	Boston	Chicago	London	Minn.	NYC	SF	Vienna	WDC
1	0.05	0.06	0.07	0.05	0.13	0.04	0.05	0.09
2	0.08	0.11	0.11	0.08	0.21	0.07	0.08	0.14
5	0.16	0.20	0.20	0.14	0.35	0.13	0.15	0.24
10	**0.25**	**0.29**	**0.30**	**0.21**	**0.47**	**0.21**	**0.23**	**0.34**
20	0.36	0.39	0.40	0.29	0.58	0.31	0.34	0.44
30	0.43	0.45	0.46	0.34	0.63	0.37	0.41	0.50
60	0.54	0.55	0.56	0.45	0.71	0.48	0.53	0.60

Table 3.2: The proportion of interaction collisions, $c_{\Delta d}$, to interactions $i_{\Delta d}$. Rates relate strongly with T_d/B_{max} levels shown in Figure 3.2.

While DAM is the simplest to apply it is expected that IAM and SAM perform better due to their finer temporal and spatial scales respectively. IAM compensates for the variation in daily activity, the morning and afternoon peaks and SAM for individual stations having different usage frequencies.

3.4 Results

We begin by presenting the results of the synthetic data analysis, based on OD trips, at various temporal intervals, the relationship to interaction collision rates and aggregations techniques based on temporal and station interaction distributions. The day aggregation model (DAM), interval aggregation model (IAM) and station aggregation models (SAM) are applied to the eight synthetic BSS data sets. The analysis is repeated for the station level data and compared with the synthetic equivalents. Through the use of synthetic and station level quantities rebalancing is analysed. Finally DAM, IAM and SAM are trained, coefficients applied to validation sets and error rates reported.

3.4.1 Synthetic data analysis

We strictly focus on synthetic data, based on OD trips, for this section. We first show the difference between $z_{\Delta d}$ and $i_{\Delta d}$ (Equation 3.13) before applying the models. All values in tables where $\Delta = 10$ are bold for later comparison with data collected from station level scraping.

Synthetic data descriptive analysis

Table 3.2 shows the proportion of interaction collisions, $c_{\Delta d}$, to $i_{\Delta d}$ at multiple intervals. Interestingly we see large variations of $c_{\Delta d}$ between cities at the same time Δ. The rates relate directly to Figure 3.2. All else being equal, the number of interactions per bicycles in a system will very strongly relate with interaction collision. Interaction collisions also depend on the spatial morphology of origins and destinations as well the tendency for trips to occur simultaneously. Polycentric cities are more likely to have widely distributed station interactions compared to a highly centralised city with strong temporally coincident commuting.

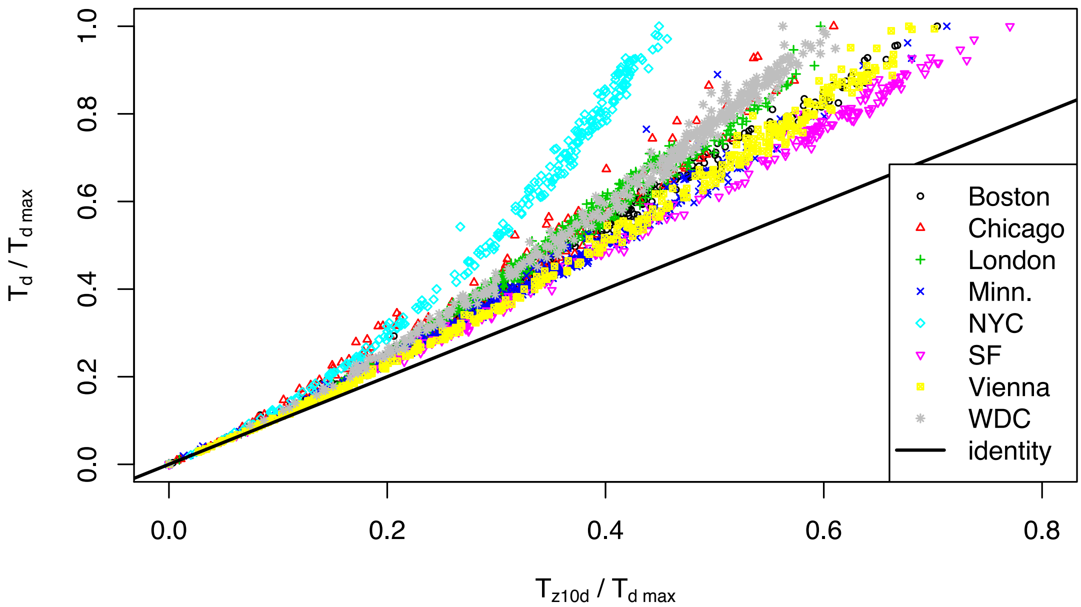

Figure 3.3: Normalized T_d plotted against T_{z10d} for the eight case studies showing the amounts of interaction collisions.

A comparison of interaction collision proportions for Washington D.C. (WDC) in 2011, 2012 and 2013 show a minor but consistent increase across the years. The cause of the change cannot be explicitly determined as between 2011 and 2014 WDC experienced a doubling of annual trips (1.2 to 2.6 million) and stations (145 to 310) as well as weather variations (and other unknown factors). Despite this, it is likely the increased number of stations made the system accessible or desirable to new users whose interactions have not been restricted to new stations. This likely made pre-existing stations busier, causing the increase in interaction collisions observed. Analysis of WDC data shows that the rate of interaction collisions, c_{10sdt}, per interactions, i_{10sdt}, correlates significantly with the proportion of active stations, A_{10dt}, to built stations reassuringly showing the tendency of BSS stations to not be used uniformly.

Comparing T_{z10d} (normalized by T_d) and T_d values in Figure 3.3 we see that at a fixed number of daily trips, the interaction collision rates, the horizontal distance between points and the identity line, are greater for larger BSS (Chicago, NYC, London and WDC - see Table 3.1).

For increasing Δ values in $T_{z\Delta d}$ we can see, using Vienna as an example in Figure 3.4, days with greater number of trips experience more interaction collision variability and reduce exponentially the number of $T_{z\Delta d}$ observations. For this latter reason the individual and combined DAM contain a quadratic term.

Focusing on individual $z_{\Delta sdt}$ values, the finest data resolution available, to estimate interactions, $i_{\Delta sdt}$, is, however, ineffective for our model due to the wide dispersion of the

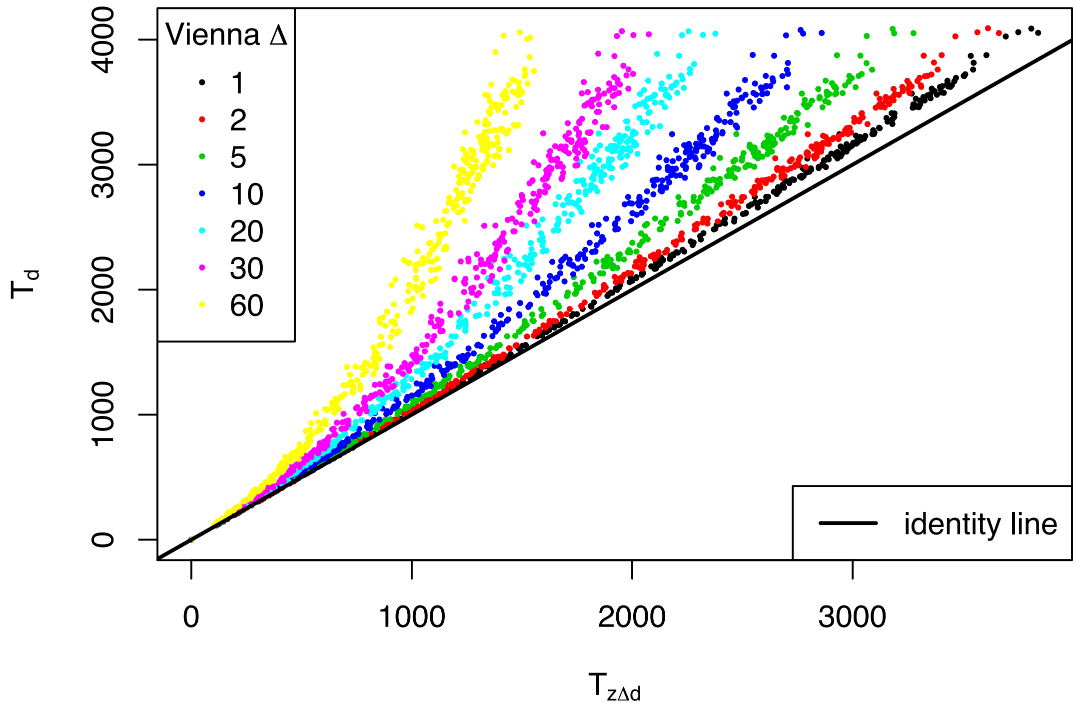

Figure 3.4: Vienna's daily observed trips from synthetic levels against actual daily trips. The seven thin lines from left to right show 60, 30, 20, 10, 5, 2 and 1 minute intervals. The thicker line being the identity line.

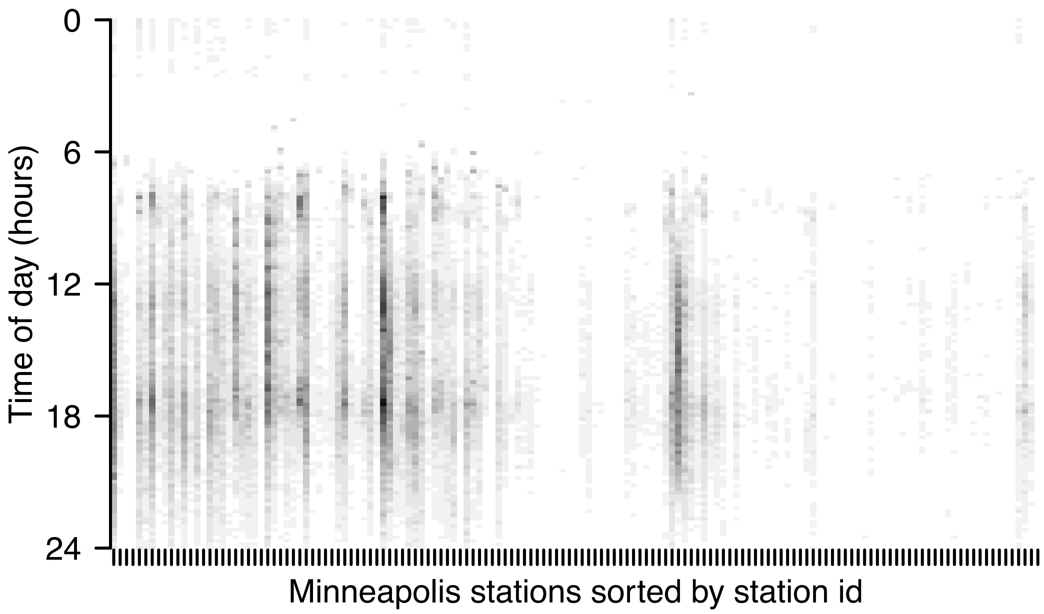

Figure 3.5: The sum of i_{10sdt} values across all days in the Minneapolis data set. The day aggregated model (DAM) aggregates all interactions in a day while the interval (IAM) and station (SAM) aggregated models sum rows and columns respectively. The visible columns suggest SAM is optimal due to the reduced variability in aggregation.

explanatory variable caused by the unpredictable presence of interaction collisions. For example, if a station, within a time interval, experiences three interactions, the absolute value of the observed z_{10sdt} will be either three or one depending on the interaction types.

Clearly some aggregation is necessary to understand the tendency of BSS station observations to omit interactions. Aggregations that minimize the summing of contrasting variances will improve the estimation accuracy. The DAM dependent variables, $T_{z\Delta d}$, from Equation 3.19, sum stations and time intervals, which vary spatially, and in intensity of use, throughout the day. The interval aggregation $z_{\Delta dt}$, from Equation 3.21, sums across all station values. As can be seen in Figure 3.5, some stations have higher usage rates than others and are therefore more likely to experience interaction collisions. A model that isolates stations is expected to better estimate varying levels of collisions as well. DAM and IAM have attempted to handle the varying size of BSS through normalization using the number of active stations using $A_{\Delta d}$ and $A_{\Delta dt}$. Using the SAM model, station normalization $A_{\Delta sd}$ is used.

Synthetic β_1 coefficients (T_{z10d})

Δ	B	C	L	M	N	S	V	W
1	1.03	1.02	1.02	1.03	0.99	1.02	1.01	1.03
2	1.05	1.04	1.04	1.04	0.98	1.03	1.01	1.04
5	1.11	1.08	1.09	1.06	0.94	1.07	1.02	1.07
10	**1.20**	**1.14**	**1.15**	**1.09**	**0.90**	**1.10**	**1.02**	**1.11**
20	1.34	1.23	1.23	1.14	0.92	1.14	1.02	1.17
30	1.49	1.30	1.31	1.19	1.07	1.19	1.02	1.25
60	1.87	1.56	1.62	1.29	1.78	1.40	1.01	1.61

Synthetic β_2 coefficients (T^2_{z10d})

Δ	B	C	L	M	N	S	V	W
	(10^{-5})	(10^{-5})	(10^{-6})	(10^{-5})	(10^{-5})	(10^{-4})	(10^{-4})	(10^{-5})
1	1.12	0.99	2.18	1.63	0.65	0.26	0.17	0.95
2	2.11	1.90	3.81	3.16	1.32	0.50	0.32	1.80
5	5.15	4.30	8.19	7.64	3.42	1.10	0.76	4.13
10	**9.90**	**7.54**	**15.4**	**13.2**	**6.94**	**2.43**	**1.49**	**7.88**
20	18.9	13.2	29.7	23.0	12.9	5.20	3.08	14.7
30	24.9	18.3	41.5	31.8	17.1	7.48	4.72	20.3
60	37.5	29.2	57.7	62.4	21.6	11.8	10.1	28.4

RMSE/$\overline{T}_d$

Δ	B	C	L	M	N	S	V	W
1	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.01
2	0.02	0.03	0.02	0.04	0.02	0.01	0.01	0.01
5	0.03	0.06	0.03	0.05	0.03	0.02	0.02	0.02
10	**0.04**	**0.08**	**0.04**	**0.06**	**0.03**	**0.02**	**0.03**	**0.03**
20	0.05	0.11	0.05	0.07	0.05	0.03	0.04	0.04
30	0.07	0.14	0.06	0.08	0.07	0.04	0.05	0.06
60	0.09	0.18	0.10	0.10	0.13	0.04	0.07	0.10

B:Boston, C: Chicago, L: London, M:Minneapolis, N: NYC,
S: San Francisco, V:Vienna, W:Washington D.C.
Robust standard error (White, 1980) sign. levels < 0.001 for all values.
Adjusted r-squared values for all BSS at all intervals are greater than 0.97.

Table 3.3: Individual day aggregated model (DAM) regression coefficient results of synthetic delta station states at multiple time intervals for the case studies.

Synthetic data model applications

Applying the *individual* DAM (Equation 3.19) linear regression to the cities at multiple intervals we estimate the number of daily trips from $z_{\Delta sdt}$ summed to $T_{z\Delta d}$ using Equations 3.2, 3.3, and 3.5. The data and linear regression results maintain statistical assumptions (Gelman and Hill, 2007: 45) except for homoskedasticity for which we compensate for by using White's (1980) robust standard error method to recalculate significance levels.

The β_1 coefficients in Table 3.3 are quite similar between BSS at short intervals yet, like in Table 3.2, differences between the systems occur at longer intervals. Strangely Vienna keeps a fixed coefficient near 1.01 at all interval levels while having a stronger β_2 coefficient for the longer intervals than the other cities. Vienna's β_2 coefficient perfectly

	DAM			IAM				SAM			
	$T_{z\Delta d}$	$T^2_{z\Delta d}/A_{z\Delta d}$ (10^{-3})		$z_{\Delta dt}$	$A_{\Delta dt}$	$A^2_{\Delta dt}$ (10^{-4})		$z_{\Delta sd}$	$A_{\Delta sd}$	$A^2_{\Delta sd}$ (10^{-2})	
Δ	β_1	β_2	R^2	β_1	β_2	β_3	R^2	β_1	β_2	β_3	R^2
1	1.00	1.96	1.0	1.18	-0.13	13.9	.99	1.18	-0.23	0.11	1.0
2	0.99	4.17	1.0	1.53	-0.48	10.6	.99	1.30	-0.42	0.27	.99
5	0.92	11.3	1.0	2.65	-1.62	-5.81	.98	1.55	-0.95	0.99	.98
10	**0.82**	**23.2**	1.0	**3.30**	**-2.18**	**-21.1**	.97	**1.82**	**-1.65**	**2.71**	.95
20	0.70	44.9	.99	3.34	-1.80	-30.2	.96	2.09	-2.68	7.54	.91
30	0.66	62.4	.99	3.25	-1.25	-34.2	.94	2.25	-3.43	13.6	.88
60	0.80	94.8	.98	3.10	*n.s.*	-42.9	.90	2.45	-4.80	36.8	.82

Reported significance levels are adjusted for heteroskedasticity using White (1980).
All p-values $< 10^{-10}$ unless indicated as non-significant (*n.s.*).

Table 3.4: Regression results using day (DAM), interval (IAM) and station (SAM) aggregated models at multiple Δ for the combined data set containing Boston, Chicago, London, Minneapolis, New York City, San Francisco, Vienna and Washington D.C.

represent the trip losses due to interaction collisions. The β_2 coefficient consistently increases with longer intervals as is expected due to greater probability of interaction collisions.

Combining the BSS case studies into one regression model for generalized estimation using Equation 3.19 is insufficient due to the BSS having different interaction collision rates, as seen in Table 3.3, likely dependent on the number of bicycles, demand and stations among other factors. We control for this effect using the number of active stations, $A_{\Delta d}$, (Equation 3.16) in the regression (Equation 3.20) to yield synthetic estimates for our combined BSS (Table 3.4).

Individual DAM

The combined DAM $T_{z\Delta d}$ coefficients in Table 3.4 decrease while in the individual DAM model (Table 3.3) they increased. The individual DAM model due to its simplicity is more intuitive than the combined. The combined model requires the more complex $\frac{T_{z\Delta d^2}}{A_{\Delta d}}$ term to be effective as using distinct variables in the model, $T^2_{z\Delta d}$ and $A_{\Delta d}$, yielded coefficients of inconsistent sign for the BSS.

Combined DAM

The combined DAM (Equation 3.20) was tested using the built number of stations, rather than the more temporally variable $A_{\Delta d}$, but was found less effective. $A_{\Delta dt}$ (Equation 3.16) covaries with T_d rather than simply differentiate BSS sizes. The drawback, however, of using an indirect measure, when we wish to estimate the number of daily trips, is the risk of predicting a more generalized count such as using weather or other cycling determinant variables (Parkin, Wardman, and Page, 2007).

As we have shown earlier in Figure 3.3, the percentage of synthetic trips, T_{z10d}, varies non linearly with the number of trips, T_d. Days of higher activity with greater interaction collisions result in lower observed trip percentages than on calmer days. The same occurs throughout the day between periods of high and low activity. We attempted to address this by aggregating the interactions across stations at the interval temporal scale, $i_{\Delta dt}$, in order to reduce daily variance error from our model.

IAM

Performing regressions for the combined case studies at each interval using IAM produces very different coefficients than in our daily trip aggregated model as we are now analysing interactions (Table 3.4) rather than trips.

Resulting coefficient of IAM application are not continuous. The $z_{\Delta dt}$ coefficient jumps with the reversal of $A^2_{\Delta dt}$ to a negative coefficient at $\Delta = 5$. The negative coefficients reduce the interpretive power of the model. Perhaps these results are partially due to the aggregation within Δ intervals across stations of strongly contrasting variability as can be seen in Figure 3.5.

SAM

The SAM application, using Equation 3.22, provides coefficients (Table 3.4) easier to interpret than IAM and consistently increase in magnitude across intervals. The $A_{\Delta sd}$ coefficients are still negative however but well behaved. SAM achieves equivalent RMSE rates to DAM (Table 3.5).

Looking at DAM in Table 3.5 we see Minneapolis, Chicago and San Francisco experience higher RMSE values for mid and long Δ while London, New York City and Vienna increase almost linearly.

While IAM yields equivalent error rates at $\Delta = 1, 2$, it shows generally disappointing results with Boston, Minneapolis, San Francisco and Vienna doing especially poorly.

Finally the SAM values show a few different patterns, Washington D.C. maintains very low values, Minneapolis rises much higher at mid Δ values but returns to the average at the sixty minute Δ and Chicago and San Francisco which plateau early and remain stable. SAM consistently has slightly lower averages than DAM.

Synthetic model error

Looking at the DAM, IAM and SAM we see some BSS behave similarly across the models. We see London, New York City and Washington D.C. (the three BSS with large amounts of interaction collisions in Figure 3.3) with lower RMSE while Minneapolis is erratically high.

Synthetic station state analysis shows, using three models, the efficiency of estimating the number of daily trips for multiple BSS at different data gathering time intervals. In Table 3.5 we see the DAM and SAM providing lower RMSE than IAM although all three models where expected to be similar when comparing regression results (Table 3.4). The SAM and DAM RMSE results at $\Delta = 10$ of 0.11-0.12 are encouraging for the application of station level data. The high accuracy of the results suggest their is no need for more complex modelling techniques. Estimations using observed station level data is presented next, showing that IAM and SAM models are more susceptible to rebalancing.

Δ	B	C	L	M	N	S	V	W	mean
	Synthetic combined DAM RMSE/$\overline{T}_d$								
1	0.02	0.03	0.01	0.05	0.01	0.01	0.01	0.03	0.02
2	0.03	0.06	0.02	0.09	0.02	0.03	0.02	0.05	0.04
5	0.04	0.13	0.04	0.19	0.04	0.09	0.03	0.09	0.08
10	**0.06**	**0.18**	**0.07**	**0.29**	**0.05**	**0.15**	**0.05**	**0.13**	**0.12**
20	0.08	0.23	0.09	0.37	0.08	0.22	0.07	0.16	0.16
30	0.09	0.26	0.11	0.40	0.11	0.25	0.08	0.18	0.19
60	0.13	0.28	0.16	0.38	0.18	0.23	0.14	0.20	0.21
	Synthetic combined IAM RMSE/$\overline{T}_d$								
1	0.02	0.02	0.05	0.04	0.05	0.02	0.02	0.02	0.03
2	0.08	0.03	0.08	0.08	0.09	0.04	0.03	0.02	0.06
5	0.24	0.12	0.11	0.27	0.13	0.13	0.12	0.08	0.15
10	**0.38**	**0.19**	**0.09**	**0.43**	**0.13**	**0.26**	**0.24**	**0.14**	**0.23**
20	0.46	0.25	0.09	0.57	0.17	0.42	0.35	0.18	0.31
30	0.49	0.29	0.11	0.67	0.21	0.52	0.41	0.20	0.36
60	0.51	0.39	0.15	0.86	0.27	0.66	0.48	0.22	0.44
	Synthetic combined SAM RMSE/$\overline{T}_d$								
1	0.02	0.02	0.01	0.05	0.01	0.02	0.01	0.02	0.02
2	0.03	0.05	0.02	0.08	0.02	0.04	0.03	0.02	0.04
5	0.05	0.10	0.04	0.16	0.04	0.09	0.06	0.03	0.07
10	**0.08**	**0.13**	**0.08**	**0.23**	**0.08**	**0.12**	**0.10**	**0.03**	**0.11**
20	0.13	0.14	0.11	0.26	0.14	0.13	0.17	0.04	0.14
30	0.16	0.14	0.14	0.25	0.18	0.12	0.20	0.05	0.16
60	0.18	0.14	0.17	0.17	0.26	0.11	0.24	0.09	0.17

B:Boston, C: Chicago, L: London, M:Minneapolis, N: NYC,
S: San Francisco, V:Vienna, W:Washington D.C.

Table 3.5: Mean T_d and interaction normalized RMSE at multiple Δ for the day (DAM), interval (IAM) and station (SAM) aggregated models. DAM and SAM have lower error than IAM.

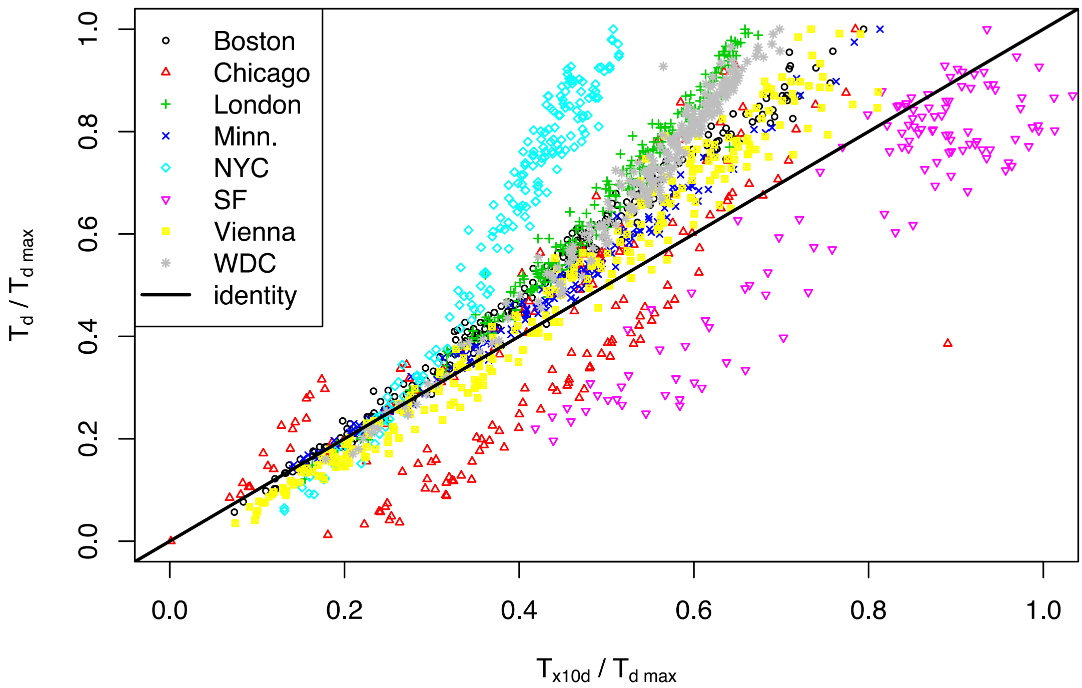

Figure 3.6: Normalized T_d against T_{x10d} for the eight case studies showing combined interaction collisions and rebalancing effects.

3.4.2 Observed station level data analysis

The sole difference between $z_{\Delta sdt}$ and $x_{\Delta sdt}$ data are the presence of rebalancing, consisting of rebalancing operations, technical issues and maintenance, in $x_{\Delta sdt}$ data. Recall Equation 3.13 and 3.14 from which rebalancing can be isolated: $r_{\Delta sdt} = x_{\Delta sdt} - z_{\Delta sdt}$. Before applying the models to the observed station level data (Section (Section 3.4.2) we present the relationship between T_d and $T_{x\Delta d}$ and rebalancing (Section 3.4.2).

Observed data descriptive analysis

Plotting T_d against $T_{x\Delta d}$ (Figure 3.6) we see Chicago, San Francisco and to a lesser extent Vienna behave erratically. Recalling from Equation 3.18 that $i_{10sdt} = |x_{10sdt} - r_{10sdt}| + c_{10sdt}$, we can recognize that disproportionate amounts of rebalancing occurring for Chicago and San Francisco are the cause. This is likely due to technical problems with the BSS hardware or software.

Similarly to Table 3.2 in our synthetic analysis we compare proportions of x_{10d}, c_{10d} and r_{10d} against i_{10d} in Figure 3.6.

Rebalancing, the moving of bicycles from one station to another, is done to prevent the situation where a station has no available docks or bicycles. When either occurs, half of the functionality of a BSS station is lost, either no bicycle can be returned or taken.

BSS	$\frac{\overline{c_{10d}-r_{10d}}}{\bar{i}_{10d}}$	$\frac{\bar{c}_{10d}}{\bar{i}_{10d}}$	$\frac{\bar{r}_{10d}}{\bar{i}_{10d}}$
Boston	0.07	0.26	0.19
Chicago	-0.37	0.29	0.67
London	-0.58	0.30	0.88
Luxembourg	-0.82	0.13	0.96
Minneapolis	-0.02	0.21	0.23
New York City	0.10	0.48	0.38
San Francisco	-1.55	0.21	1.76
Vienna	0.00	0.23	0.22
Washington D.C.	0.12	0.35	0.23

Table 3.6: Bicycle sharing system (BSS) proportions, normalized by $\bar{i}_{10d}$, of $\overline{c_{10d} - r_{10d}}$, interaction collisions reduced by rebalancing, as well as $\bar{c}_{10d}$, interaction collisions, and $\bar{r}_{10d}$, rebalancing alone. NYC has a particularly high collision rate meaning many of the transactions are not visible in station level data, x_{10sdt}.

Well managed systems aim to avoid these situations by predicting when they are likely to occur based on travel patterns throughout the day/week. It cannot be stated that systems with greater rebalancing quantities are better managed as individual BSS may have non-symmetric spatial tendencies, such as elevation differences, that accentuate the need for rebalancing.

By substracting z_{10sdt} from x_{10sdt} we can see the proportions of rebalancing occurring for each BSS (Table 3.6)[8]. Chicago, London, Luxembourg and especially San Francisco have disproportionately larger rebalancing quantities. As we stated earlier we use 'rebalancing' to refer to the rebalancing but also technical issues and maintenance. Chicago and San Francisco, during the span observed, experience increasing numbers of fluctuating station level states caused by technical issues either at the dock or station level.

Interestingly rebalancing amounts for Boston, Minneapolis, Vienna and WDC similarly account for about twenty percent of the interactions, and, including NYC, almost completely offset the collision amounts. The effects of the larger rebalancing quantities on estimation will not be trivial. We expect especially larger error for San Francisco.

Comparing the daily number of rebalancing and trip interactions (Figure 3.7) we see that Chicago, London, and Luxembourg have multiple groupings caused by an unknown technical issue occasionally inflating values. Vienna seems to be experiencing an occasional glitch as well due to stations reporting no bicycles for periods of a few hours before returning to normal. While all rebalancing quantities increase relative to trips, San Francisco does so exceedingly. Following a basic analysis, the behaviour of rebalancing for certain BSS varies between due to unknown technical issues that would require a deeper methodological analysis to remedy, outside the scope of this analysis. These irregularities do not suggest improvements which could be added to our estimation models to compensate.

[8]Note the small differences between collision amounts in Table 3.6 and Table 3.2 due to the synthetic and observed data sets having dissimilar time spans. See Table 3.1.

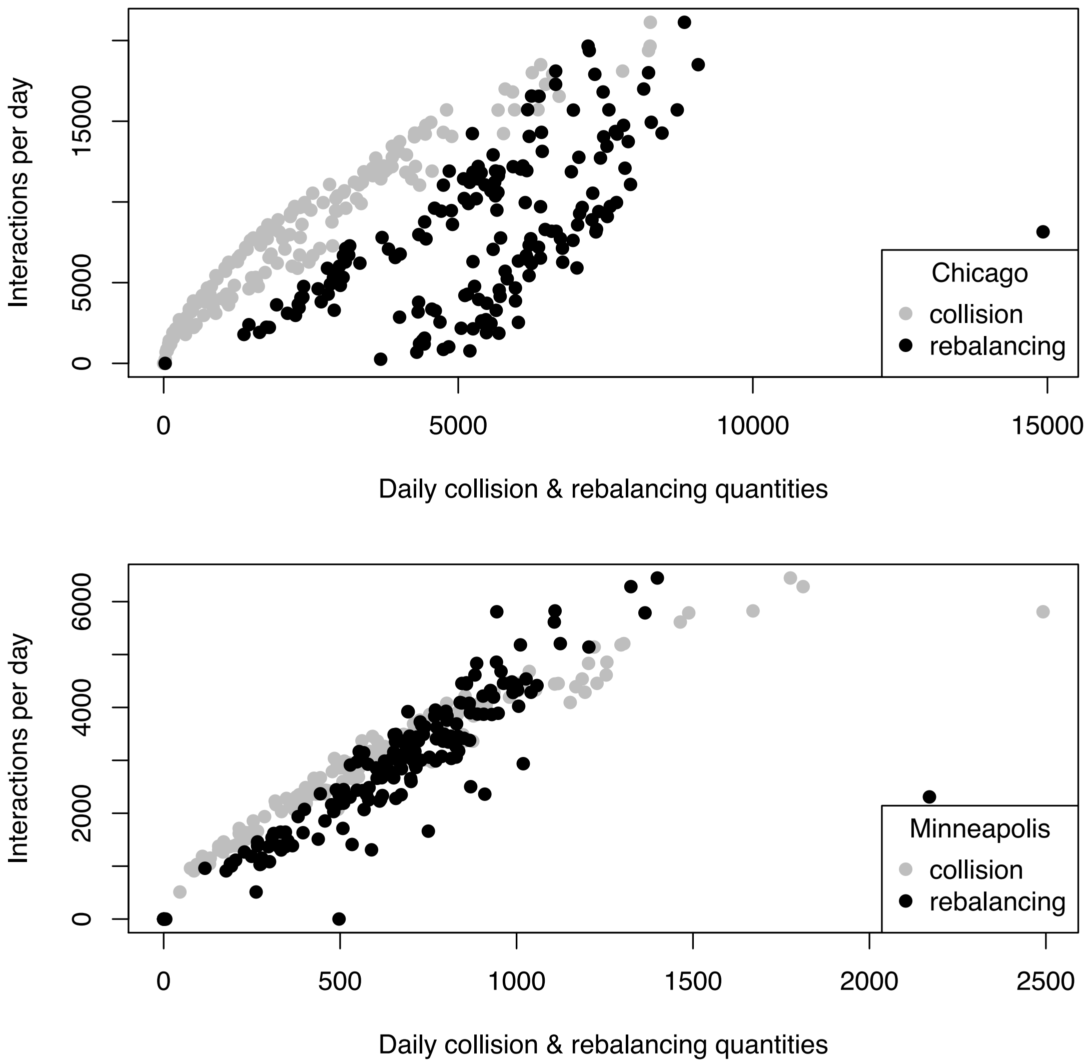

Figure 3.7: The c_{10d} and r_{10d} quantities in relation to the the number of daily trip interactions (i_{10d}). Note that Chicago's station level data contains errors inflating rebalancing amounts.

BSS	$\frac{RMSE}{\overline{T}_d}$	T_{x10d}	$T^2_{x10d} \times (10^{-5})$
Boston	0.05	1.06	8.19
London	[b]0.04	0.74	3.28
Minneapolis	0.04	0.93	11.8
New York City	0.08	0.26	8.23
San Francisco	0.14	0.35	47.6
Vienna	0.09	0.79	14.7
Washington D.C.	[b]0.04	0.70	9.74

[b] Mean of bimodal distribution.

Table 3.7: Error and coefficients of the individual day aggregated model (DAM).

Observed data model applications

We now present results of the application of DAM, IAM and SAM to the BSS for which we have collected station state values, X_{sdt} , and converted to delta station states, $x_{\Delta sdt}$, using Equation 3.1. Chicago is not used in this analysis but saved for validation (Appendix A.1).

The results of ten thousand samples are presented. Unless specified the distributions of the coefficients, significance values and RMSE in the results are all normal.

The individual BSS DAM model (Equation 3.19) is applied to the seven BSS in order to determine what optimal RMSE rates are possible for each and to compare with the synthetic analysis results. Table 3.7 shows the normalized RMSE and BSS specific coefficients. In comparison with the equivalent synthetic analysis (Table 3.3) the station level data reduces the linear coefficient, T_{x10d}, to account for the added rebalancing interactions. Further, NYC and SF can be seen compensating for their large collision and rebalancing proportions respectively by reducing their linear T_{x10d} coefficients.

The same process is repeated but using Equation 3.20 which considers active stations, $A_x 10d$. Table 3.8 shows that the combined DAM equation, applied to *independent* BSS, achieves similar error rates to the individual DAM (Equation 3.19). The independent DAM achieve RMSE, normalized by the BSS $\overline{T}_d$, of 0.04 with the exception of NYC, SF (as expected) and Vienna with rates of 0.08, 0.14 and 0.09 respectively. These independent applications Equation 3.20 serve as a baseline for comparison with combined DAM results using the same equation.

The combined application of the DAM yields surprisingly similar results to the independent DAM with the exception of Minneapolis and San Francisco (SF). While the error is expected for SF due to the technical issues defined earlier, Minneapolis is a surprise. Looking at Figure 3.2 we see that the same two BSS have low usage rates in terms of bicycles (and also stations) in the system. This model may poorly estimate trips for BSS with lower system usage rates. Minnesota also has high error rates in the synthetic combined DAM results (Table 3.5). Without a deeper analysis of Minnesota it is impossible to determine what causes this effect.

As the IAM model is at the interval temporal resolution, the estimates are aggregated to the day for normalized RMSE values (Table 3.8). The result of ten thousand samples with replacement of each BSS yielded low error rates for the individual application of the

	DAM		IAM		SAM	
BSS	Indep.	Comb.	Indep.	Comb.	Indep.	Comb.
Boston	0.04	0.05	0.08	0.29	0.11	0.15
London	[b]0.04	0.04	0.15	0.28	0.08	0.14
Minn.	0.04	0.17	0.09	0.43	0.09	0.24
NYC	0.08	0.10	0.13	0.30	0.15	0.20
SF	0.14	0.28	0.23	0.87	0.30	0.47
Vienna	0.09	0.12	0.11	0.52	0.10	0.35
WDC	[b]0.04	0.08	0.07	0.16	0.06	0.11
Mean	0.07	0.12	0.12	0.41	0.13	0.24
Valid.	-	0.13	-	0.40	-	0.23
β_1	-	0.751	-	0.470	-	1.55
β_2	-	1.81×10^{-2}	-	1.58	-	-1.46
β_3	-	-	-	6.95×10^{-4}	-	2.26×10^{-2}

[b] Mean of a bimodal distribution

Table 3.8: Bicycle sharing system (BSS) RMSE values for the day (DAM), interval (IAM) and station (SAM) aggregated models, normalized by the BSS mean trips/interactions, when cross-validated independently and combined. The means of BSS means are also provided for comparison with the validation test set.

model, however, the coefficients vary in sign and magnitude between BSS which foretells of problems with the combined model. In effect the application of IAM (Equation 3.21) to the combined BSS sets shows higher error rates (Table 3.8) than DAM as expected from the independent coefficients and the IAM synthetic analysis (Table 3.5) results. Importantly the coefficients' signs and magnitudes no longer resemble those given in the synthetic analysis (Table 3.4) making interpretation of the effects of rebalancing on the IAM impossible.

Repeating the same methodology for SAM, the individual BSS analysis results in Table 3.8 show similar BSS specific RMSE results to IAM. Unlike IAM, SAM shows consistent magnitudes and signs for the model coefficients with the exception of Vienna. For the combined normalized RMSE results SAM provides consistently lower error than IAM as expected from the synthetic results in Table 3.5. Vienna and SF experience much greater error than the rest. Vienna's station level data was one of the few provided by the operator (Boston is the other) rather than collected directly. It is unclear if their data collection methodology differs, is erroneous or whether they have fundamentally different rebalancing operations.

While the DAM and SAM show equally low error in the synthetic analysis (Table 3.4), the rebalancing interactions contained in observed station levels solely increase the error of the SAM (Table 3.8). The SAM is sensitive to rebalancing as station focused interactions increase the x_{10sd} coefficient without correspondingly increasing the number of A_{10sd} which has a negative coefficient. The DAM is advantageous in this regard as it compensates for rebalancing, relative to the synthetic coefficients, by slightly decreasing the coefficients. As rebalancing interactions, excluding technical issues, account for about ten percent of usage interactions (Table 3.6) it is apparent why SAM performs worse.

3.5 Conclusions

The number of trips a BSS experiences daily is typically inaccessible. Published metrics are typically incomparable, of dubious accuracy (e.g., tons of carbon monoxide saved) or available for short time spans that do not allow comparison or analysis to reveal if a problem exists in the provisionment, suitability or demand of a BSS. The popularity of BSS reflect positively on electees and are lucrative for advertisers. Without public access to usage data knowing whether a BSS is the best investment for the limited amount of funds allocated to forms of non-motorized transport cannot be determined. Electees and provisioners hold usage data but are potentially conflicted with making it public as this could have few benefits in the best case, while being politically damaging and threatening provisioner contract renewal in the worst case. Regardless, data which is not publicly available, using this methodology, can be estimated using our methodology.

Contracts between municipalities and BSS provisioners come with many clauses regarding quality of service. Rebalancing frequency and quantity are defined in some agreements. The quality of the service provided by BSS operators is not easily verifiable. Our methodology can reveal spatial and temporal frequencies of rebalancing completed by provisioners and allow municipal oversight of service agreements.

Our work utilizes trip data, gathered from the few BSS provisioners who do make their trip data public, to test trip estimation models which use scraped station level data, gathered at regular intervals, as their inputs. The resulting error rates show that the daily aggregated model (DAM) consistently provides the best estimates of trips using a simple methodology. The analysis of the created synthetic data sets at various Δ intervals allowed the comparison of estimation error at different data collection frequencies showing that ten minute intervals can provide sufficiently good estimates. The application of the DAM on scraped station level data at a ten minute Δ also supports that low-error estimations of T_d (for those BSS not experiencing technical issues) can be accomplished. Logistically, gathering data at this frequency to apply the DAM is not a strain on network limitations or storage and individuals could perform these estimations independently.

In an effort to democratize the evaluation of BSS we created new sets of data beyond observed station levels, $x_{\Delta sdt}$, typically used for analysis. We formalized interactions, $i_{\Delta sdt}$, synthetic levels, $z_{\Delta sdt}$, rebalancing, r, collisions, c, and their relationships. We believe our formalization of the properties and relationships open up possibilities of deeper BSS analysis beyond which has been done to date and that our methodology has applications for other systems that contain flow data sampled repeatedly at fixed points.

The estimated number of daily trips can serve as an indicator of potential problems with a BSS. A deeper quantitative and especially qualitative analysis is necessary to make statements as to whether a BSS is a success or a failure. Until trip data or daily trip counts are consistently available this work provides a method for estimating the daily trips in order to open a discussion or analysis about the efficacity of a BSS and whether it may be linked to provisioner management, station density, scheme pricing, urban structure, cycling infrastructure or local legislation.

Chapter 4

Rebalancing strategies, patterns and purpose

Outline

We provide a first spatio-temporal exploration of bicycle sharing system (BSS) rebalancing patterns from data extracted for individual stations at a fine temporal scale and operator interviews. Analysing rebalancing operations for nine BSS we describe implications for operators, municipalities and future optimization work. We find that stations adjacent to transit hubs receive disproportionate amounts of rebalancing relative to trips and that rebalancing is more often responding to morning and afternoon demand exceeding station dock capacities rather than longer term accumulations of bicycles. More importantly we observe some operator' rebalancing behaviours constrained between opposing goals of maximizing trips, profits and service level agreements. Many BSS have no explicitly defined purpose, but existing rebalancing strategies can support or clash with the purpose or suggested benefits of a BSS.[1]

4.1 Introduction

In the last ten years bicycles sharing systems (BSS) became standard in large European and North American cities. As a by-product of their success, the dominant complaint of BSS users is the occurrence of stations being completely empty or full (Raviv, Tzur, and Forma, 2013). Bike-share operators aim to minimize these occurrences by redistributing bicycles between stations, and subsequently freeing docks. This rebalancing process is a theoretically complex optimal routing problem with added complexity due to truck and station capacity limitations, concurrency (multiple trucks) and spatial demand prediction, all within a spatio-dynamic system. The variety of terms used to describe the process, balancing (Benchimol et al., 2011; Kloimüllner et al., 2014; Rainer-Harbach et al., 2013), rebalancing (Erdoğan, Battarra, and Calvo, 2015; Regue and Recker, 2014),

[1]This chapter is based on (Médard de Chardon, Caruso, and Thomas, 2016).

repositioning (Forma, Raviv, and Tzur, 2015; Han, Luong, and Ukkusuri, 2015; Raviv, Tzur, and Forma, 2013), relocation (Erdoğan, Laporte, and Calvo, 2014) and redistribution (Labadi et al., 2012; Labadi et al., 2014; Lin and Chou, 2012; Nair et al., 2013; Pfrommer et al., 2014), stems from the many disciplines studying the problem (operations, logistics, engineering, economics, mathematics and computer science).

This chapter analyses BSS spatial and temporal rebalancing operations for nine BSS (Boston, Chicago, London, Luxembourg, Minneapolis, New York City, San Francisco, Vienna and Washington) and describes implications for operators, municipalities and future optimization work. We first provide definitions and position our work in the literature.

We define the moving of bicycles as *redistributing* and the *state* of a BSS as the momentary distribution of bicycles and available docks. Rebalancing implies redistribution to achieve a state where all stations have roughly equal proportions of bicycles to docks. An analysis of 38 BSS by O'Brien, Cheshire, and Batty (2014) shows the typical ratio of docks to bicycles to be about two to one. This means that it is possible to have each station in a BSS be about half full. We call this *total balance*. From a user's perspective a BSS could be considered in good order so long as one bicycle and dock is available at each station. In the literature the term 'balanced' is used in terms of *desired balance* (Benchimol et al., 2011; Chemla, Meunier, and Wolfler Calvo, 2013; Erdoğan, Laporte, and Calvo, 2014; Forma, Raviv, and Tzur, 2015; Kloimüllner et al., 2014). In reality no BSS should aim to be totally balanced as short-term demand would quickly cause an undesirable state. We therefore use the term *balanced* to imply having the *desired balance* and define the process of *rebalancing* as *striving to obtain a desired balance*. Literature analysing other BSS aspects refer to rebalancing (Ahillen, Mateo-Babiano, and Corcoran, 2015; Beecham, Wood, and Bowerman, 2014; Parkes et al., 2013; Wood, Slingsby, and Dykes, 2011; Zhao, Deng, and Song, 2014), or redistributing (Nair et al., 2013; Ricci, 2015; Shaheen, Guzman, and Zhang, 2010) and describes the state of a BSS when many stations are full or empty as unbalanced (Ahillen, Mateo-Babiano, and Corcoran, 2015; Borgnat et al., 2011). Operators refer to full or empty stations as experiencing an *outage*, while otherwise being *normal*.

Within the BSS literature, rebalancing is a mature subfield due to the rapid evolution of the theoretical work (Benchimol et al., 2011; Erdoğan, Battarra, and Calvo, 2015; Erdoğan, Laporte, and Calvo, 2014; Forma, Raviv, and Tzur, 2015; Han, Luong, and Ukkusuri, 2015; Kloimüllner et al., 2014; Labadi et al., 2012; Labadi et al., 2014; Lin and Chou, 2012; Nair et al., 2013; Pfrommer et al., 2014; Rainer-Harbach et al., 2013; Raviv and Kolka, 2013; Raviv, Tzur, and Forma, 2013; Regue and Recker, 2014) in which we see three distinct types of rebalancing. *Static* rebalancing (Benchimol et al., 2011; Chemla, Meunier, and Wolfler Calvo, 2013; Erdoğan, Battarra, and Calvo, 2015; Forma, Raviv, and Tzur, 2015) simulates the optimal redistribution of bicycles to reduce station outages when system use is at a minimum, i.e., during the night. *Dynamic* rebalancing (Kloimüllner et al., 2014; Labadi et al., 2012; Pfrommer et al., 2014; Regue and Recker, 2014) strives to achieve the same goal but while the system is in use. This is much more relevant for BSS operators, which mostly only redistribute bicycles during the day. New York City[2] (NYC), London and Paris are known exceptions. Paris, for example, uses 20 trucks (Shaheen, Guzman, and Zhang, 2012), each with a capacity of 25 bicycles (Forma, Raviv, and Tzur, 2015), for rebalancing 24 hours a day (Benchimol et al., 2011). Finally, the third rebalancing behaviour, which is also dynamic, aims to reach a bicycle distribution matching a forecast *demand* (Nair et al., 2013; Regue and Recker, 2014). Existing literature discusses how to optimally rebalance, but for those BSS constrained by high usage, such as NYC, outages are inevitable and *where* to prioritize rebalancing, rather than *how*, is of greater importance. Each of these optimal rebalancing models, preoccupied with minimizing outages through various implementations result in different outcomes. Meanwhile operators may have contrasting practical priorities, such as maximizing trips or revenue.

While optimisation literature is abundant, no work describing spatial rebalancing patterns or operations of BSS in depth has been found. We aim to fill this gap using discrete historical station rebalancing quantities combined with station levels, trip flows and operator interviews to explore the spatial and temporal rebalancing behaviour for nine case studies. Further, just like different optimal rebalancing models result in different outcomes, we propose that rebalancing behaviour heavily influences the outcome of BSS in regards to their goal (maximizing trips, profits, equity, cycling modal share, etc.). Hence, we not only analyse rebalancing outcomes but also how these operations relate to the purpose of a BSS.

We begin by presenting our research methodology (Section 4.2), the results of our operator interviews (Section 4.3) and spatio-temporal analysis (Section 4.4), followed by a discussion of how rebalancing impacts outcomes (Section 4.5) and conclude (Section 4.6).

4.2 Methodology

4.2.1 Case studies

Data availability determined our selection of case studies. Station level data can be gathered from most BSS freely, but trip data, providing origins and destinations, requires operators making it available. Our nine case studies differ by operator, size and density, data collection period and usage intensity (Table 4.1).

Our case studies capture different operations motivations: Non-profit (Minneapolis), contract (Motivate and Serco), advertising (JCDecaux) and a hybrid of the latter two (Gewista).

San Francisco is the smallest of our case studies and London the largest. London has twice the number of stations as NYC but a lower density[3]. The remaining case study densities (Table 4.1) are well below the 10 to 16 stations per square kilometre

[2]For simplicity, in the balance of this chapter, we refer to a city's BSS by naming the principle city alone rather than the brand name or specifying that we are referring to its BSS.

[3]The same methods as O'Brien, Cheshire, and Batty (2014) is used to calculate station densities but with 300 metre buffers as this is the distance between stations recommended by The Institute for Transportation and Development Policy (Gauthier et al., 2013).

BSS	Launch year	Operator	Stations count[a]	Station density[b]	Bicycle count[a]	Days of data[c]	Trips[c]/day[c] /bicycle[d]	Data date range
Boston	2011	Motivate[e]	95	4.4	767	177	3.3	2011-08-23 - 2012-09-28
Chicago	2013	Motivate	300	4.6	2,406	127	2.6	2013-06-28 - 2014-01-01
London	2010	Serco	725	7.5	9,250	175	3.1	2013-03-25 - 2014-01-27
Luxembourg	2008	JCDecaux	72	4.9	698	589	0.8	2011-12-15 - 2014-05-27
Minneapolis	2010	Non-profit[f]	167	4.4	1,410	125	1.1	2013-04-24 - 2013-11-04
New York City	2013	Motivate	330	9.5	5,568	134	6.2	2013-07-15 - 2014-01-27
San Francisco	2013	Motivate	67	5.2	606	104	1.6	2013-08-30 - 2014-01-27
Vienna	2003	Gewista[g]	102	4.0	1,141	233	1.8	2012-01-01 - 2012-12-27
Washington	2010	Motivate	305	4.8	2,560	172	4.0	2013-04-24 - 2014-01-01

[a] Maximum observed. [b] Per km^2, [c] Weekdays. [d] Mean values biased for data sets with partial years.
[e] Formerly called Alta Bicycle Share. [f] Nice Ride Minnesota. [g] Majority owned by JCDecaux.

Table 4.1: Descriptive statistics for the nine studied BSS.

recommended (Gauthier et al., 2013). The spatial shape and density of case study stations, which can impact rebalancing, are displayed in Figure 4.1.

Our data covers spans from 2011 to 2014 (Table 4.1). To simplify analysis we focus on weekdays alone, regardless of holidays. As the number of trips fluctuate between seasons, some date ranges engender an aggregation bias due to incomplete years. We believe data span to be of lesser importance than the fact that data for Chicago, NYC and SF encompass months directly after system launch, likely containing more irregular usage and rebalancing than mature systems. Although NYC launched within our data span, it has the highest number of trips per day per bicycle (6.2), with Washington, Boston, London and Chicago in the middle range (4.0 - 2.6) and Vienna, SF, Minneapolis and Luxembourg at the low end (1.8 - 0.8).

4.2.2 Interviews

We contacted the nine BSS operators desiring to know what strategies they apply, how many vehicles of what capacity are operated, how many bicycles are rebalanced, what they believe the main constraints to rebalancing to be, how service level agreements affect rebalancing and what information systems are used by operators to facilitate rebalancing.

Of the nine operators, Boston, Minneapolis and NYC completed telephone interviews, Vienna provided full responses by email and San Francisco and London provided some of the details requested by email. Media articles and reports were used to complement missing information.

4.2.3 Rebalanced effective usage (REU)

Rebalancing analysis requires understanding how BSS stations are used. Paradoxically, many trips are only possible due to rebalancing, and, conversely, certain trips increase the need for rebalancing. Past analyses have used station clustering (Froehlich, Neumann, and Oliver, 2009; Lathia, Ahmed, and Capra, 2012) of daily *normalized available bikes* (NAB) to characterize BSS. A drawback of this technique is that rebalancing operations affect station profiles and clustering of stations for generalization. Instead of NAB, we define *rebalanced effective usage* (REU) of stations, combined with departure and

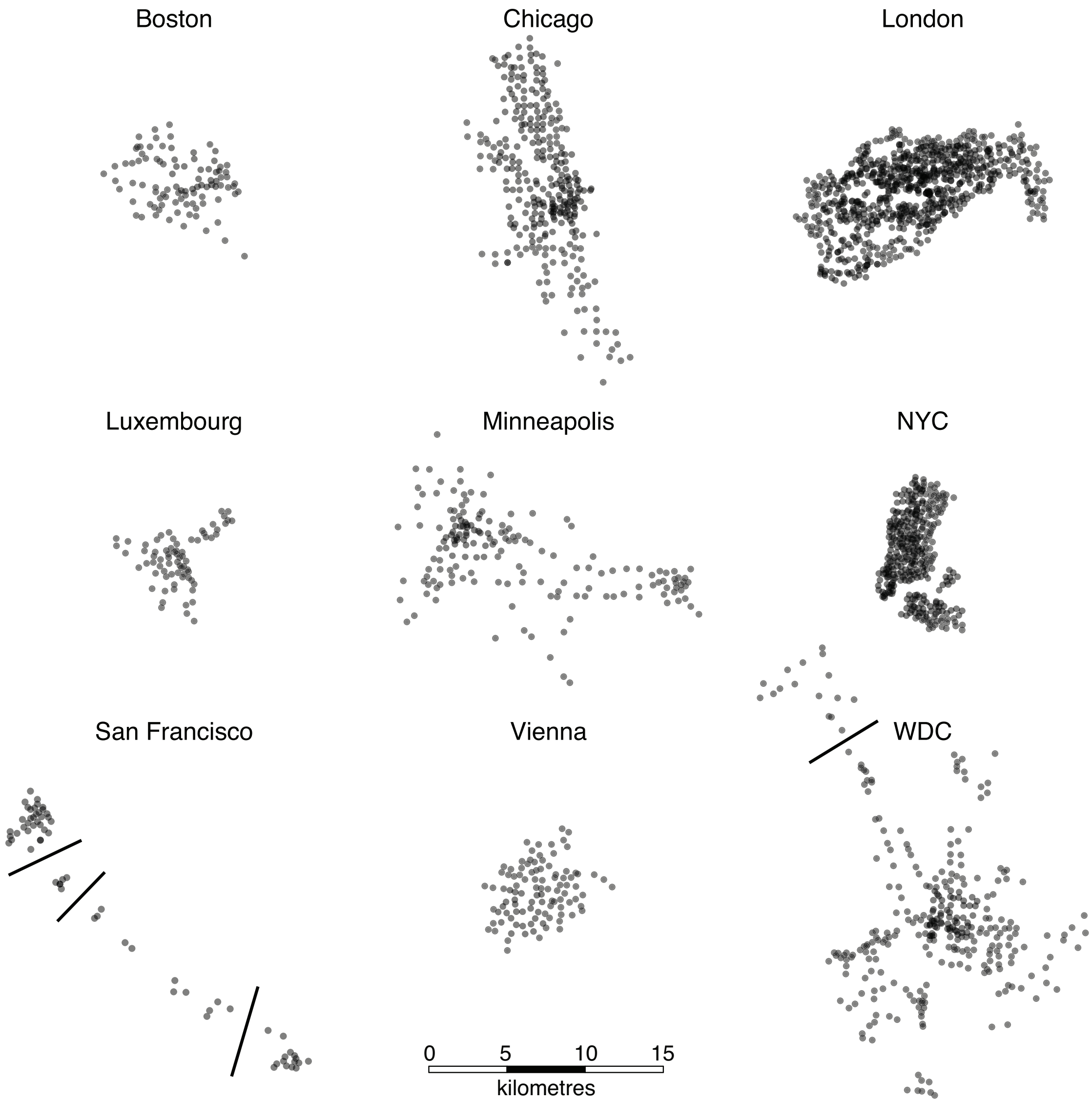

Figure 4.1: Case study stations plotted at the same scale.

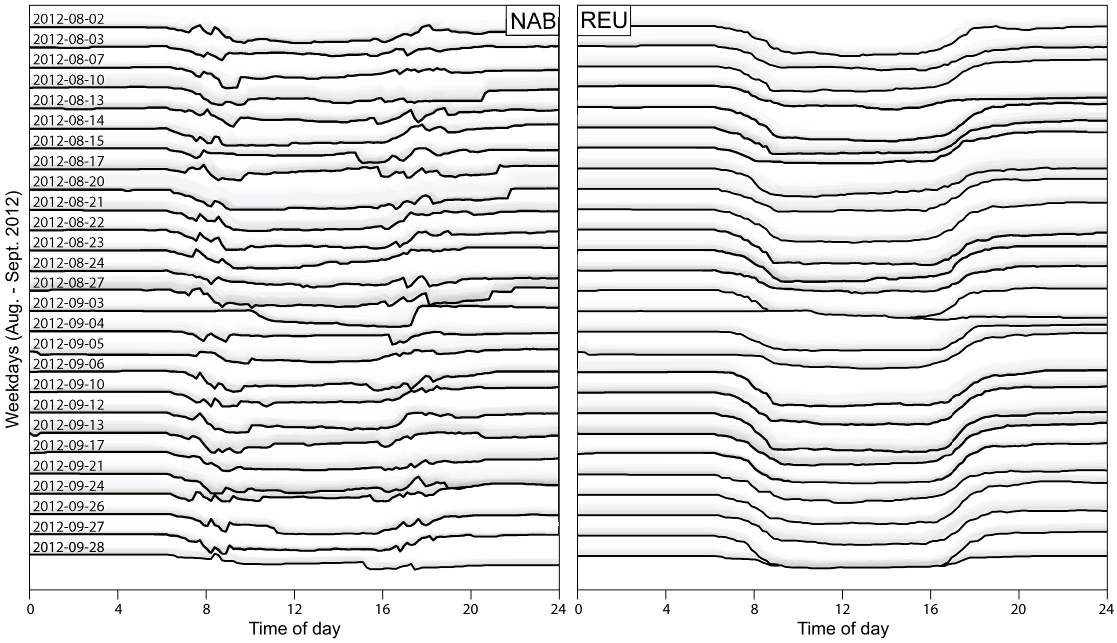

Figure 4.2: Normalized available bikes (NAB) and rebalanced effective usage (REU) at Boston's North Station (weekdays Aug. - Sept. 2012)

arrival profiles for cluster analyses, using Ward's hierarchical algorithm[4] (Murtagh and Legendre, 2014), in order to characterize stations ahead of rebalancing analysis.

Rebalanced effective usage (REU) of stations is the cumulative sum of bicycle check-ins minus check-outs within time intervals, illustrating the trips rebalancing affords. Figure 4.2 compares RUE and NAB with Boston data as an example. The REU plots omit rebalancing and *collisions* i.e., coincident check-in and check-out *transactions* which occur within a station level retrieval period. Collisions are desired transactions for a BSS, as they require no rebalancing. Measuring *mean* REU amplitude (Figure 4.3) provides the number of docks needed, based on historical averages, to satisfy equal trips without rebalancing. Station mean REU plots also allow categorization of stations based on net tendency (B and B' quantities in Figure 4.3): stations that have roughly equal numbers of trip starts and ends (transaction balanced), more people leaving (transaction negative) and finally stations with more arrivals than departures (transaction positive). Any station that is transaction positive or negative will require rebalancing. Conversely, a station being anything but transaction balanced is *caused* by rebalancing. Amplitudes that exceed dock count are another indication of rebalancing.

[4]As we aggregate data to hours and use local time, we do not expect station values to be out of phase and therefore do not use a temporal clustering technique such as dynamic time warping(Froehlich, Neumann, and Oliver, 2009). We found the clustering of the alternative measures provide clearer spatial structures than NAB.

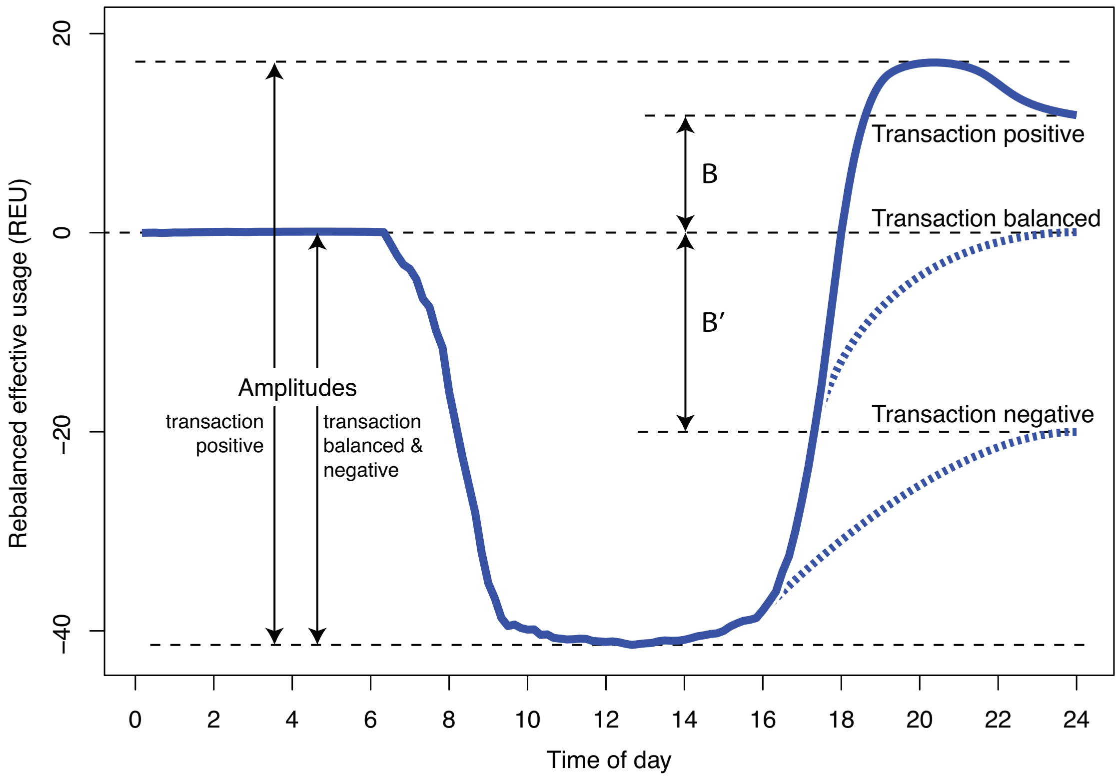

Figure 4.3: Mean rebalanced effective usage (REU) for a station with 30 docks showing amplitude and net tendencies (B and B').

4.2.4 Rebalancing analysis

We performed analysis using a variety of statistical and visual analysis methods. First, identical reports were generated for each BSS containing: temporal and spatial evolutions of the number of stations, trips and rebalancing quantities, hierarchical clustering of stations, station REU profiles, net flow vector maps, occurrences of full or empty stations, relationships between trips and rebalancing, net distributions of origins and destinations across portions of the day and other summary statistics. Second, animations were used, displaying synchronously mean station levels, net rebalancing quantities and net transactions. Then an interactive web based map (bikeshare-research.org/rebalancing) was used to superimpose stations, trips and rebalancing over different periods. Selecting stations provides detailed station profiles in terms of daily distribution of full and empty outages, origin and destination trips, withdrawals and deposits of bicycles by rebalancers, as well as NAB and REU profiles. Third we also visualize daily historical station levels, user check-ins and check-outs as well as rebalancing deposits and withdrawals.

4.3 Interview results

From interviews, media and data sources we present rebalancing components and operational strategies while considering how these impact potential BSS goals.

4.3.1 Vehicles, facilities and staff

Vans, cube and pickup trucks, trailers, electric carts and even bicycles with trailers are used in different combinations (Table 4.2). Vans with a capacity of about 25 bicycles are used by most systems. Inclement weather and weekends typically require fewer rebalancing vehicles. Rebalancing vehicles reportedly consume between 8 - 17 litres per 100 kilometres (City of Seattle, 2016c; Fishman, Washington, and Haworth, 2014) making alternatives important if the BSS purpose relates to CO_2 emission reductions. London in the past operated electric vehicles pulling trailers carrying up to 20 bicycles but now solely uses cube trucks from which emissions now possibly exceed reductions from user modal shift (Fishman, Washington, and Haworth, 2014). Bike trailers, a sustainable alternative, rebalance 4 bicycles at a time. While Boston and Washington find these of limited use due to their small carrying capacity (Capital Bikeshare, 2013), NYC regularly uses 12 bike trailers for their efficiency at moving bicycles short distances and ability to bypass congestion. This contrast in opinion is likely associated with NYC's higher station and cycling infrastructure density (Table 4.1).

Chicago and Washington, each having about 300 stations, require roughly 260 hours of rebalancing work per week[5]. As BSS trips vary by season, weather and day of the week so does rebalancing and demand for rebalancers. Many operators provide seasonal

[5]Chicago uses about 43 employees with six hour shifts and Washington 25 with ten hour shifts (Capital Bikeshare, 2015c; Maus, 2013; Steinberg, 2014). Chicago rebalancers and technicians do not receive health benefits due to short shifts and have been trying to unionize in order to do so (Steinberg, 2014).

BSS	Vehicle quantity	Vehicle capacity	Reb. hours	Daily $\overline{trips}$	Daily $\overline{reb.}$	Rebalancing quoted	SLA % station normal
Boston	4/1	25/4	16	1,420	168	18K/month	85%
Chicago	5-7[a]	25	18	3,830	809	1-1.3K/day[a]	-
London	17-21	18	24	23,393	4,989	-	82%
Luxembourg	-	-	16	476	102	-	-
Minneapolis	3	15	16	1,516	148	250	none
NYC	3/6/12	45/22/4	24	26,497	2,564	30-65K/month	98%
San Francisco	2/1	25/4	16	928	130	-	-
Vienna	3	20	8	1,809	124	4% of trips	none
Washington	10[b]	25	20[c]	7,842	923	2,600/weekday[c]	-

[a] Gardner (2013) and Weissmann (2014). [b] Maus (2013).
[c] Capital Bikeshare (2015c).

Table 4.2: Summary of case study rebalancing operations.

contracts or sub contract rebalancing during busy periods. Some outsourced bicycle trailer rebalancers are paid per bicycle moved, sometimes leading to unsurprising side-effects. For those BSS seeking equity, regular work shifts are more ethical than these profit maximizing techniques.

Rebalancing operations vary from 8 to 24 hours a day (Table 4.2) and can be deduced from rebalancing. Chicago operates three 6 hour shifts (Figure 4.4). For NYC, which operates 24 hours a day, rebalancing shifts have different responsibilities. During rush hour, fixed rebalancing patterns are carried out by all vehicles attending to areas of expected high demand. Between daily rushes, half of off-peak rebalancers address undesirable station imbalances. Finally, night shifts address bicycle, dock and station repairs and the redistribution of the relatively static system for the morning rush. Other BSS typically balance their systems at the end of the day or early morning for the forthcoming morning rush. Night shifts have reduced traffic congestion and associated emissions but also increased efficiency and decreased costs as a result. Night rebalancing therefore supports profit *and* sustainability oriented operators.

Our mean rebalancing quantities observed (Table 4.2 - Daily reb.) are lower than reported in interviews and media, with the exception of Vienna[6], likely due to many systems having grown since our data gathering. Rebalancing quantities for five case studies are around 10% of the number of trips, while Chicago and Luxembourg, have 20%, and London and San Francisco, about 35%. We observe erratic station level data for San Francisco and Chicago, explaining their higher rates.

As is the case in most public-private partnerships, an expected level of service is defined (Table 4.2). For example, Boston's service level agreement (SLA) requires that between 6 a.m. and 10 p.m. each station be *normal*, not full or empty, 85% of the time, meaning outages can occur up to a maximum of 144 minutes per station per day. Some SLA define outages as when a station and its neighbour(s) are not normal but this was found difficult to measure and enforce. London and NYC use a priority system, where a

[6]Vienna's information system, at times, erroneously reported zero bikes for minutes or hours before returning to the previous bicycles availability, exaggerating rebalancing observed.

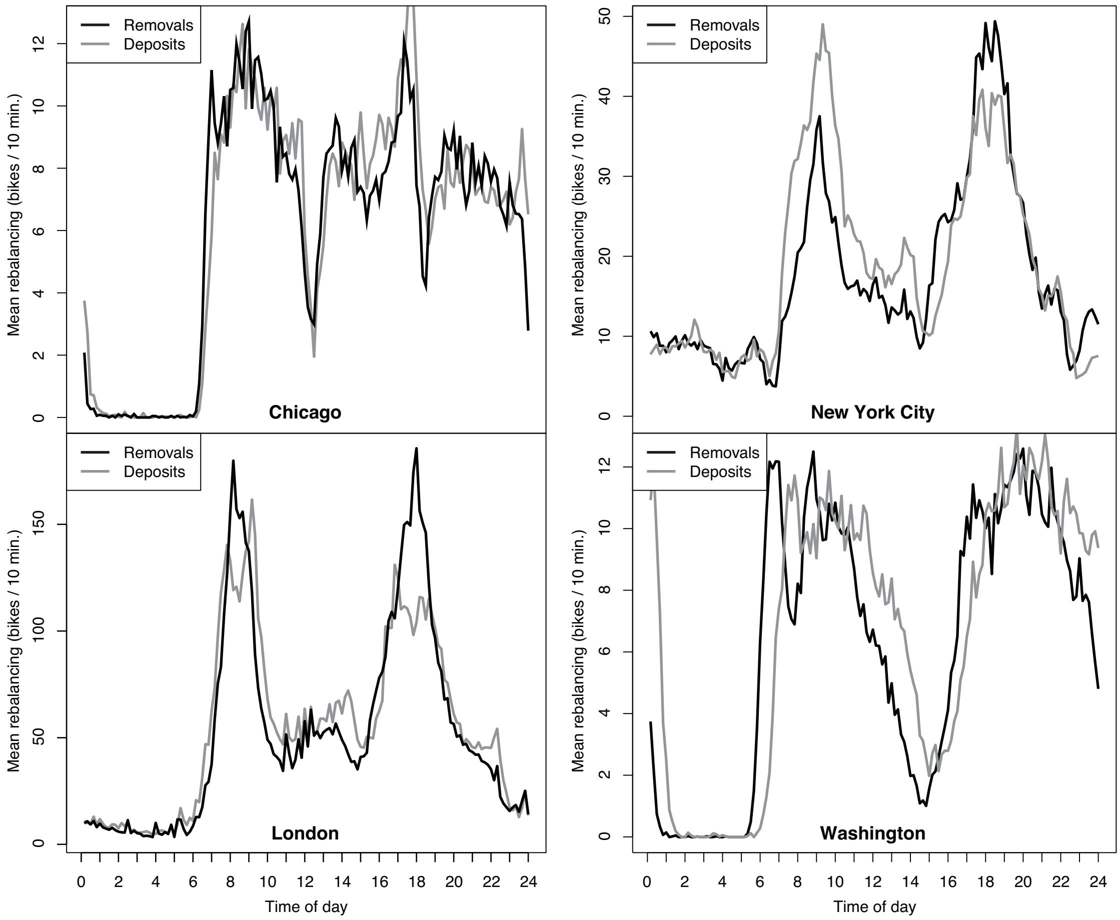

Figure 4.4: Daily mean rebalancing activity for Chicago, London, New York City and Washington.

number of stations are given more stringent outage limits than others. Priority stations in NYC, with 32 minutes of outage allowed per day, are challenging to maintain during busier months (NYCBS, 2015a).

4.3.2 Valet and corral service

Although terminology differs, a valet service is typically where rebalancing staff removes bicycles from station docks to prevent popular stations filling up. Bikes are either loaded into vehicles or 'corralled' on the side walk or between docks until the process is reversed. Valet services reduce operator costs and improve reliability by guaranteeing users the ability to return their bicycles. Users sometimes abandon undocked bicycles adjacent to full stations or call customer service for assistance. More serious are reports that some members simply do not rely on the systems due to the anxiety of not finding free docks at their destination and are less likely to renew their subscriptions. Valet services guarantee users can deposit their bicycle, providing a better user experience and reduce costs and potentially lost membership revenue.

Reverse valet services, refilling empty stations, are infrequently provided as operators prioritize full station avoidance over empty ones. Full outages are more frustrating for users and more reported by media. Empty outages therefore are understandably seen as of inferior importance even though SLA do not typically distinguish between the two. Prioritising full outages in SLA could increase quality of service.

Replacing valet service with more stations or docks is not necessarily effective in preventing outages due to latent demand. London's Waterloo train station initially provided a BSS valet service (Transport for London, 2010) but stopped after a 126 dock station was installed to provide rail commuters equivalent quantities of bicycles. In 2012 Waterloo station once again had a valet service for morning and evenings with the peculiarity of a night guarded corral.

Rebalancing trucks, during rush hour, operate similarly to a reverse valet service as bikes are often checked out as quickly as *rebalancers*, those doing the rebalancing, unload the bicycles from trucks and dock them for use. The repositioning of bicycles results in better service relative to corrals as bikes remain usable within the system but at a higher cost and potentially with greater CO_2 emissions.

Valet services further intensify rebalancing's nature of distorting station usage relative to demand. A station with corral service at central London's Stonecutter Street, for example, has 30 times the number of trips of an adjacent station 100 metres away while no train station or landmark makes it distinctive.

Valet services typically run seasonally, in good weather and at popular destinations, usually at CBD and large universities in the morning and train stations and residential areas in the afternoon, but also for special events. A weekend valet service is unusual, but present in Chicago (Divvy Bikes, 2014). Valet services currently exist in Boston, Chicago, London, NYC and Washington (Capital Bikeshare, 2015a).

The number of bicycles handled by valets varies. New York City's Penn Station (Figure 4.6) provides 400 bicycles from an adjacent warehouse each morning, with the opposite process in the evenings. This reverse valet service still runs out of bicycles during the morning. Depending on the goal of a BSS, such as increasing private utility cycling modal share, running expansive valet services, with non-negligible costs, may be counterproductive. Alternatively, in order to maximize profits, increasing service dependability through valets is key.

4.3.3 Software

Despite the extensive number of optimal rebalancing publications, no known operator has adopted such software. Vienna *tested* an optimal rebalancing methodology (Kloimüllner et al., 2014) but the operator stated obtaining better results by relying on staff experience.

All rebalancing operators use applications and maps, mainly developed by third parties, showing the locations of full and empty stations in conjunction with local expert knowledge of traffic conditions and special events. Cycling and BSS enthusiasts are responsible for developing many of these applications out of curiosity and interest. CabiTracker, showing station locations, states and outage durations, facilitates operator SLA compliance. The creator was later hired by Alta Bicycle Share (Capital Bikeshare, 2014), making the software available to many of their systems (cabitracker.com, hubwaytracker.com, divvytracker.com, cogotracker.com, citibiketracker.com). Oliver O'Brien's web maps (bikes.oobrien.com) are also commonly used in Minneapolis, NYC, San Francisco and Washington (Maus, 2013) dispatch centres. New York City is the sole operator we know using custom software forecasting station demand and trip flows while London has trialled similar software (Serco, 2015). Stock software is provided by hardware vendors but operators stated these do not provide the clarity of information desired.

4.3.4 Strategy

Multiple rebalancing strategies exist and operate under different constraints.

Minneapolis initially aimed to have stations be half full, totally balanced, before quickly realizing this should not be their goal and may be counterproductive. Stations are divided into high and low value based on how many trips they generate. Rather than spending time addressing outages indiscriminately, as SLA typically require doing, their priority is on high value stations where outages of short duration will have greater impacts on customers than longer outages at low-value stations. This strategy is possible for Minneapolis by not having an SLA specifying acceptable outage durations. Minneapolis is also innovative in their labour practices by encouraging multi-skilling through the rotation of shift leaders to make decisions regarding rebalancing. Vienna also has no SLA but rebalancing is more focused on moving bicycles back uphill as the city is on a slight slope.

Routine dictates rebalancing for NYC during peak periods as demand is largely consistent. Trucks and bicycle trailers follow their set patterns every day, unless weather or special circumstances change requirements. Between peak periods, adjustments are made to address outages but also prepare for the next peak period. Rather than rebalance at the system scale, NYC and Washington delineate smaller control zones to rebalance within, similar to some optimal rebalancing models in the literature. The shorter rebalancing distances have a few benefits. Bicycles with trailers are used in NYC for rebalancing short distances. The bicycles have no emissions, are more cost-effective and, due to traffic, can move bicycles faster than trucks. Rebalancing efficiency, the moving of bicycles by an individual, varies from 16 to 33 bikes per hour in Chicago, NYC and Washington (Capital Bikeshare, 2015c; Weissmann, 2014) but it is unclear if this is due to vehicle choice, congestion, station density or strategy.

Bike depots, present in major neighbourhoods, allow NYC operators to quickly respond to high demand stations, typically in conjunction with a valet service, by stocking bicycles in close proximity. Some of these depots, near major transportation hubs, are rebalanced by bike trailer. Depots often hold 200 to 400 bicycles overnight and are combined with repair services. Washington, rather than store bicycles in depots, collects corralled bikes with large trucks to redistribute the bicycles in residential areas (Capital Bikeshare, 2015c) in the outskirts of the system. Depots allow faster distribution with the concession of perhaps reducing system bicycle availability.

In discussions with operators regarding rebalancing strategies, they distinguished between optimizing customer experience and satisfying outage SLA. The two goals are not seen as coincident. While existing optimal rebalancing models are complex, the application still requires many practical non-trivial facets of BSS operations relating to BSS purpose be integrated. For example, an operator prioritizing sustainability may only be interested in models using bike trailers and electric vehicles, having different constraints than gasoline vehicles.

4.4 Data analysis results

For brevity, rebalancing validation is in Appendix B and we present maps of only four case studies, with the remaining five, as well as additional analysis tools, animations, plots and maps available on the web addendum (bikeshare-research.org/rebalancing/).

4.4.1 Characterising trips

Looking at the dispersion of trips, many BSS have a few stations with disproportionately large amounts of trip origins and destinations made possible through rebalancing and valet services (Figures 4.5 and 4.6). In Boston, for example, trips to and from North and South Stations account for almost a fifth of trips in the system[7]. Weekday mornings, North Station has large net outflows while South Station has similar quantities of check-ins and check-outs. The yellow cluster shows stations with higher morning destination trips and higher evening origin trips. The navy blue stations are high volume stations

[7]Our data only contains a short span of trips from the summer 2012 system expansion, from roughly 60 to 95 stations, into Cambridge, Brookline and Somerville. We do not observe the known substantial number of trips north of the Charles River, especially surrounding MIT. The system has continually expanded and has 140 stations as of 2014 (Hubway, 2014). Cambridge accounts for 20-25% of system activity in 2014.

but generally balanced, and finally the light blue stations indicate stations of lower usage. Cluster colours are nominal and not comparable between case studies.

Normalized available Bicycles (NAB) and rebalanced effective use (REU) station clustering were tested but using distinct check in and check out mean values was found to best represent station usage while reducing error, which NAB contains, and maintaining intensity, partially removed by REU.

Alternative methods effective at abstracting BSS characterization also included mapping morning and evening net flow using glyphs, showing the orientation and magnitude of trip flows (web addendum), and proportional symbols showing the net check-in, check-out balance at stations (Figures 4.7 and 4.8).

Trip data is representative of where bicycles and spaces are available at the time of demand and therefore biased, not representing demand homogeneously. As rebalancers affect the spatial and temporal presence of bike and dock availability they directly impact which trips can occur. Further, operator spatial demand preconceptions may therefore be self-fulfilling as areas with few bikes allow few trips and appear to represent low demand.

Station trip imbalances (more trips starting than ending at a station, or vice versa) over time is only possible due to rebalancing. It therefore becomes impossible to discuss trips without rebalancing. While rebalancing aims to limit the occurrence of full and empty stations, it is logistically unlikely this is spatially and homogeneously achieved.

As seen earlier, rebalancing is often prioritized where it is deemed most useful according to *operator* goals of profit, satisfying user demand or SLA obligations. However, current demand reinforces itself as existing flows are facilitated by rebalancing and unexpected journeys are not. The resulting bias due to operator preconceptions and station constraints temper trip data's ability to represent natural population flows and subsequent analysis. Making any conclusions based on trip data *requires* understanding the character of spatial and temporal rebalancing. So while the purpose of a BSS may be defined it is unclear whether municipalities and operators are aware of how rebalancing shapes system use, perhaps in contrast to the *municipal* purpose of the BSS.

4.4.2 Rebalancing

Rebalancing types

Some rebalancing in Paris is allocated to moving bicycles uphill due to people mostly riding downhill. Special stations, named $V+$, were created offering time-in-lieu rewards for members riding bicycles back uphill. This type of rebalancing is dominant in Luxembourg and Vienna where noticeable slopes are present. We call this type of rebalancing *polarized rebalancing*, where either rebalancing deposits or withdrawals consistently occur at a station, in this case related to the relative elevation of stations. Polarized rebalancing is necessary for any station with a positive or negative REU profile tendency (Figures 4.3 and 4.11).

The second rebalancing behaviour we observe, especially at transit hubs, is caused by morning bike demand exceeding supply and afternoon return trips struggling to find

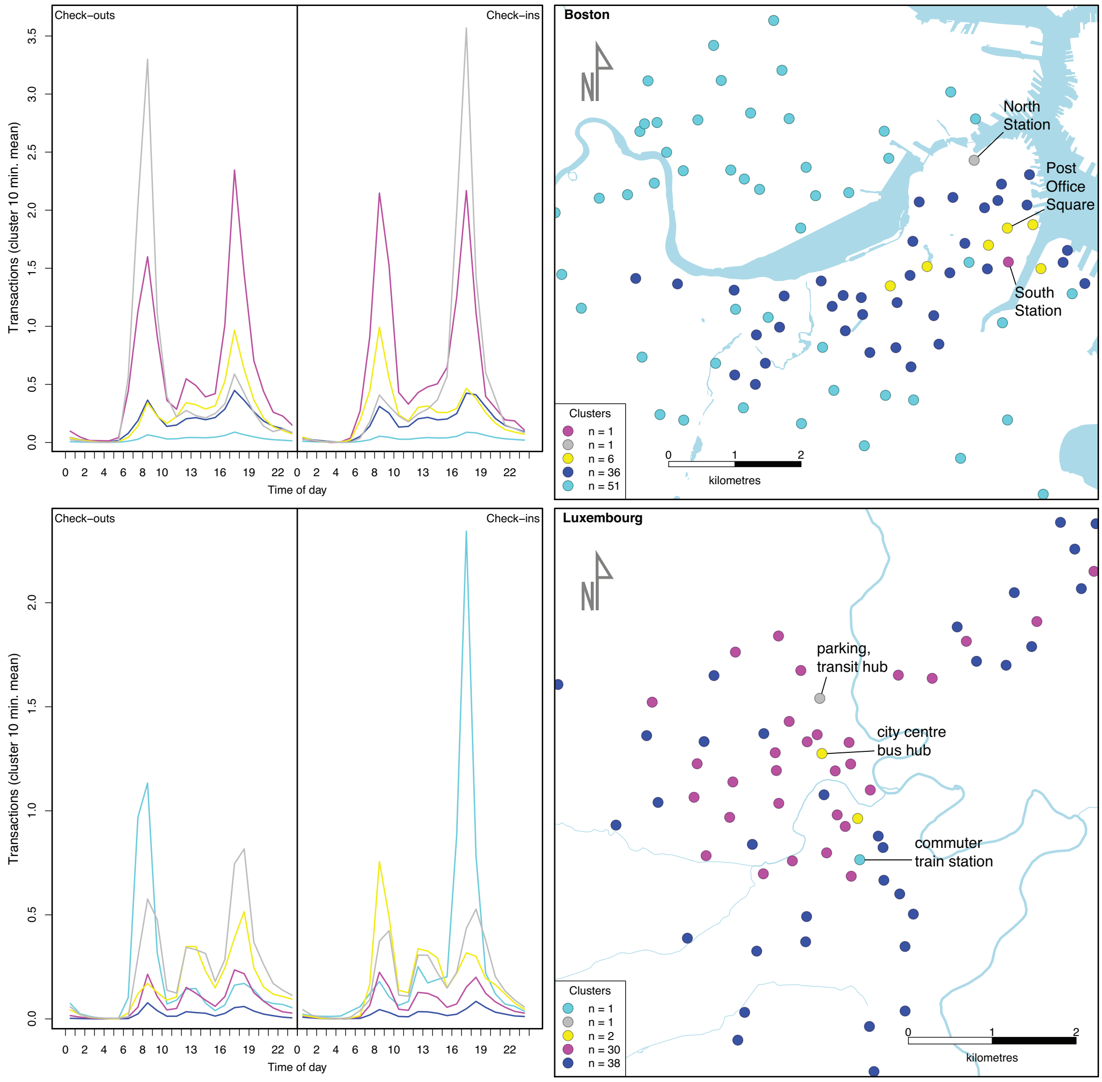

Figure 4.5: Trip check-in/out profile clusters for Boston and Luxembourg. Clusters are nominal and not comparable between case studies.

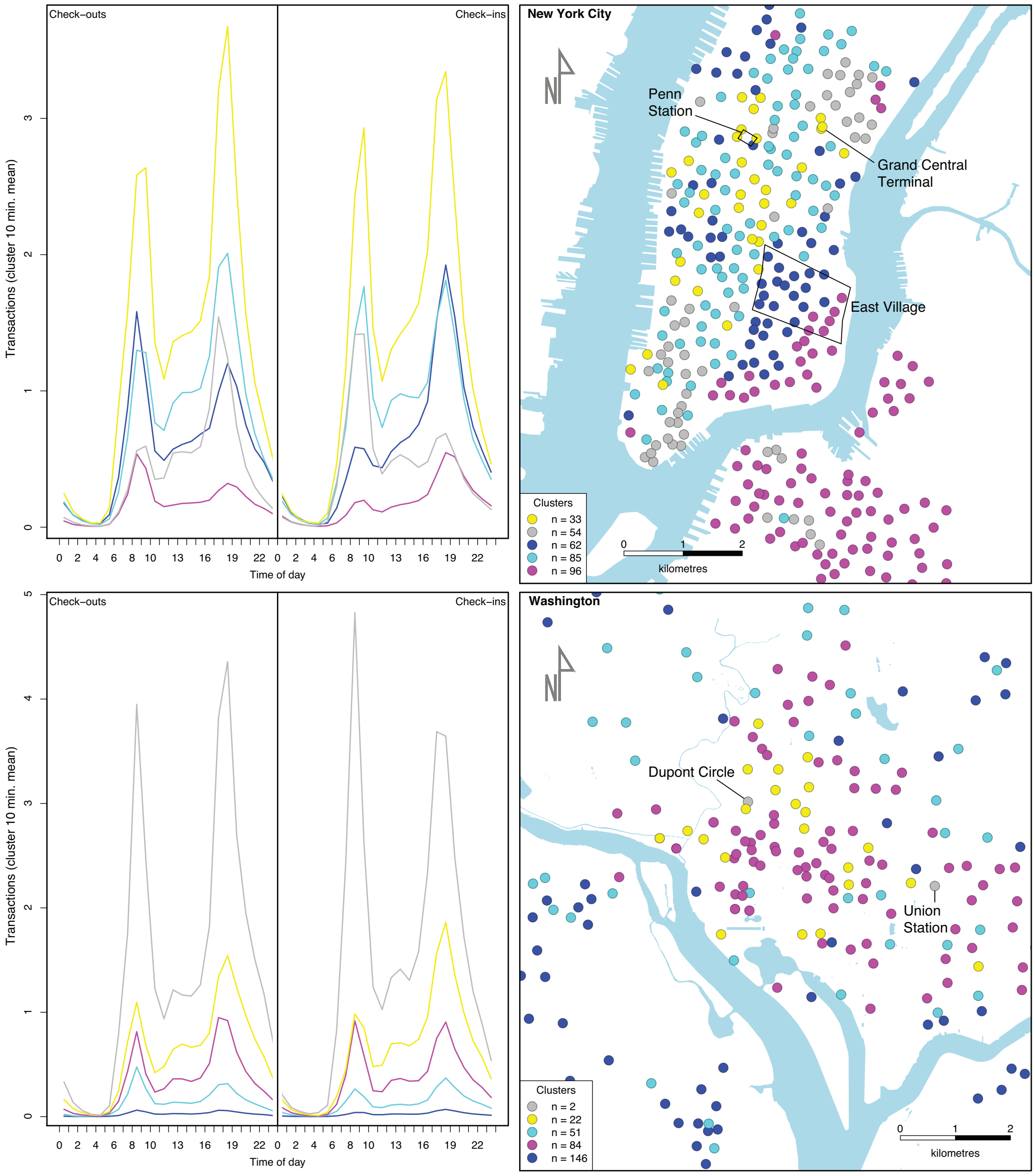

Figure 4.6: Trip check-in/out profile clusters for New York City and Washington. Clusters are nominal and not comparable between case studies.

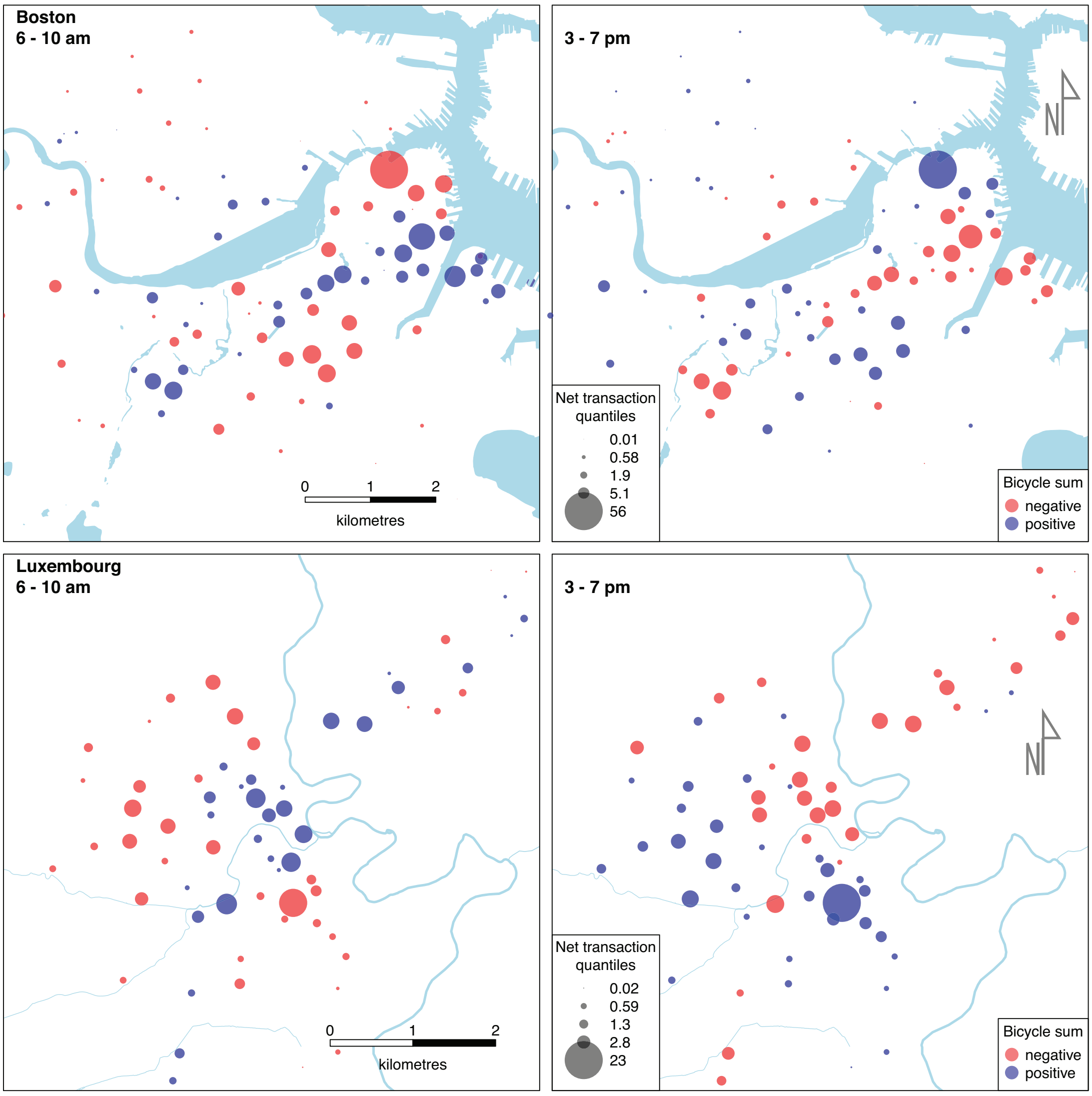

Figure 4.7: Morning and afternoon net check-in/out for Boston and Luxembourg.

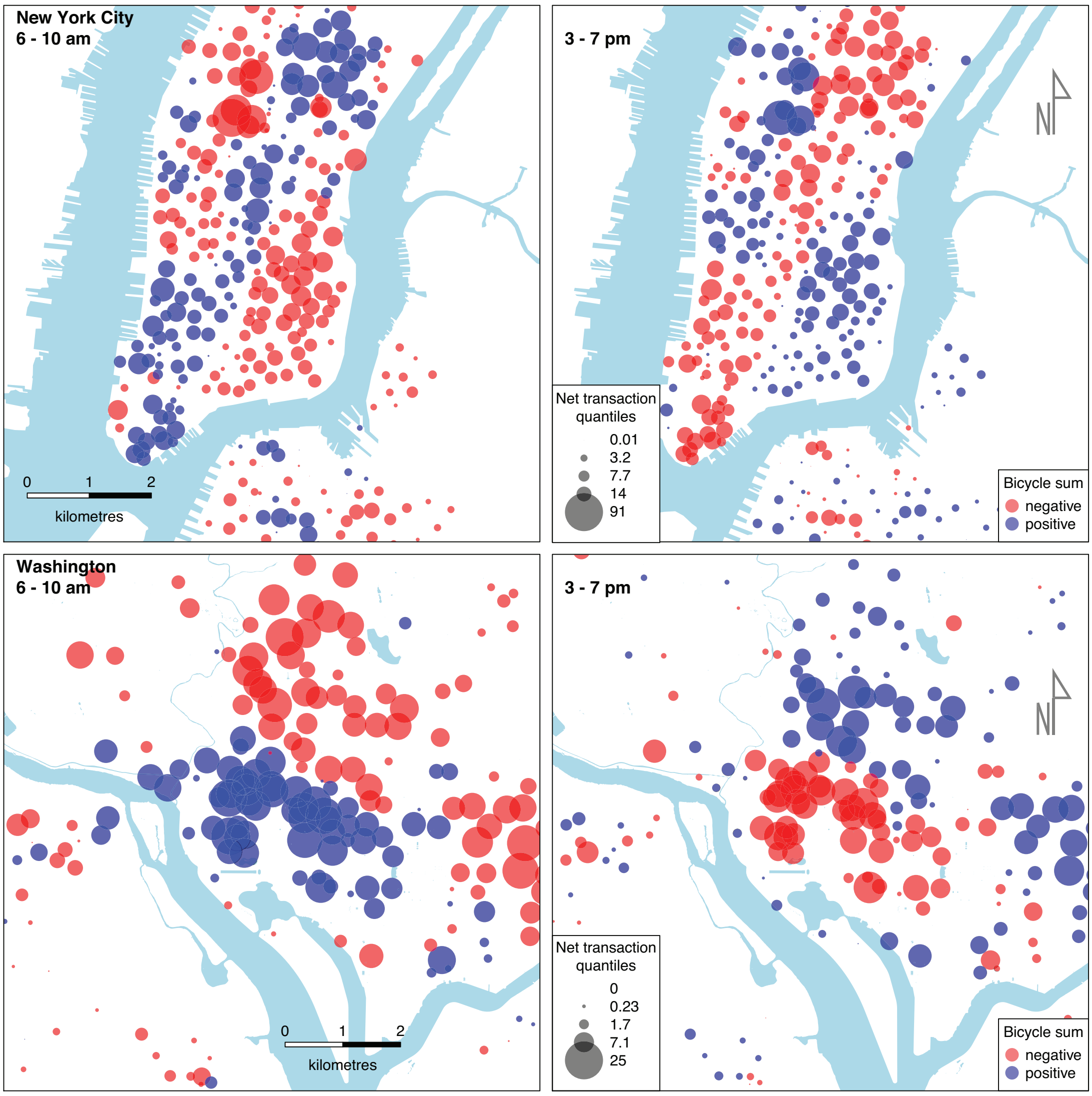

Figure 4.8: Morning and afternoon net check-in/out for New York City and Washington.

free docks. Operators address this by depositing bicycles as rapidly as possible at the origin of trips in the morning and performing the reverse in the afternoon. For central business district (CBD) stations the opposite occurs, emptying in the morning, filling in the afternoons. Operators extend the capacity of bicycles available at stations through rebalancing, we therefore define this as *station extension rebalancing* (SER). This costly process relocates bicycles so they may either be immediately reused during the same peak period or simply put in another station or depot for storage. Stations adjacent to those experiencing SER sometimes serve as rebalancing storage but depots have reduced this behaviour for some BSS. We observe frenzied SER in Boston, Chicago, London, SF, NYC and Washington.

Neither polarized rebalancing or SER is theoretically worse than the other, they both typically require one bicycle being moved for one additional trip. There are however a couple additional inefficiencies associated with SER. In some situations SER not only requires providing bikes at origins but also supplying docks at destinations. The second problem lies in the decreased efficiency of SER often causing too many bicycles to be moved in one direction only to be moved back again.

Station REU plots clearly illustrate the presence of polarized and SER rebalancing (Figure 4.11). The net use of a station, bicycle check outs minus check ins, exceeding the number of docks available at a station indicates where rebalancing has occurred. In these cases a symmetric shape is caused by SER rebalancing and polarized rebalancing if not.

Spatial distribution

Net rebalancing, the sum of bicycle deposits minus withdrawals, shows that differences in elevation cause greater trip flows downhill in Luxembourg and Vienna, where polarized rebalancing is predominant. In London and Washington users have a greater tendency to cycle inwards towards the system centre, visible by the net tendency of rebalancing bikes from the centre to the outer half of the system. While other BSS have some spatial clusters they show no consistent spatial tendencies relating to employment or residential areas.

Morning (6 - 10 a.m.) and afternoon (3 - 7 p.m.) net rebalancing provide clear patterns but generally not surprising ones. Across most case studies we see operators in the morning remove bicycles from popular destinations such as universities, peri-urban train stations and the CBD to drop them off at CBD train stations, bus depots and residential areas. Minneapolis' strategy of proximity rebalancing is visible, as only stations within two kilometres of the CBD are refilled using bikes arriving in the core, while Luxembourg and Vienna show redistribution consistently moving bicycles uphill during mornings and afternoons (Figure 4.9). Afternoons we observe rebalancing in the opposite direction for Boston, Chicago and London but Washington has a unique rebalancing pattern where bicycles are withdrawn from a ring around the CBD and deposited within and the outskirts (Figure 4.10). Washington's rebalancing is also distributed more evenly across many stations while Boston, Chicago and New York City focus on fewer stations with greater intensity. Finally, while New York City and Washington usage trends are

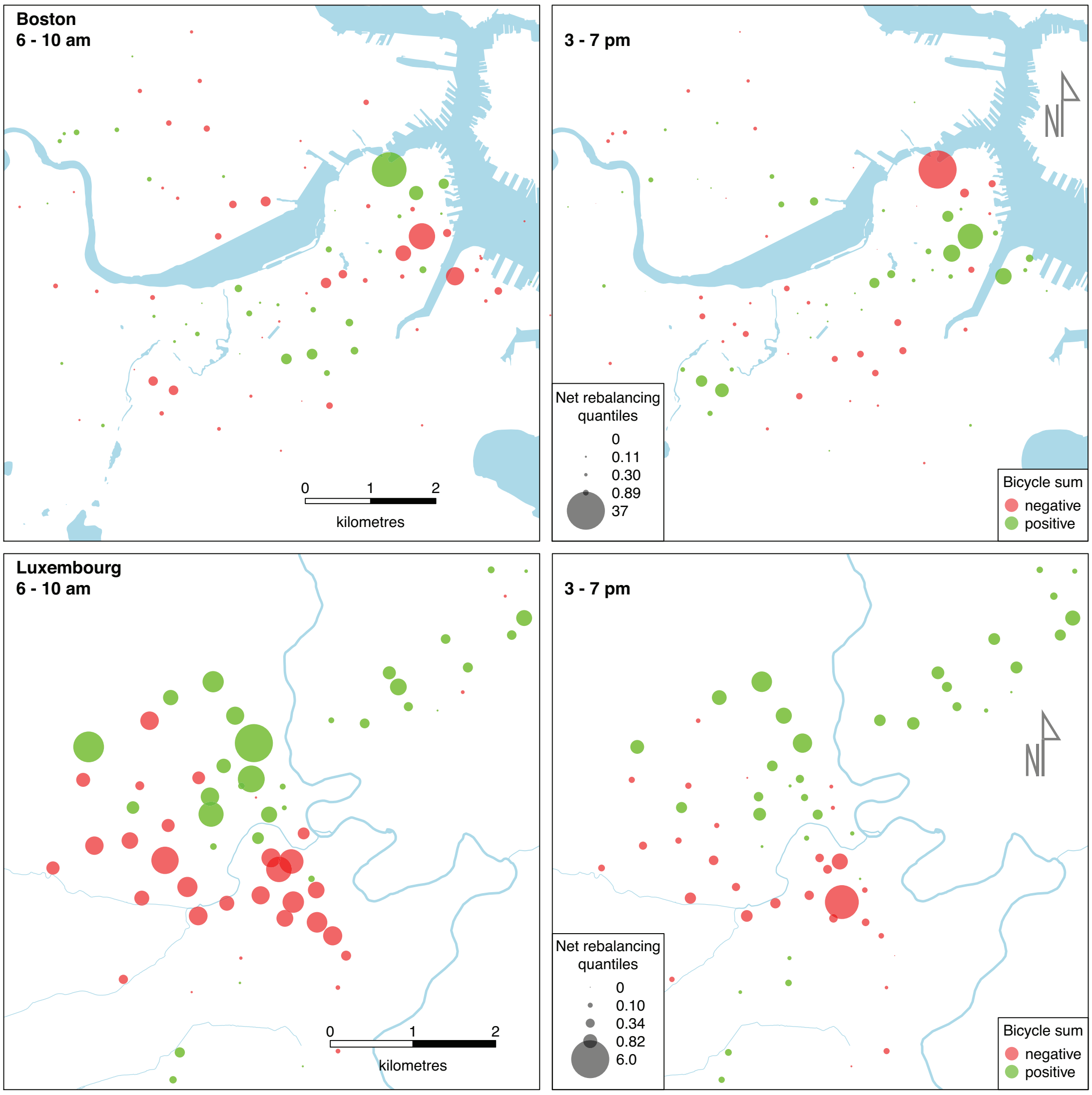

Figure 4.9: Morning and afternoon rebalancing for Boston and Luxembourg.

mirrored morning and afternoon (Figure 4.8), rebalancing strategies are not (Figure 4.10).

Spatial distributions of rebalancing and user transactions do not match. A few stations are being heavily rebalanced while many other stations have little rebalancing yet still generate significant numbers of trips. Operators justify the priority of modal transition locations with the need for punctuality. Having no dock available to return a bicycle when needing to catch a train causes great frustration. Operators have facilitated expectations of high quality service at modal transfer hubs without perhaps considering if this quality, and concentration of operator resources, *constrained* by space, cost, and an SLA can be sustained as it gains popularity or even whether serving commuters supports the system purpose.

Time and space constraints

Operator rebalancing is constrained by road traffic and the extremely high demand over short periods of time. Peak BSS usage coincides with road traffic, and as such dampens operator's ability to reposition bicycles when most needed. While the fear of cycling due to car traffic is well documented, road congestion preventing effective BSS rebalancing is another example of cars preventing people from cycling in Boston and Washington (Capital Bikeshare, 2013).

Restocking stations with extremely high demand to meet SLA requirements may not be cost effective for operators. In Boston, Chicago, NYC and Washington deposits of dozens of bicycles in high demand locations and periods are often all checked-out before trucks are emptied. Rebalancers' innability to keep up with demand is visible in some station REU profiles (Figure 4.11). What appears to be sharp demand followed by decreased demand is an artefact of outages and rebalancing affording a decreased trip rate.

Logistically keeping up with short term demand, especially at transit hub stations, is virtually impossible. Bicycles cannot be restocked quickly enough and increasing bicycle supplies can be inefficient due to latent demand. Penn Station, in NYC, is the system's busiest and considered the most cost effective by the operator. So servicing commuters can be profitable to operators but it is unclear whether the large distortion of rebalancing allocation benefits local residents or the BSS goals.

Larger stations, in terms of docks, provide greater flexibility to reduce outage occurrences. Station sizes, however, are constrained by sidewalk and road space available. While sidewalk space is restricted by pedestrian use, trees, lamp posts, bus shelters and parking meters among others, the removal of on-street parking is a sensitive political issue, can be costly if the BSS must offset lost parking revenue and may compete with other cycling demands such as cycle track development. The space constraint means that in some instances station sizes are insufficient to handle daily fluctuations of bicycle and dock demand.

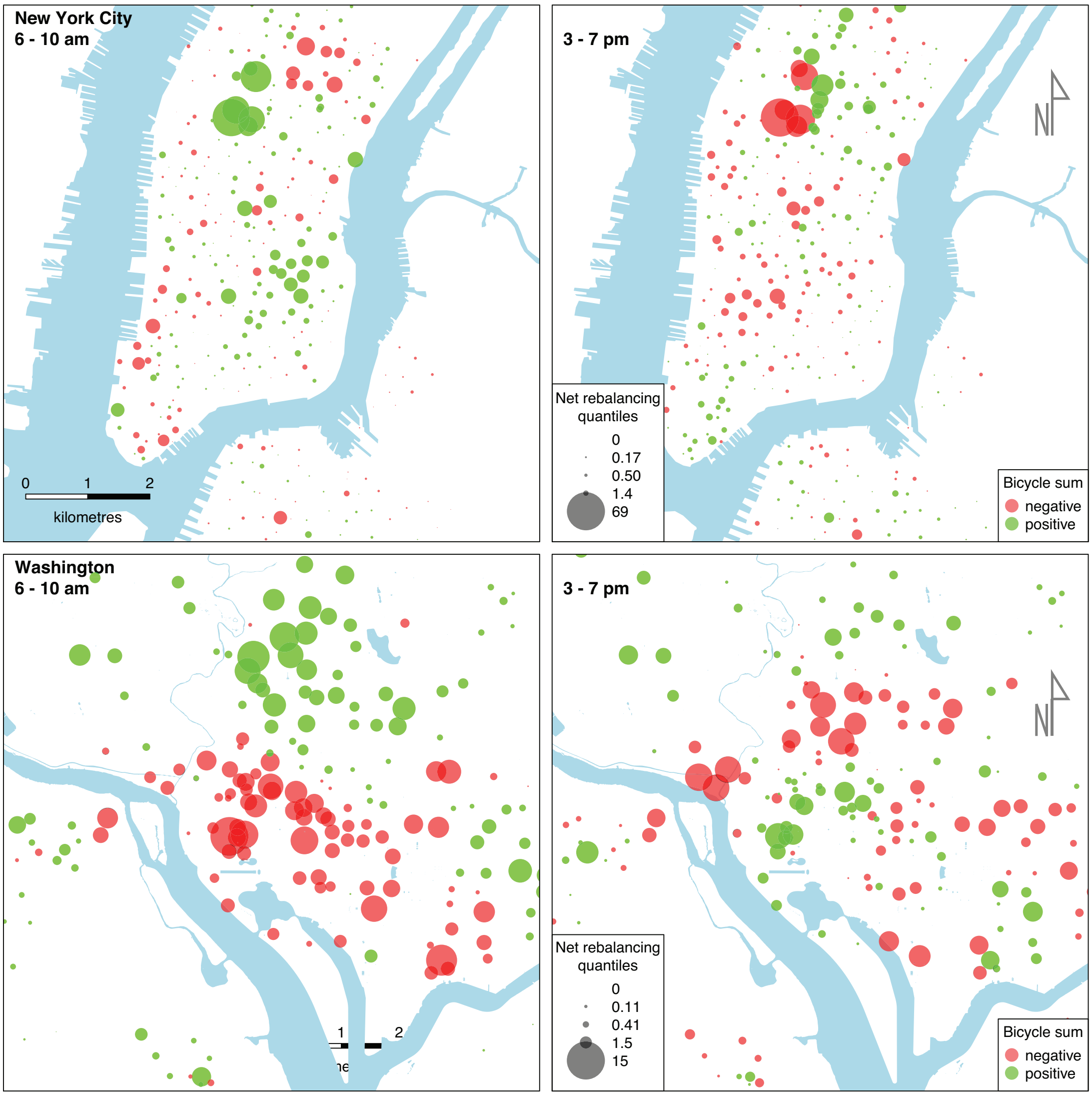

Figure 4.10: Morning and afternoon rebalancing for New York City and Washington.

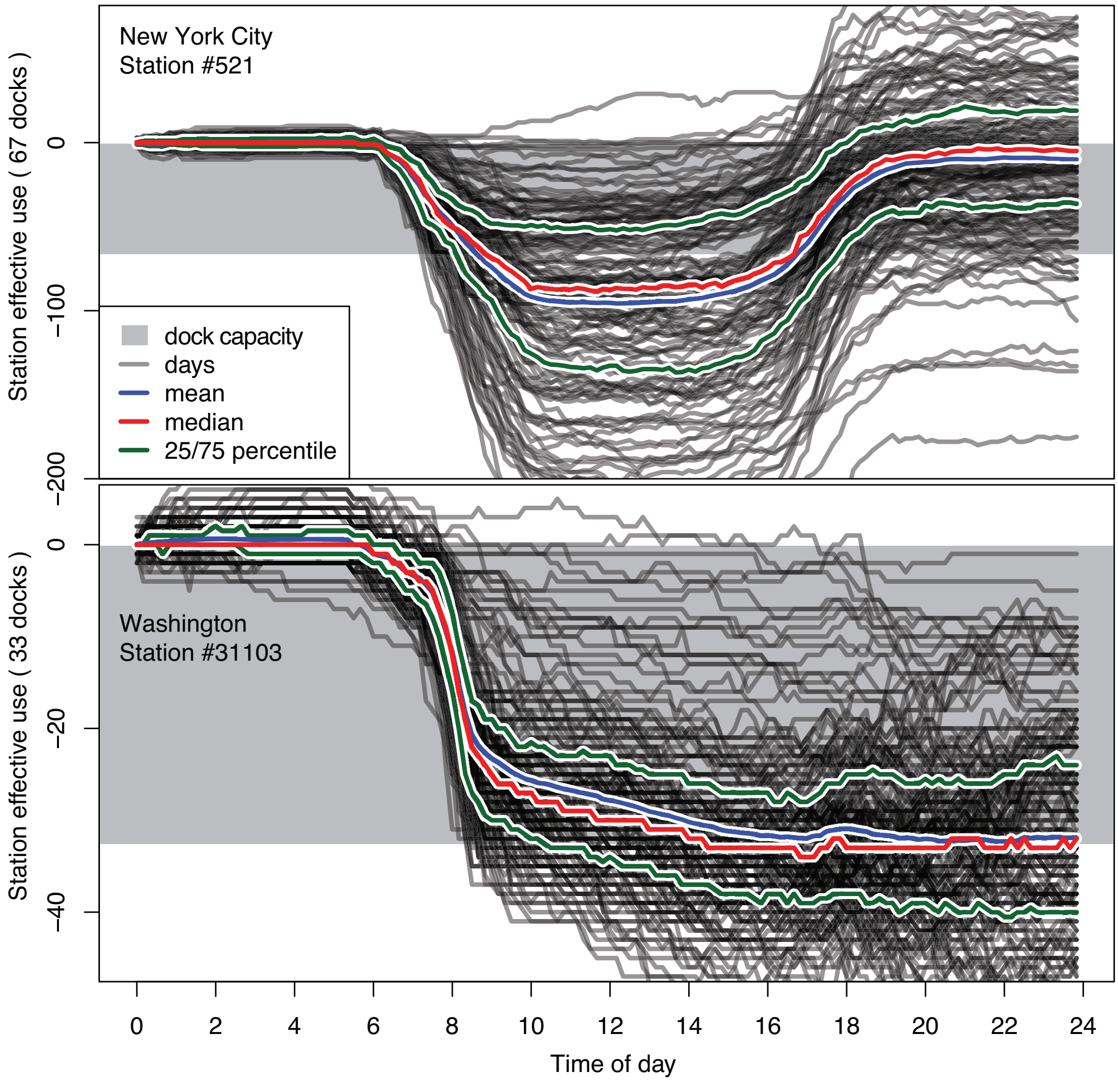

Figure 4.11: Rebalanced effective use (REU) profiles showing station extension rebalancing (SER) and polarized rebalancing for stations in New York City and Washington respectively.

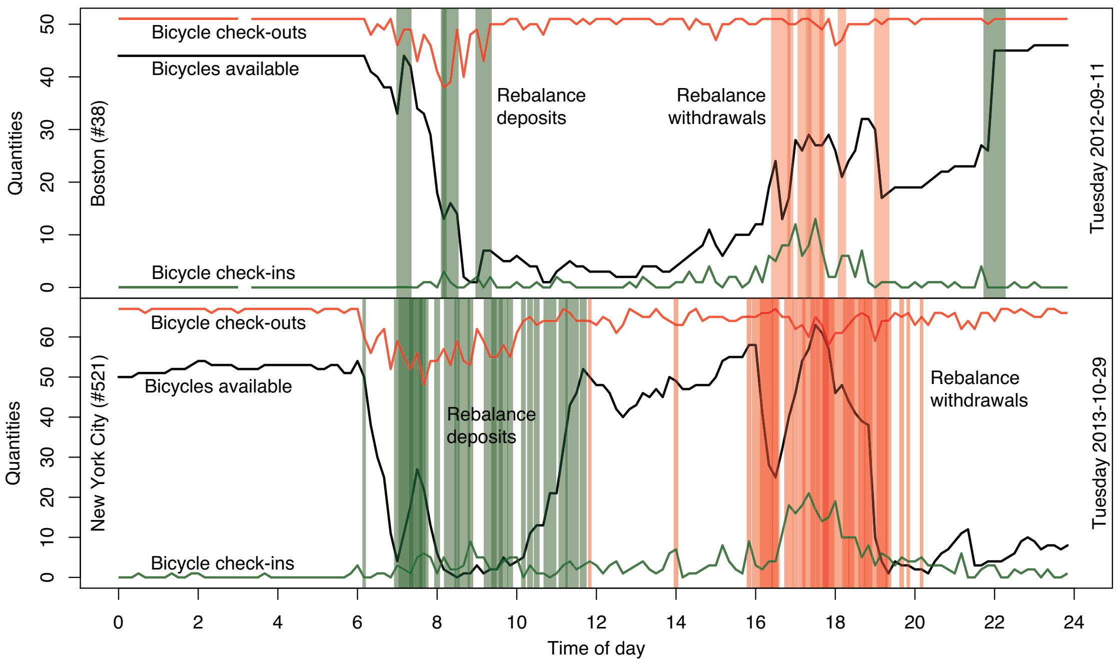

Figure 4.12: Rebalancing, transactions and bicycle and dock availability for a Boston and NYC station.

Efficiency

An important motivation for the reduction of SER is its inefficiency. For most BSS we observe occurrences of stations being rebalanced in excess following morning peak periods only to require the opposite rebalancing for the next peak period. The same often occurs following afternoon peak periods requiring further rebalancing during the night or next morning (Figure 4.12). Rebalancing inefficiency may be caused by a variety of factors. Morning crews may have defined station state goals contrasting with afternoon requirements. Rebalancers, who are sometimes paid per bicycle moved, may not worry about the purpose of their actions. It appears target station states are generally not defined. A solution to increasing system efficiency would be creating time of day station fill rate targets or quotas dictated by REU profiles.

Stations that are generally and naturally balanced, not simply constrained into being so by rebalancing or a lack thereof, provide an important opportunity for requiring little SER, if they can be sufficiently expanded. Stations that are transaction positive or negative will always require polarized rebalancing.

If space is unavailable to increase station size, a new station nearby may better suit space constraints. Providing stations which are a little less accessible in proximity to transportation hubs can provide important resilience. Spontaneous users will ignore these stations while determined users will be grateful for the station's bike or docks. While stations have overhead costs, reallocating station size expenditures to new station

	Busiest station		2^{nd} busiest		3^{rd} busiest	
BSS	id	score*	id	score*	id	score*
Boston	22	22.8	38	2.7	36	27.2
Chicago	91	2.4	90	6	35	7.7
London	14	1.4	154	1.2	194	2.6
Luxembourg	2	2.8	17	3.8	12	7.4
Minneapolis	30042	5.2	30029	4	30006	12.8
NYC	519	5.3	521	2.6	497	10.2
San Francisco	70	4.1	50	12	77	14
Vienna	1022	38.4	1032	30.3	1067	44.3
Washington	31623	11.6	31200	23.8	31201	15.1

* Where score = transactions/rebalancing over a period.

Table 4.3: Effective transaction ratings for top three stations in terms of trips.

locations increases coverage, proximity to services and residents and trip resilience.

A measure of station efficiency can be created by comparing trips and rebalancing. Boston's North Station (Figure 4.5), for example, served as the origin or destination for 30,134 weekday trips and had 11,168 bicycle rebalancing deposits or withdrawals. South Station (Figure 4.5) in contrast had 37,011 transactions but only 1,625 rebalancing actions. Transforming these values into *effective transaction ratings*, $e_p = t_p/r_p$, where t_p and r_p are the transactions and rebalancing at a station over a period p, creates station and BSS comparable values (Table 4.3). Boston's North and South Station (id 38 and 22) yield values of 3 and 23 respectively, meaning enabling North station transactions is much costlier. While it may appear that preventing outages at high e_p stations is of greater importance, these stations are also more likely to self balance. However, if reducing outages is the goal then a small rebalancing effort at higher e_p will have longer lasting effect.

The concentration of rebalancing quantities at few stations also evokes questions of efficiency. Boston's top 10% of stations, in terms of rebalancing, experience half of all system rebalancing but only 26% of transactions (Table 4.4). Similarly, NYC's busiest stations for rebalancing have 38% of the activity and also half the amount of transactions (19%). With the exception of Vienna, and its inflated quantities, the other BSS experience higher rates of transactions for the most rebalanced stations. This suggests Boston and NYC more heavily rebalance stations dependent upon it, such as train stations. Alternatively, taking the top 10% of stations with the most transactions we see that the rebalancing to transaction proportions are fairly similar, with the exception of Vienna and Washington, where Washington's rebalancing is more widely dispersed than other systems.

Observing past station states (Figure 4.12) we see stations experiencing large outage rates, where known demand exists and would likely generate additional trips, yet are consistently and consciously infrequently rebalanced. This is an explicit example of how operators shape trips and potentially perceived spatial demand.

Providing larger stations rather than repeatedly rebalancing busy transit hubs has depraved results. Rebalancing provides a continual, but not demand satisfying, refill of

	Rebalance top 10%		Transaction top 10%	
BSS	Rebal. (%)	Trans. (%)	Rebal. (%)	Trans. (%)
Boston	50	26	40	32
Chicago	50	37	46	39
London	39	30	36	31
Luxembourg	36	31	33	34
Minneapolis	41	32	39	35
NYC	38	19	30	24
San Francisco	44	29	36	36
Vienna	30	13	15	29
Washington	34	29	24	37

Table 4.4: Transactions and rebalancing captured by the top 10% stations in terms of rebalancing and transactions.

stations and outage reduction *over time* (Figure 4.12). Having bicycles available earlier in the morning makes it likely such stations incur empty outages *sooner* while satisfying equal trips as without SER.

Rebalancing a bike costs JCDecaux three dollars (DeMaio, 2009). A case study operator estimated rebalancing costs of two dollars per bicycle while an annual membership generates sixty cents per weekday. For daily commuting members who require rebalanced bikes, such as at transit hubs, it is unclear how subscriptions offset costs. Revenue from short-term memberships and annual members who occasionally use the system likely offset commuter trips requiring rebalancing.

Finally, although some transit hub stations may be less efficient, in terms of trips per rebalancing actions, they do provide transactions to other stations in the system. So any reduction in morning bicycle provision for a popular trip origin station impacts the balance of destination stations, perhaps increasing their rebalancing requirement. As trips flows are a complex spatio-temporal web it is difficult to generalize rebalancing changes' effects beyond individual BSS.

Outages and SLA adherence

Service level agreements (SLA) specify a variety of factors, such as: the number of functioning bicycles, stations, response times to calls, emails and broken docks, stations and bicycles. Outages are only one of the many service metrics, but the most dynamic and therefore hardest to achieve.

Generally empty station outages exceed full station outages in duration (Table 4.5). Occurrence of full and empty outages covary with some temporal lag for full instances. Outages typically peak in the mornings between 9 a.m. and 11 a.m., and less intensely in the evenings, sometimes extending throughout the night. Night outages are often ignored by SLA. As night outages last longer, since little or no rebalancing occurs, they outweigh daytime outages in duration resulting in residential areas appearing to experience greater full outages while the CBD and suburban train stations have greater empty outages. Outages (Table 4.5) do not represent the duration of unmet dock or bike demand. Clearly some outages do not concern any users while other short outages affect many. At stations where operators are constrained to new lower SLA outage durations, dramatic rises in trips have occurred due to the increased availability and reliability of finding bikes at these stations.

Depending on operator motivation, SLA outage specifications can be a constraint preventing increased BSS use by forcing rebalancing at locations of little usage rather than carrying out other strategies to maximize trips. If a profit-seeking operator is constrained in achieving their SLA outage targets they may prioritize low usage stations over those in high demand as they are more likely to stay normal longer.

	Minutes		Percent
BSS	full	empty	normal
Boston	65	75	93
Chicago	5	19	98
London	69	110	90
Luxembourg	25	33	97
Minneapolis	2	16	99
NYC	14	130	90
San Francisco	7	10	99
Vienna	88	[a]130	[a]86
Washington	41	81	92

[a] Due to station level data error.

Table 4.5: Mean station outage durations and normal percentage (weekdays 6:00 - 22:00).

4.5 Discussion

4.5.1 Rebalancing literature

Contrary to what Erdoğan, Battarra, and Calvo (2015) suggests, no case study operators actively use rebalancing optimizing software. Existing optimal rebalancing models may benefit operators in the future, but currently further work on optimizing rebalancing priorities and expenditures, evaluating SLA requirements and providing alternative services could be of greater interest to operators. We find that even if such software could effectively assist rebalancers, the question of what state of balance, maximizing what purpose, needs to be further discussed by operators, municipalities and perhaps users who pay membership fees related to how they collectively use the system.

4.5.2 Policy and recommendations

Bicycle sharing systems consist of combinations of municipal, non-profit and private actors. Municipal involvement is typically required as stations are regularly placed on public land. While municipalities have preconceptions about BSS benefits, less often a clear goal. Private companies or non-profits typically become the operators rather than a public transportation authority. This results in BSS municipalities and operators as distinct and with differing goals. Non-profits do not usually have SLA as they have similar motivation as the municipality, and in fact may have been a main driver for BSS adoption. Service level agreements are used to constrain profit maximizing operators to specified outcomes. It appears to be taken for granted by municipalities that SLA bound operators will naturally cause BSS to induce desired beneficial outcomes. Our analysis reveals how rebalancing operations impact BSS outcomes towards profit maximization, SLA compliance or increased trips, among others.

Rebalancing *responds* to fluctuating spatio-temporal patterns of full and empty outages but also creates a dependence on it. What dependences help achieve BSS goals needs to be specified by municipalities. Rebalancing so that bicycles and docks are available at all stations is not cost effective. One operator found SER at a transit hub to be profit generating, but energy requirements and the disproportionate allocation of resources for a few stations and their users, may contradict the purpose of the system. Alternatives options to excessive rebalancing exist. Stations may be moved, removed or rebalancing reduced. A reduction in rebalancing from where bikes would be utilized need not be anathema. We have observed clear absences of rebalancing where high demand exists. Municipalities must specify to operators which trips to facilitate over others or operators will choose for themselves.

Outage importance relates to trips potentially lost. Yet, most SLA do not distinguish between the location of stations or outage types. Figure 4.13 illustrates *some* of rebalancing's exclusive goals of maximizing profits, increasing trips and reducing outages to satisfy SLA. If rather than having SLA focusing on outages but on trips this triangle would become a continuum between trips and profits. In the case of non-profit BSS operator the strain disappears and only the *purpose* of the BSS is of importance. We refer to trips as the goal but it may be modal shift, equity, health or other. The important aspect is that current SLA may not be maximizing system goals.

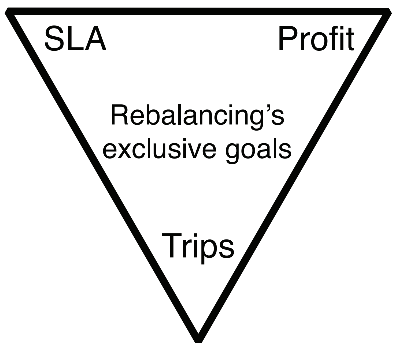

Figure 4.13: Exclusive outcomes of rebalancing behaviour.

Polarized rebalancing is necessary for stations requiring it to maintain usefulness but SER can contradict BSS purpose. Whether SER is a more worthwhile investment is impossible to determine without clear BSS goals. Regardless, over time BSS users develop a dependence on rebalancing while alternative investments may be more cost effective at maximizing a desired outcome.

The most surprising revelation of our analysis is the extremely imbalanced demand at transit hubs. Rebalancing transit hubs requires a large proportion of BSS resources for the benefit of relatively few. While train stations are natural locations for bicycles to be available and can increase cycling and public transit use (Pucher and Buehler, 2012), we have shown that BSS stations located at train stations are utilizing a disproportionate amount of system resources. Beecham, Wood, and Bowerman (2014) has also noted out-of-town commuters arriving at rail hubs requiring more rebalancing than Londoners' more varied trips. For one profit seeking operator these stations are reported to be cost effective, but for municipalities seeking a modal shift to private utilitarian cycling, supporting transit hub rebalancing demand makes little sense.

Transportation hub BSS users are mainly commuters and likely the most demanding as they rely on bicycles being available to reach their work on time or catch a specific train home. These commuters are prime candidates for shifting to private cycling as it offers greater benefits than BSS. For commuters, the main limitation of BSS are the availability of bikes and docks, as required, and potentially the locations of stations, while the benefits are the availability of bikes in working condition without the worry of theft. The development of secure parking with bicycle maintenance facilities, perhaps provided by BSS operators, makes private cycling more attractive (Martens, 2007) and reduces the energy intensive rebalancing process transit hubs require.

As a system's use increases, so does the occurrence of outages, a symptom of congestion, decreasing its reliability and attractiveness. When deciding whether to use the BSS, users must now weigh the risk of having no bicycle available at their point of departure, or more frustratingly, having no dock available at their destination or selecting an alternative transportation option. Much like car traffic adjusts to new higher capacity roads, BSS usage increases until congestion effects, namely outages, create a new equilibrium as alternative modes of transport become equally attractive. Clearly some BSS have reached levels of congestion requiring extensive rebalancing. But just like widening roads may not reduce long term congestion, increasing rebalancing may not support BSS goals.

Any option, such as secure private bicycle parking, that lessens the burden of rebalancing but provides a similar alternative, perhaps at reduced cost, could be more beneficial. Bicycle sharing system costs have important ramifications as revenue generation sometimes undermine system goals. Users of BSS typically make up a small proportion of cities yet subject a large population to advertising. Advertising isn't unethical by nature, but conventional use does promote conspicuous consumption and a car dependent lifestyle that clearly contradicts the sustainability purpose of many BSS.

Based on our quantitative and qualitative analysis we provide rebalancing recommendations grouped by potential goals: general, sustainability, equity, private utility cycling and profit (Table 4.6).

4.6 Conclusion

Understanding rebalancing requires a characterization of trips, which are themselves, ouroborosly, heavily influenced by rebalancing. Our analysis provides a description of

General
Rebalancing strategies determine BSS outcomes. State clear purpose and goals for the BSS.
Define BSS target users (e.g., equity, locals, commuters).
Weigh SLA station outages according to goal.
Weigh full outages more severely than empty.
Weigh larger station outages more severely than smaller stations.
Not all outages need be considered as operational failures.
Establish polarized rebalancing and SER quotas.
Adopt better station and rebalancing analytical software.
Increase system resilience with transit hub perimeter stations.
Mixed land use areas require less and easier rebalancing.
Any optimal rebalancing software must maximize goals not only minimize outages.
Sustainability
Integrate BSS operations with secure private bicycle storage and repair services at transit hubs.
Increased station density facilitates bike-trailer rebalancing.
Use bike trailers during the day and vehicles at night or on occasion.
Allow rebalancing vehicles in restricted HOV and bus lanes.
Equity
Encourage operator multi-skilling. Rotate rebalancing staff roles.
Ask target residents what investment is most required. It may not be rebalancing or BSS related.
Prohibit rebalancer contracts limiting health insurance coverage and unsteady employment.
Private utility cycling
Limit rebalancing of transit hubs. Provide a convenience service, not a commuter service.
Have BSS operator also provide secure private bicycle storage at transit hubs.
Profit*
Hire seasonally or subcontract rebalancing for part time contracts.
Use gasoline vehicles in conjunction with other vehicles if traffic congestion is a problem.
Use valet services to reduce rebalancing costs, increasing dependability and reliability on system.
Run valet services seasonally and according to weather.

* May reduce the efficacy of sustainability, equity or private utility cycling goals.

Table 4.6: Rebalancing operations recommendations.

rebalancing for nine bicycle sharing systems (BSS) and found the relationship between trips and rebalancing to be more complex than anticipated. Trips, especially at transit hubs, are limited by the quantity of bicycles rebalanced, and, outages, the occurrence of full or empty stations, impact trip numbers more than expected. As rebalancing affects trips, conclusions from aggregated spatio-temporal trip flows should be tempered as they do not represent spatial demand or flows homogeneously or unconstrained. The research of BSS trips without thorough rebalancing analysis may lead to erroneous conclusions.

Satiating demand at transit hubs, through increased rebalancing, produces less trips per expenditure. Additionally, due to latent demand providing more docks and bicycles at busy stations increases trips and, to prevent outages, requires operators rebalancing further. For operators bound by SLA, increasing dock counts at stations experiencing station expansion rebalancing (SER) may have little effect on reducing outages while supporting BSS use by commuters.

Most operators use software showing the presence of outages and station fill rates with some historical demand statistics aggregated over time as well. Existing optimal rebalancing models provide theoretical solutions to dynamic and demand predictive rebalancing. While operators would also require real-time traffic and road closures included for such software to be of use, demand may also exist for models integrating SLA adherence, profit, trip maximization and other possible goals. Further it seems that simpler information could already greatly benefit operators. Feedback from operators to historical plots combining rebalancing, trips and station levels (Figure 4.12) and rebalanced effective use (REU) plots (Figure 4.11) have been appreciated for increasing their understanding of their own behaviour and (in)efficiency. So as rebalancing optimization software may be effective theoretically, in practice it has yet to be shown. A more fundamental problem precedes the need for such software: knowing what distribution of bicycles, and expenditure, at what stations is desired. Something that from discussions with operators is still very much unclear and requires discussion with the municipalities regarding the *purpose of their BSS*.

The purpose of BSS may appear tangential to the rebalancing discussion but actually dictates where and how much rebalancing should take place. The profit-SLA-trips triangle (Figure 4.13) illustrates our findings that some existing SLA appear to diverge from maximizing the number of trips or other possible BSS goals. The large quantities of rebalancing have evolved from satisfying SLA constraints without discussing whether this is desirable or worthwhile in achieving the goal of the BSS.

Getting high BSS usage rates depends on attracting many members from diverse locations to use the system. While, stations with many transactions of one dominant type, such as transit hubs, will always have a strong tendency to be empty, opening BSS to more users means a more stochastic system, providing more mixing of bicycles spatially and likely reducing outage occurrences and durations for many other stations. An interesting consideration is whether raising fares reduces the diversity of users, increases the share of commuters who's trips are typically in mass and require greater rebalancing at higher cost.

Bicycle sharing systems are truly complex systems, changing rebalancing behaviour at one station can have unexpected effects at others. Based on existing employment, transit and residential distributions, rebalancing may be more efficient in areas of mixed origin and destination demand. In addition the density of stations and road congestion may alter the efficiency of rebalancing modes (van or bicycle).

Regular rebalancing creates a status quo bicycle distribution and therefore a dependence. Rebalancing is necessary to provide a quality of service that is sufficiently reliable to be considered a legitimate form of public transport. If outages are chronic and widespread this cannot occur, yet the onerous amounts of rebalancing enable a continued dependence of BSS as a commuting tool. For most BSS sustainability is a major reported benefit, yet extensive rebalancing is not sustainable. The use of BSS as a transitional tool to private utilitarian cycling should be pursued if the desire for sustainability is genuine and not political green washing. Bicycle sharing systems can be part of larger utility cycling plans, serving as private cycling catalysts but also flexible, convenient and enjoyable addition to a more resilient public transport system.

While our analysis evaluates day to day rebalancing operations, we are not able to take into consideration weather, operational, cost and policy challenges the operators must deal with. Bicycle sharing systems are truly complex systems and our observations should not be taken as a critiques of their work ethic, but as a narrow-minded observation of one aspect of BSS operations. Many BSS are still expanding and evolving their rebalancing behaviour. Our analysis may obviously understate new flows in expansion areas and does not describe recent changes to operations.

Chapter 5

Determinants of 'success' for bicycle sharing systems

Outline

Many municipalities assert bicycle sharing systems (BSS) as having many benefits, justifying their adoption, yet few explicitly state the purpose of their system making comparisons or determinations of success impossible. In addition, the apprehension of many BSS operators to share data further hinders comparison. This paper estimates the number of daily trips from publicly available data for 75 BSS case studies across the world and provides trips per bike per day scores as a comparison of performance and success. Results reveal that a third of case studies have fewer than the psychologically important one trip per bicycle per day. To ascertain what factors are associated with this metric we estimate models with independent variables related to system attributes, station density, weather, geography and transportation infrastructure. Our analysis provides strong evidence undermining the 'network effect' promoted by influential BSS policy makers that expanding system size increases performance. Larger systems are not a requirement for success nor a guarantee, but results support that station density and cycling infrastructure are associated with higher BSS performance. [1]

5.1 Introduction

Many bicycle sharing systems (BSS) are regularly called successful by operators and politicians without providing a reason or metric. While metrics are sometimes quoted, they often lack comparative potential or the methodologies and assumptions used to derive values appear dubious. As most BSS operators do not provide consistent and comparable metrics of system use, mainly the number of trips per day, the evaluation of individual systems against others is largely impossible. By using a common metric this

[1] This chapter is a working paper submitted for publication.

paper provides a first comparison of a wide number of BSS in Australia, Europe and the Americas, followed by an analysis of what factors impact the metric.

The criteria for a BSS being successful depends on a purpose being defined, something that is done vaguely or typically not at all (Ricci, 2015). New York City's BSS's purpose is to offer an affordable transportation alternative at no cost to taxpayers (New York City, 2012) yet is called a success based on trips completed and unspecified emission reductions (New York City, 2013). There exist many reported benefits of BSS, such as the reduction of travel time, roads and public transit congestion, carbon emissions and increases in cycling modal share, financial savings to users, physical and mental health, transportation resilience, connectivity and convenience, social equity and increasing private utility cycling modal share (Fishman, Washington, and Haworth, 2013; Ricci, 2015; Shaheen, Guzman, and Zhang, 2010). Unfortunately some of these benefits have been shown to be hard to measure, trivial or non-existent.

While social equity is a plausible effect of BSS due to the relatively low costs of the service, members are observed to be wealthier, younger, white, male and more likely to own a car compared to the local population (Fishman, 2015). In addition, inadequate cycling infrastructure causes gender disequity for BSS and private utility cycling due to women being more risk averse (Garrard, Handy, and Dill, 2012; Goodman and Cheshire, 2014). Women using London's BSS have reduced health benefits, compared to men, owing to increased rates of injury (Woodcock et al., 2014). The cost of BSS membership impacts user demographics and equity (Goodman and Cheshire, 2014). Membership discounts of varying amounts are therefore available for BSS in Chicago, Boston, New York and Washington. The shift from sedentary travel modes to cycling has clear health benefits but net quantities are overstated due to the reduction in walking, which has greater health benefits for a fixed distance travelled (Fishman, Washington, and Haworth, 2015; Murphy and Usher, 2014; Woodcock et al., 2014). Reduction in other public transport systems is not consistent, the use of rail by BSS users has been shown to increase in some cities and decrease in others (Ricci, 2015). Reductions in road congestion are also unproven (Ricci, 2015). Perhaps the most exaggerated BSS benefit is the reduction in carbon emissions. Multiple studies have shown that publicized estimates of carbon dioxide reductions are often overstated as only a small portion of car trips are replaced using BSS (Ricci, 2015). In the case of London it is estimated that the vehicles rebalancing bicycles within the system may surpass any emission reductions from modal shift (Fishman, Washington, and Haworth, 2014). So while BSS appear to have many benefits some are not consistent or as salient under scrutiny.

Bicycle sharing systems do have indisputable benefits however. They provide an alternative mode of transport, increase accessibility, trip resilience and flexibility, lower the barrier to exploring urban cycling, increase the visibility of bicycles, bicycle awareness by drivers and normalizing the image of cyclists in casual clothing (Fishman, Washington, and Haworth, 2013; Goodman, Green, and Woodcock, 2014; Murphy and Usher, 2014; Ricci, 2015).

Between the promoted 'benefits' of BSS by operators and the lack of goals, stating that an individual BSS is successful is challenging and the comparison of multiple systems arduous. Media (Bialick, 2013; Cripps, 2013; Goodyear, 2013; Mead, 2016.04.01), reports (Curran, 2008; Gauthier et al., 2013) and publications (Fishman, 2015; Fishman, Washington, and Haworth, 2013; Ricci, 2015; Zhao, Deng, and Song, 2014) use the number of trips per day per bike (TDB) as a comparable measure of success for small numbers of BSS. As success depends on a goal however, we refer to this metric as one of *performance*.

The first goal of this work is to provide a comparison of a large number of BSS using the TDB performance metric to encourage debate, especially, but not only for low performance systems, regarding what purpose their BSS has. Few economic, social equity and environmental benefits may be present if systems are little used.

Our second goal is to determine what attributes impact BSS performance. Past research has studied the effect of weather, infrastructure, station density and demographics on trips within individual BSS (Corcoran et al., 2014; Faghih-Imani et al., 2014; Gebhart and Noland, 2014). Zhao, Deng, and Song (2014) evaluates the effects of demographics, employment, system members and size as well as quality of service over one month for 69 BSS in China. We provide a comparison of BSS attributes, system compactness, geographic variables, weather and transportation infrastructure for 75 case studies around the world over a period of 12 months. Beyond simply describing which variables are related to performance we also describe those that are explicitly not. Resulting analysis and model estimates will serve municipalities desiring to increase BSS intensity of use.

Given these facts, our methodology consists of selecting and collecting data; computing validity and comparing TDB, our success metric, across case studies; and revealing what factors determine TDB from estimating OLS and mixed models. We begin by detailing our data and performance metric as well as the choosing of independent variables and expected impact on TDB (Section 5.2). In the results (Section 5.3) we present and compare TDB scores across case studies and our model coefficients before discussing causality and policy recommendations.

5.2 Data

5.2.1 Case study selection and data collection

In March 2013 we selected BSS with a minimum of 20 stations requiring bicycles be docked (not free floating as is common in Germany and some newer BSS in North America). Our 75 case studies (Table 5.3) are predominantly in Europe (49) and the United States (18), but also in Canada (3), Brazil (2), Australia (2) and Israel (1). While there are many BSS in Asia (Zhao, Deng, and Song, 2014) data access was limited.

We gathered the number of bikes and spaces available at each station at a ten minute interval between March 2013 and July 2014. As some BSS opened after March 2013 or were added later the number of records varies between case studies, totalling 909 months of data. Only months with more than 15 days of data, each with 95% of daily records, are used. Using the station level data we can estimate the number of trips per day, T_d (Médard de Chardon and Caruso, 2015). The station level data also provides a good estimate of the number of bicycles in the system, B, as well as the quality of rebalancing in terms of outages, where stations have no docks or bicycles available (Médard de Chardon, Caruso, and Thomas, 2016).

5.2.2 TDB performance metric

To compare BSS we calculated a global trips per day per bike (TDB) score for each. From T_d we calculate a monthly mean ($\overline{T_d}$) normalized by the maximum number of bicycles observed docked during the month (B_M) i.e., $TDB_M = \overline{T_d}/B_M$. As BSS usage varies with season we take the average of any duplicate months across years. The mean of TDB_M providing overall BSS performance. Clearly BSS that have more months with enjoyable cycling weather will have an advantage. Likewise, of two BSS experiencing similar continental weather patterns, if one stays open during the winter this may reduce its score as the other's winter usage will not be included in the mean score. Conversely, being open all year round may be beneficial in terms of constancy, there existing less need to advertise resumed service and repeatedly motivate a modal shift in order to ramp up usage each spring.

We use the monthly average of trips per day per bike (TDB_M) as dependent variable in our regression models rather than daily for multiple reasons. Trip estimates are susceptible to over or under stating and some attributes, such as the number of bicycles active in a BSS, can better be represented from a month's observations. Additionally weather is most likely to account for daily variations in BSS usage (Corcoran et al., 2014; Faghih-Imani et al., 2014; Gebhart and Noland, 2014) while we are interested in other factors.

To validate monthly and global performance estimates we compare operator data for 11 case studies (Table 5.1) by calculating absolute ($\overline{|\epsilon_M|}$) and mean error ($\overline{\epsilon_M}$) percentages as well as operator and estimated TDB for a number of months, n_M, where data overlaps. Ignoring known problems with data feed reliability for Chicago and San Francisco, the estimation error percentages are around 10%. This error is acceptable based on the large range of TDB values estimated for the 75 case studies (from 0.22 to 8.4).

5.2.3 Independent variables

Zhao, Deng, and Song explored the impact of geographic and demographic features, system characteristics and composite indicators for 69 Chinese BSS. Using 69 months of data, they found population, government expenditure and number of members and stations related to TDB.

Our scope is different, we study the impacts of a broader set of variables relating to operator determined attributes, compactness, geography, weather and transportation infrastructure. Our model also applies a longitudinal analysis, with 909 months of data, to intercontinental case studies.

		Monthly TDB		Overall TDB	
Case study	n_M	$\overline{\lvert\epsilon_M\rvert}$ (%)	$\overline{\epsilon_M}$ (%)	reported	estimate
Boston, US	7	9.4	9.4	3.89	4.19
Chicago, US	12	*64	64	2.37	2.95
London, UK	14	4.3	-4.1	2.14	2.06
Luxembourg City, Lux.	14	11	-11	0.62	0.54
Minneapolis, US	6	13	-13	1.10	0.96
Montreal, Canada	1	4.4	-4.4	3.37	3.22
Namur, Belgium	12	23	-23	1.30	1.00
New York City, US	12	10	4.0	4.85	4.83
San Francisco, US	11	*28	28	1.39	1.75
Vienna, Austria	10	15	15	1.60	1.79
Washington DC, US	13	7.2	-7.2	3.38	3.13

* Partially due to data feed misreporting bicycle count.

Table 5.1: Validation results of monthly and overall trips per day per bike (TDB) estimates.

BSS attributes

Many attributes of a BSS are defined by the operator and municipality. We distinguish between operator types: for profit, non-for-profit, advertising and transport authorities to see if it impacts usage. (DeMaio, 2009) notes university and government operators also exist but none are within our case studies. Operator names are also used to determine whether company specific management impacts BSS performance. As membership costs impact annual membership number and system usage (Goodman and Cheshire, 2014) they are included (converted to Euro using January first, 2014 exchange rate). The mean number of docks impacts the likelihood of having a dock free to return a bicycle as well as rebalancing necessity. Conversely, larger docks mean a compromise against more smaller stations with an increased coverage and density, both of which have benefits. Dock counts likely match expected demand rather than being constant so we also measure the standard deviation of station docks. As discussed earlier, whether BSS operate all year or halt during colder months may also impact usage. The daily operating hours of BSS varies, some close during the night for only a few hours, others up to eight hours. Like any service, reduced hours decrease potential service time but also its dependability as a transport mode for return trips in the evenings.

The above attributes are kept static over time, the following vary for each month of data. The monthly maximum sum of bikes and docks are observed and also used for a monthly 'dock to bike' ratio. (O'Brien, Cheshire, and Batty, 2014) noted a mean ratio of 2.08 for their case studies (measured as the inverse and named maximum load factor). Finally, with a potentially more explicit impact on BSS usability, we track the mean daily number of minutes that stations are full and empty for each month.

The number of stations in a system are summarized by the monthly mean of daily observations. The number of stations increases exponentially the number of unique origin-destination trips possible according to the number of edges in a directed complete graph ($s^2 - s$). Sometimes called the *network effect*, it is plausible that increased number

Variable name	Description	Temporal resolution	Expected effect	Mean	Std. dev.
Dependent variable					
TDB_M	Mean number of trips per day per bike	monthly		2.42	2.33
BSS attributes					
op_type	Operator type (priv., non-profit, advert. or PTA)	static	categ.		
op_name	Operator name (e.g., JCDecaux, Motivate)	static	categ.		
seasonal	Partially or fully closes during winter	static	categ.		
annual_cost	Annual membership cost (€)	static	-	47.5	44.9
open_hours	Daily number of hours system is open	static	+	22.7	2.57
open24h	Binary variable of open hours	static	categ.		
dock_mean	Mean number of docks at station	static	-	20.3	6.07
dock_sd	Std. dev. of number of docks at station	static	-	6.02	3.12
stations	Mean number of stations	monthly	+	125	191
bicycles	Maximum observed bicycles docked	monthly	-	1291	2560
bicycles_per_stn	*bicycles/stations*	monthly	+	8.20	2.73
docks_per_bike	Ratio of docks to bikes	monthly	-	2.22	0.789
outages_full	Station full outage ratio	monthly	-	0.0244	0.0241
outages_empty	Station empty outage ratio	monthly	-	0.0539	0.0750
Density & compactness					
density	*stations/area_km2*	static	+	5.68	1.53
$area_{300m}$	Area within 300m of stations (km^2)	static	+	20.6	24.0
compactness	$4\pi \times area_{1000m}/perimeter^2$	static	+	0.683	0.156
stn_spacing	Mean euclidean distance to 3 closest stations (m)	static	-	552	256
Geographic					
country	Country	static	categ.		
continent	Continent	static	categ.		
helmet	Helmets are mandatory for cyclists	static	-		
latitude	Latitude (*degrees*)	static	-	39.8	17.5
hemisphere	Hemisphere	static	categ.		
network	Network to euclidean distance ratio	static	-	1.51	0.196
altitude_sd	Hilliness: Std. dev. of indiv. station altitudes (m)	static	-	13.0	12.1
daily_sun	Mean hours of sunlight	monthly	+	14.4	2.3
pop	Population of primary city of BSS	static	+	922K	1,640K
Weather					
humidity	Mean monthly relative humidity (%)	monthly	-	70	9.7
temp_C	Monthly mean temperature (*Celsius*)	monthly	+	14.5	7.30
precip_mm	Mean monthly precipitation (*mm*)	monthly	-	1.45	1.77
wind_kmhr	Mean monthly wind (*km/h*)	monthly	-	12.3	3.92
Transportation infrastructure					
cyclinf_density	Cycling infrastructure density (km/km^2)	static	+	2.83	1.76
bus_density	Bus stop density ($per\ km^2$)	static	+	14.8	10.1
rail_density	Railway, subway and tram stop density ($per\ km^2$)	static	+	3.74	5.33

Table 5.2: Variable definitions and summary statistics.

of stations, typically with a corresponding increase in bicycles, increases performance (which normalizes linearly by number of bicycles which is highly correlated with the number of stations) due to the exponential increase in possible trips of number.

Influential practitioners promote this exponential 'network effect' as justification for increasing the number of stations to increase performance. Scott Kubly, the former president of Alta Bicycle Share and Seattle's current Department of Transportation Director gives the example of Washington DC's transition from the 10 station system (SmartBike DC) to the 100 station system (Capital Bikeshare) with a stated increase in performance from 0.7 - 0.8 to 50 times[2] greater (City of Seattle, 2016c). Nicole Freedman, head of the North American Bikeshare Association (NABSA), formerly Boston's and now Seattle's current BSS manager, states in regards to growing Seattle's BSS from 50 to 100 stations, that "doubl[ing] the size of the system [results in a] three to five fold increase in trips - that's the network effect" (City of Seattle, 2016b). Clearly existing practitioners believe the number of stations to play an important role in determining BSS performance.

Density and compactness

The location of BSS stations are a compromise between municipalities, politicians (especially when on street parking is potentially removed), system operators, local businesses, advertisers, system utility and profit potential, street and cycling network, civil engineering (whether underground cables are present or wheel chair access is obstructed) and, finally, public interest. We characterize the distribution of stations by the system's density, area, compactness, distance between stations and the number of stations.

Density of stations relates to the closeness of stations to origins and destinations. Convenience is an important factor for BSS use (Fishman et al., 2014; Fishman et al., 2015). Unlike (O'Brien, Cheshire, and Batty, 2014) we use a 300 metre buffer around stations to measure the density and area of BSS as this distance is the commonly recommended distance between stations (APUR, 2006; Gauthier et al., 2013) and similar to the distance transit users are willing to walk to use a service (Kittelson & Associates et al., 2003).

Compactness, a measure of roundness of station distribution ($4\pi area$ / $perimiter^2$) is sensitive to the buffer distance used. As (O'Brien, Cheshire, and Batty, 2014) noted having short buffer distances creates gaps between stations, dramatically impacting compactness scores, we also use a 1000 metre buffer for this measure as it better distinguishes BSS with higher station spacing. Our observed mean (Table 5.2) falls within the range of 0.55 - 0.72 observed by (O'Brien, Cheshire, and Batty, 2014). In addition we calculate the mean euclidean distance between each station and the three closest neighbouring stations. We use this measurement rather than network distance due to the uncertainty of existing cycling network data.

[2] Washington's BSS had about 3 TDB with 300 stations in 2014-2015. A four-fold TDB increase from the earlier 10 station system.

Geographic

To capture demographic, cultural and legal effects we provide BSS continent, country, municipality population, latitude, monthly mean hours of sunshine and whether a helmet requirement legislation exists. We also measure the topography in terms of standard deviation of station elevation and urban connectivity. Hilliness is a common resistance to urban cycling and balanced BSS use (Westneat, 2016). Urban connectivity is the ratio of bicycle street network distance, using Google Maps Directions API, to euclidean distance for a random sample of C_n connections between stations, where C_n is whichever is greater: 20 or 10% of the number of stations. This variable helps determine whether grid and historic urban structures impact BSS usage. We select the population within the city proper of the primary municipality in which the BSS resides (United Nations Statistics Division and National Institute of Statistics and Economic Studies) rather than the population strictly within the area of the BSS or the greater metropolitan area that may be accessing it. Retrieving the population of either of these options are equally faulty as BSS users typically start or end a trip adjacent to a station out of convenience (Fishman et al., 2014), perhaps as part of a multi-modal commute, rather than based on administrative boundaries. Estimating an accurate measure of the population which has access to the BSS is not feasible for the 75 case studies in a consistent manner. Higher population density is linked to higher performance (Zhao, Deng, and Song, 2014) and recommended by (Gauthier et al., 2013). While population within BSS coverage area is ideal, it still excludes commuters and tourists that are an important proportion of users (Gauthier et al., 2013). Helmet requirement and use has been suggested as a barrier to cycling for private utility cycling (Bateman-House, 2014; Robinson, 2006) and BSS use (Basch et al., 2014b; Fishman et al., 2014).

Weather

Bicycle sharing systems in warmer climates, such as in Spain, have mild, if any, decreases in daily trips during the winter compared to temperate (e.g., San Francisco, Washington) or continental climates (e.g., Chicago, Toronto), and obviously those that partially or completely close (e.g., Boston, Minneapolis, Montreal). High temperatures and humidity can also decrease cycling. While BSS with comfortable climates can more easily maximize cycling, developing a cycling culture and infrastructure maintenance (keeping cycle tracks clear of ice and snow) can reduce seasonal impacts, as is done in Copenhagen (Appendix C.1).

Weather effects are estimated using relative humidity, temperature, precipitation and wind for each day averaged for the month. These are the same indicators used in previous work measuring the impact of weather on BSS trips (Corcoran et al., 2014; Faghih-Imani et al., 2014; Gebhart and Noland, 2014) and cycling (Meng et al., 2016).

Transport infrastructure

Cycling infrastructure promotes cycling (Marqués et al., 2015), can increase safety, the perception of safety and cycling rates of women and children (Garrard, Handy, and

Dill, 2012; Martens, 2007; McDonald, 2012; Rietveld and Daniel, 2004). Integrating cycling infrastructure with other modes of public transport can be mutually beneficial and economical for individuals and municipalities (Chow and Sayarshad, 2014; Pucher and Buehler, 2009; Pucher and Buehler, 2012). Cycling infrastructure within 250 metres of stations has been linked to higher BSS station usage (Faghih-Imani et al., 2014) although it's unclear if this is endogenous. (Castillo-Manzano and Sánchez-Braza, 2013) state Seville's high BSS usage and cycling modal share is the result of the development of extensive new cycling infrastructure. In order to estimate public transportation and cycling infrastructure we extract Open Street Map features within 300 metres of BSS stations.

Lovelace (2015) shows that Open Street Map (OSM) can provide a better representation of existing cycling infrastructure than the UK's Ordnance Survey. We apply the same methodology. The limitation of this methodology lies in the quality of cycling infrastructure (e.g., sharrows and cycle tracks) being valued equally in our analysis (by length) while unlikely to be similarly effective at providing safety or even an appearance of safety to riders. As cycling 'infrastructure' varies from fully segregated cycle tracks to simply being designated as cycling paths without any indication on the road, the effectiveness of this attribute is limited. We apply similar feature extraction for rail and bus infrastructure in proximity to BSS stations (Appendix C.2).

Untracked attributes

Desirable attributes for which we do not have data, due to being too laborious to gather for such a large data set or not easily quantifiable are: cycling modal split, cycling culture, quality of cycling infrastructure, sign-up method (on the spot, on-line or by mail), universal transit card integration, access (residents only, requires credit card), station proximity to residences, employment and services (Fishman et al., 2014), demographics (Rietveld and Daniel, 2004) and road congestion. Clearly the location of stations relative to trip generating areas is of great importance but a data hungry and intensive exercise. In addition to these desired inputs are the level of promotion of BSS within the municipality, the level of political support and supportive policies, public support, the attitude of car drivers towards cyclists and the number of subscribers to the service. All of which are difficult to measure or access for such a large data set.

5.3 Results and discussion

5.3.1 TDB performance comparison

We present TDB estimates in Table 5.3. The range of estimated TDB values, 0.22 - 8.4 is similar to those observed in 69 Chinese case studies, 0.7 - 9.5 (Zhao, Deng, and Song, 2014), but with a much lower mean. The value of 1.0 TDB is psychologically important as those systems below this value imply some bicycles being unused all day. Surprisingly a third of the BSS in our sample have such ratings. More worrisome are the 10 systems with ratings below 0.5 TDB, as this means most bicycles are not used on a daily basis.

Note the presence of Ljubljana, Dublin and Vilnius with high TDB values of 8.2, 8.0 and 6.0 while having few stations, 33, 49 and 33 respectively, relative to similar TDB values. These three systems contradict the mantra that BSS need to be big to be 'successful'. Conversely, Brussels, Minneapolis and Brisbane with TDB values of 1.1, 1.0 and 0.32, and 323, 169 and 151 stations respectively, have not managed to reach the 3 TDB performance of most other similarly sized systems.

The only similar large scale evaluation of BSS in Europe is by the Allgemeine Deutscher Automobil-Club (ADAC, 2012) which looked strictly at accessibility, information, ease of rental and bicycle quality for 40 systems but not the context in which they are placed. This leads to contrasting rankings to our results (Table 5.3). The ADAC highly ranked Brussels and Luxembourg while Barcelona and Dublin were located in the lower half, a reversal from our results. The attributes evaluated by ADAC may have some impact but are unlikely strong performance determinants.

5.3.2 The network effect fallacy

Looking at our data sets' number of stations versus performance, a relationship clearly appears to exists (Figure 5.1). This same relationship exists with the number of bicycles as the number of stations and bicycles are highly collinear between BSS. When discussing increases in system size and station numbers an associated increase in the number of bicycles is implied. The network effect promoted by practitioners appears related to TDB (Figure 5.1) and possibly causal through its justification by increased origin-destination pairs allowing exponentially greater possible trips. A deeper analysis however reveals inconsistencies, challenging that a direct link exists.

For a hypothetical 50 station BSS, assuming a TDB value of 1 with 10 bicycles per station, increasing the number of stations to 100 should then result in a conservative TDB increase of at least 50% but potentially doubling or much more according to practitioners (Section 5.2.3). This translates to increasing the number of trips in the system from 500 to 1,500 - 2,500. While achieving 1,000 trips is plausible given an adjacent area of similar activity and travel density, higher usage is only possible if BSS users are highly dependent on using many stations, especially within the expansion area (and reciprocally within the expanded area), and that individual stations have very high degrees of connectivity with other stations. We explore both assumptions further.

Using London (2012) and Denver (2013 - 2015) data, unique for containing user identifiers to link trips, we can estimate how many stations users typically visit as either a trip origin or destination. During these periods London and Denver had about 600 and 80 stations and 13 and 11 median station visits per user respectively. Increasing coverage and number of stations increase *potential* destinations, but doesn't appear to alter much the number of stations actually visited. Considering the small quantity of stations visited by individuals, new stations likely impact a small proportion of users. Further, as initial BSS deployments typically expected high demand areas for station placement, any future expansion is unlikely to match the same TDB due to diminishing returns as new stations are placed in lower demand areas. The only exception is perhaps for extremely small systems where the number of stations serves too few origins and

	Main city	Country	Brand name	Operator	Number of stations	Number of bicycles	TDB estimate
1	Barcelona	Spain	Bicing	BSM	420	4,852	8.4
2	Ljubljana	Slovenia	Bicike(LJ)	JCDecaux	33	252	8.2
3	Dublin	Ireland	dublinbikes	JCDecaux	49	584	8.0
4	Turin	Italy	[TO]BIKE	Comunicare	136	495	7.9
5	Zaragoza	Spain	Bizi	Clear Channel	130	1,211	7.3
6	Valencia	Spain	Valenbisi	JCDecaux	276	2,403	6.6
7	Vilnius	Lithuania	Cyclocity Vilnius	JCDecaux	33	245	6.0
8	Lyon	France	Vélo'v	JCDecaux	346	3,301	5.3
9	Paris	France	Vélib'	JCDecaux	1,228	17,151	5.2
10	Milan	Italy	bikeMi	Clear Channel	187	2,832	5.1
11	Tel Aviv	Isreal	Tel-O-Fun	FSM GS Ltd.	177	1,411	4.9
12	Oslo	Norway	Oslo Bysykkel	Clear Channel	100	882	4.8
13	New York City	US	CitiBike	ABS/Motivate	357	5,208	4.7
14	Bordeaux	France	VCub	Keolis	139	1,279	4.7
15	Boston	US	Hubway	ABS/Motivate	115	1,037	4.2
16	Seville	Spain	Sevici	JCDecaux	260	2,203	3.9
17	Nantes	France	bicloo	JCDecaux	102	887	3.8
18	Toulouse	France	VélÔToulouse	JCDecaux	256	2,193	3.8
19	Lille	France	V'lille	Keolis	214	2,038	3.6
20	Montreal	Canada	Bixi	PBSC/Bixi	421	4,044	3.6
21	Nancy	France	vélOstan'lib	JCDecaux	29	245	3.1
22	Washington DC	US	Capital Bikeshare	ABS/Motivate	297	2,278	3.0
23	La Rochelle	France	Yélo	RTCR	57	210	2.9
24	Marseille	France	Le Vélo	JCDecaux	123	661	2.9
25	Chicago	US	Divvy	ABS/Motivate	300	2,191	2.8
26	Gothenburg	Sweden	Styr & Ställ	JCDecaux	57	728	2.7
27	Miami	US	DecoBike Miami Beach	decobike	94	601	2.6
28	Nice	France	Vélo Bleu	Veolia Transdev	178	1,401	2.4
29	Rennes	France	Le vélo STAR	Keolis	83	779	2.4
30	Rio	Brazil	Bike Rio	Serttel	46	280	2.4
31	Valladolid	Spain	Vallabici	Ingenia Soluciones	29	181	2.2
32	London	UK	Santander Cycles	Serco	748	11,864	2.0
33	Toronto	Canada	Bike Share Toronto	PBSC/Bixi	80	769	2.0
34	Rouen	France	cy'clic	JCDecaux	21	193	1.9
35	Calais	France	Vel'ln	Veolia Transdev	36	213	1.9
36	Montpellier	France	Vélomagg'	Veolia Transdev	49	280	1.9
37	Orleans	France	vélo'+	keolis	33	309	1.8
38	Vienna	Austria	Citybike Wien	Gewista	95	1,072	1.8
39	San Francisco	US	Bay Area Bike Share	ABS/Motivate	68	611	1.8
40	Mulhouse	France	Vélocité	JCDecaux	40	245	1.7
41	Besancon	France	Vélocité	JCDecaux	30	203	1.5
42	Denver	US	Denver B-cycle	Denver B-cycle	80	569	1.5
43	Belfort	France	Optymo	Optymo	25	201	1.3
44	Amiens	France	Velam	JCDecaux	26	240	1.2
45	Madison	US	Madison B-cycle	B-cycle	32	245	1.1
46	Columbus	US	CoGo	ABS/Motivate	30	225	1.1
47	Brussels	Belgium	VillO!	JCDecaux	323	3,708	1.1
48	Sao Paulo	Brazil	Bike Sampa	Serttel	95	571	1.0
49	Minneapolis	US	Nice Ride Minnesota	NRM	169	1,399	1.0
50	Saint Etienne	France	VéliVert	Veolia Transdev	33	229	0.92
51	Ottawa	Canada	Capital BIXI	PBSC/Bixi	25	244	0.89
52	Namur	Belgium	Li Bia Velo	JCDecaux	24	190	0.86
53	Houston	US	Houston B-cycle	Houston B-cycle	28	200	0.80
54	Nashville	US	Nashville B-cycle	Nashville B-cycle	21	166	0.79
55	Melbourne	Australia	Melbourne Bike Share	ABS/Motivate	51	546	0.71
56	Caen	France	V'éol	Clear Channel	40	350	0.69
57	Luxembourg	Luxembourg	vel'oh !	JCDecaux	72	684	0.67
58	Pau	France	IDECycle	keolis	22	199	0.66
59	Alacant	Spain	Alabici	Tevaseñal SA	24	120	0.62
60	Charlotte	US	Charlotte B-cycle	Charlotte B-cycle	21	164	0.58
61	Dijon	France	Vélodi	Clear Channel	40	401	0.56
62	Boulder	US	Boulder B-cycle	Boulder B-cycle	22	132	0.55
63	Avignon	France	VéloPop	TCRA	20	173	0.54
64	Fort Lauderdale	US	Broward B-cycle	B-cycle	25	154	0.54
65	Cergy-Pontoise	France	vélO2	JCDecaux	43	318	0.54
66	Chattanooga	US	Bike Chattanooga	ABS/Motivate	33	262	0.47
67	Santander	Spain	TusBic	JCDecaux	15	175	0.46
68	Valence	France	Libélo	Veolia Transdev	20	164	0.43
69	Clermont-Ferrand	France	C.vélo	Vélogik	10	104	0.42
70	San Antonio	US	San Antonio B-cycle	B-cycle	52	388	0.42
71	Brisbane	Australia	CityCycle	JCDecaux	151	1,856	0.32
72	Bari	Italy	BariinBici	Comunicare	32	44	0.29
73	Fort Worth	US	Fort Worth B-cycle	FW B-cycle	34	267	0.28
74	Vannes	France	Vélocéa	Veolia Transdev	25	153	0.26
75	Perpignan	France	BIP!	Clear Channel	15	123	0.22

Table 5.3: Studied BSS ranked by trips per day per bicycle.

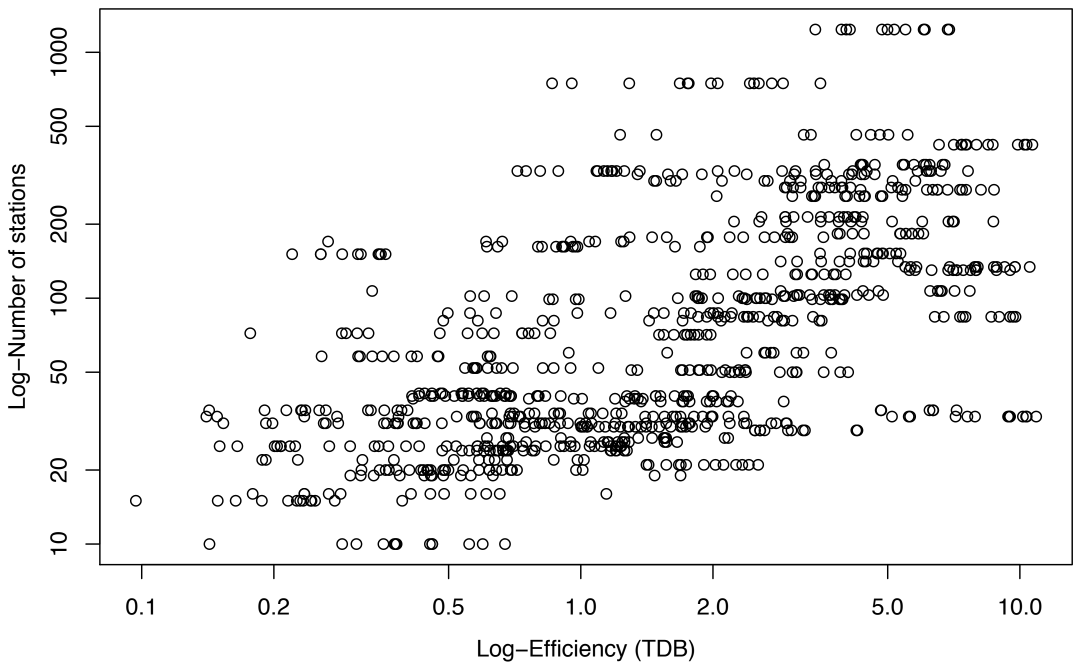

Figure 5.1: Monthly trips per day per bike (TDB) performance values relative to number of stations for our 75 case studies.

BSS city	Mean	Median	Stations
Boston	9.8	7	95
Chicago	3.3	0	300
London	46	37	741
Luxembourg	2.9	2	72
Minneapolis	6.6	3	167
New York City	38	34	330
San Francisco	7.9	4	68
Vienna	7.6	6	102
Washington	24	9	305

Table 5.4: Mean and median daily trip connectivity of stations to other stations.

destinations to satisfy individual user demand. As Ljubljana and Vilnius show (Table 5.3) however, high TDB rates can be achieved with about 30 stations if other attributes, such as sufficient trip generating land-use density, are present.

Independent of users, station connectivity through trips is limited. From each individual station there are only a small percentage of other stations that connect through trips. Typically a few stations in the centre of the system have connections to many other stations, but most stations have few stations with regular trip connections.

Using data available for a selection of cities using data from 2012 and 2013, Table 5.4 shows the mean and median number of stations that other stations connect to daily through trips (as either origin or destination). The small number of daily connections for each station disagrees with a functional network effect. So a new station is unlikely to experience many trips between many of the other stations and BSS members are mostly concerned with few stations in a system.

Another much simpler analysis to see the effect of system expansion is comparing performance over time as systems grow. Using operator data providing bicycles, trips and stations over time, Figure 5.2 shows Chicago, Denver, Minneapolis and Washington's BSS performance and station count vary independently.

The final argument against the network effect is based on our TDB estimations results (Table 5.3). Slovenia, Dublin and Lithuania have some of the highest TDB scores (6.0 - 8.2) while Brussels, Minneapolis and Brisbane with 4 - 12 times as many stations have much lower scores (0.3 - 1.1). While other factors are at play, given the purported increase in TDB associated with more stations, these values further suggest no causal link to be present. Returning to the relationship illustrated in Figure 5.1, we believe station and bicycle number to be endogenous and that large systems have had large investments in their usage, such as the development of cycling infrastructure, or conversely, had high TDB to begin with and increased in size (station and bicycle number) as result. Based on the multiple arguments presented we believe that increased TDB performance strictly based on system expansion is a fallacy.

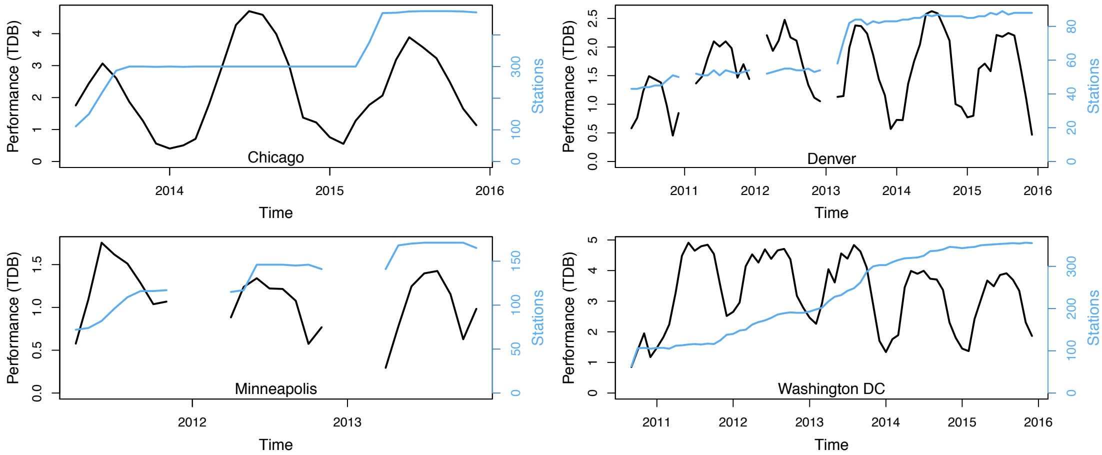

Figure 5.2: Station count and trips per day per bike (TDB) performance for Chicago, Minneapolis, Washington and New York City's BSS over time.

5.3.3 Model selection and fitting

Efforts to statistically show system size to be an endogenous variable unfit for predicting TDB using a Hausman test failed due to the lack of finding an instrumental variable unrelated to TDB. The use of system size, in terms of number of stations and bicycles, was tested in regression models, greatly reducing error, but omitted due to believing it to be endogenous.

Our analysis contained many 'independent' variables (Table 5.2) in the BSS attributes, compactness, geographic, weather and transportation infrastructure categories. Our models implement a quarter of these. We are not stating that omitted variables have no effect, only that some are perhaps weaker than our model variables or endogenous and required exclusion.

Our models aim to determine what factors impact BSS performance in terms of TDB. We create multiple models to increase the confidence of estimate variable influence: an OLS regression of mean temporal values for each BSS, a similar but robust regression (Huber, 1981), an OLS using only the month of April rather than a mean value, and finally, since we have multiple measures per BSS with dynamic variables, we use a mixed model as this minimizes variance between case studies and isolates unexplained differences between case studies such as laws, by-laws, culture, topography and history among many possible factors.

We present four models to increase robustness as we observe that many variables have outliers. Across the four models a clear set of coefficients remain similar and significant. Our original data gathering and analysis methodology planned for multiple observations per case study negating the use of OLS. We decided to explore what result mean values and a one month sample (April) would yield. Attempts to apply a linear model to means of monthly values yielded models susceptible to over-fitting due to outliers with

	OLS			Robust regression			OLS April			Mixed model		
Variable	Coef.	Robust SE		Coef.	Robust SE		Coef.	Robust SE		2.5%	97.5%	t-Value
Intercept	-8.48	-4.40	***	-8.40	-4.02	***	-4.17	-3.85	***	-0.04	0.50	1.65
op_type [advertiser]	*reference*											
op_type [np]	-0.96	-3.04	**	-0.99	-2.95	**	-0.77	-2.05	*	-1.75	-0.46	-3.37
op_type [private]	-0.10	-0.39		-0.11	-0.40		0.04	0.16		-0.62	0.15	-1.21
op_type [pta]	-0.10	-0.17		-0.12	-0.22		-0.37	-0.71		-0.96	0.69	-0.34
bicycles_per_stn										-0.23	-0.13	-6.95
outages_full : outages_empty										0.11	0.16	10.33
density	0.17	2.21	*	0.17	2.06	*	0.18	1.90	.	0.06	0.47	2.58
helmet [false]	*reference*											
helmet [true]	-2.01	-2.70	**	-2.02	-2.63	**	-2.22	-2.39	*	-3.18	-1.07	-3.96
log(pop)	0.26	3.22	**	0.27	3.13	**	0.33	3.31	**	0.20	0.58	3.91
daily_sun	0.36	2.66	**	0.35	2.41	*						
wind_kmhr							-0.06	-2.07	*			
temp_C										0.47	0.58	17.95
$temp\_C^2$										-0.39	-0.27	-10.93
cyclinf_density	0.10	1.96	.	0.10	1.88	.	0.12	1.68	.	0.04	0.38	2.54
Adjusted R^2	0.43			-			0.42			0.49^a		

Robust standard error significance values: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1

[a] Fixed effect R^2 (Johnson, 2014; Nakagawa and Schielzeth, 2013)

Table 5.5: Log-TDB model results. Mixed model coefficients on the right are scaled.

influence. A robust regression was applied as it reduces the impact of outliers (but not those with leverage and influence). The OLS using April was chosen as it is temperate in North and South hemispheres. Zhao, Deng, and Song (2014) performed a similar analysis but using different months.

The mixed model applied to multiple observations per BSS proved to be more robust. Model structure was resolved through an iterative observation of Aikake and Bayes information criterion (AIC/BIC), log likelihood and R^2 (Johnson, 2014; Nakagawa and Schielzeth, 2013). Our iterative mixed-model comparison resulted in a model containing individual BSS as random effects with the remaining variables as fixed effects described in Table 5.5. All dependent and independent variables are scaled. Scaling reduces the correlation of squared terms with their non-squared equivalent (for the temperature), prevents collinearity between interaction terms and eases some aspects of interpretation while rendering others more difficult. Due to our case studies varying in magnitude we log the dependent variable *tdb* and *pop*. In addition we maximize R^2 with restraint by maintaining only significant variables in our model while reducing the BIC.

Table 5.5 provides OLS and robust regression coefficients and 95% confidence intervals for the mixed model, based on a 10,000 iteration bootstrap. We will refer to the OLS and robust regression models as the 'simple' models. The categorical default for variables *op_type* is advertiser, such as JCDecaux and Clear Channel, and for *helmet* is false, meaning no helmet law exists. We note that all our models achieved an R^2 of 0.42 - 0.49.

Although a small sample, non-profits have a lower performance tendency to other BSS operator types. The simple and mixed models estimate a 77 - 99% and 48 - 180% decrease respectively in TDB for non-profit operators (Tables 5.5 and 5.6). With the exception of Denver (1.5 TDB) the six other non-profits in our sample are within the bottom third of our TDB ranking (Table 5.3). This may be due to non-profits having reduced access to capital to promote the system, less support from a 'champion' within the municipality (Parkes et al., 2013) or the operator having a goal other than maximizing the number of trips. Maximizing the performance of a BSS based on TDB may clearly marginalize

Variable	Effect (%) confidence interval (95%)
Non-Profit operator	48 - 180 decrease
Bicycles per station	4.9 - 8.8 decrease per bicycle
Station density	4.3 - 32 increase per station
Helmet requirement	110 - 330 decrease
Population (percentage inc.)	0.16 - 0.48 increase
Temperature	Dec. marginal returns until 17 - 31°C
Cycling infrastructure	2.6 - 22 increase per km

Table 5.6: Mixed model variable effects on performance.

social, economic, racial and gender equity outcomes many non-profits aim to prevent. Minneapolis' BSS explicitly allocates stations, bicycles and service to areas for social equity purposes while expecting an economic loss (Nice Ride Minnesota, 2012).

Our models do not directly use the number of *stations* or *bicycles* in our model even though, as mentioned, they are highly correlated with the dependent variable (Figure 5.1). Adding these variables to our models increases R^2 by 30% but as a result of endogeneity. The normalized *bicycles_per_station* alternative variable is linked with a 5 - 9% decrease in performance per bicycle (Table 5.6).

Systems with more bicycles per station require larger stations, in terms of docks, and also have greater variation in station size, hence the variables also covary. Our interpretation considers these three factors together in hypothesizing that operators which place larger stations in high demand areas, such as transit hubs, may not benefit the system as a whole. More resources are invested in replenishing these stations then focusing on a wider set of stations. Having larger stations, while all else remains equal, also means having fewer stations, based on fixed capital costs, meaning a smaller coverage area, decreasing station density and reduction in potential trip origins and destinations.

Station density was found to increase performance by 4 - 32% per station per square kilometre. The recommended density of stations by the Institute for Transportation and Development Policy is 10 - 16 stations while our case study mean is below 6 stations (Table 5.2). Density impacts the distance between users' true origin or destination and the closest bike share station. More insidious however is the distance that users must walk and/or bike if their desired station is full or empty. So density is a measure of coverage quality but also resiliency and reliability of the system.

The bicycles per station variable, found to negatively impact performance, correlates with station size and station variation suggesting more smaller regularly sized stations being more performant. The complexity in interpretation prohibits a stronger recommendation. However, in combination with the density variable significance, multiple factors point to denser small stations being more efficient than fewer larger stations over the same area. We have shown the increase of system size, in terms of stations and bicycles, does not increase performance as the TDB metric normalizes by the number of bicycles, among other factors. Increasing the number of stations while keeping the number of bicycles constant however, may increase TDB according to model estimates. A larger availability of stations, for a fixed number of bicycles, more densely concentrated increases accessibility and therefore TDB likely as well.

Whether having many small stations rather than few larger stations is more performant, as Faghih-Imani et al. (2014) suggest, has implications for BSS technology providers. Two of the largest BSS technology providers (Public Bike System Company and JCDecaux) operate *smart-station* systems where much of the technology and costs are associated with station kiosks and docks. Technology providers offering *smart-bike* systems where the technology is incorporated in the bicycles, supposedly reducing costs, may benefit by being able to offer greater density of smaller stations at lower costs.

A densification of stations through a redistribution of resources to create more smaller stations should not be confused with our earlier statement that an increase in stations does not improve performance. We refer to system expansion generally where operators typically grow their systems outwards at similar densities and increase the number of bicycles. Our results imply increasing the number of stations, while maintaining the number of bicycles, increases TDB.

The outage interactions (Table 5.5) suggest that having stations being full and empty to be an indicator of an active and performant system, clearly not a cause. Operators typically aim to prevent full outages more than empty outages, as can be observed by the mean values in Table 5.2, as they lead to greater complaints from users (Médard de Chardon, Caruso, and Thomas, 2016). We expected outages to be negatively associated with performance in terms of causality, ceteris paribus poorly rebalanced systems decreasing usage, but it is revealed as a symptom of performance.

Our model suggests a penalty of 200% for BSS with helmet requirement laws. The two Australian case studies with helmet requirements are both in the lower third of performance ranking (Table 5.3). Currently mandatory helmet legislation is only present for BSS in Melbourne, Brisbane and Seattle. We note that Seattle's BSS, of similar size to Melbourne's, is experiencing 0.9 TDB (City of Seattle, 2016b; Pronto, 2016) and was at risk of bankruptcy until the City of Seattle purchased the system in early 2016. Discussion of the cause of the deficit has largely ignored helmet regulation and rather related to unmet expectations of financing, trips, hilliness and governance structure (Bush, 2016; City of Seattle, 2016b; Westneat, 2016). The helmet variable effects of our model may partially relate to Australian cultural or behavioural factors (Section 5.2.3) rather than helmets alone.

As the number of trips directly impacts the TDB metric, it's no surprise that larger populations increase metric performance. The simple and mixed models show a percent increase in population relates to 0.26 - 0.33% and 0.16 - 0.48% increases in performance respectively.

Weather is of course a major determinant of performance. Warmer temperatures increase performance but marginal returns are maximized around 24° C. Temperatures beyond the maxima should perhaps not be interpreted as decreasing performance, rather that warm weather noticeably, but decreasingly, increases TDB up to the maxima. For the simple models, hours of daily sun were more representative of BSS usage, except for the April model (12 hours of sun for almost all BSS) for which wind plays a role. An increase in wind of 1 km/h, above the mean, suggests a 6% performance decrease. Humidity was never found significant, likely due to monthly aggregation as prior work found it relevant at shorter temporal resolution (Gebhart and Noland, 2014).

Our performance estimates (Table 5.3) bias systems with weather more comfortable for cycling. Weather is but one factor impacting ridership and as Copenhagen shows (Appendix C.1) need not be such a strong effect. As our analysis only uses data from months BSS are in operation, those that close during the winter may have higher overall performance as a result. BSS have the same capital costs regardless of seasonality. While operating costs during the winter may be greater than revenue, the winter closure may still decrease seasonal BSS revenue and performance upon reopening due to the need to reinvigorate potential members. This decision may be out of the control of the operator however, as cycle path maintenance requires municipal assistance.

Cycling infrastructure is significant in the simple and mixed models showing an effect of 11% and 3 - 22% respectively per additional kilometre per square kilometre (Tables 5.5 and 5.6). Other variables such as elevation deviation and mean dock sizes were sometimes significant but sensitive to model changes. Rail and bus infrastructure were not found to be significant although BSS stations adjacent to rail stations in Boston, Chicago, London, Luxembourg, New York City, San Francisco and Washington are some of the most used stations within their systems (Médard de Chardon, Caruso, and Thomas, 2016) and important feeders for the whole system. It is likely not the number of bus or rail stops that matter but their magnitude of traffic.

5.4 Conclusion

We provide a comparison of a large number of bicycle sharing systems (BSS), mainly in Europe and North America, using the metric of trips per day per bike (TDB). The use of TDB is *one* metric that allows a relatively simple comparison of many BSS. This exercise is worthwhile however as little quantitative work explores the determinants of BSS performance. While the *benefits* of systems are repeatedly stated by politicians and media there's little existing concrete evaluation of these and a chronic absence of a specific purpose for many BSS. A comparison based on TDB is perhaps the most fitting as it is largely indisputable. Without clear goals, BSS adoption hints to their purpose being a symbol of sophistication, equity and sustainability awareness, among others, more than part of a comprehensive public transportation tool.

In determining what factors impact BSS usage we found that system expansions (increasing the number of stations and associated number of bicycles) do not increase system performance. This is a significant finding as influential actors promote this 'network effect' to policy makers while we have found absolutely no evidence supporting this. Additionally, and unsurprisingly, cycling infrastructure is significant related to BSS performance. Politically, however, increasing BSS size may be more palatable by decision makers and less contested by the public than a redistribution of public roadways for improved utility cycling infrastructure. Results also show that non-profit operators have decreased TDB, perhaps due to addressing equity, and that temperature and wind negatively impact BSS performance as expected.

Given the presented attributes' impact on performance, policies can be put in place to maximize TDB - if this is the goal of the BSS. Alternative metrics, such as BSS self-funding through user fees or advertising, are available but can equally be criticised for lack of equity consideration. Additionally, such a metric would be more opaque to external evaluation. As we mentioned earlier, this performance metric does not align with some BSS goals. The purpose of Luxembourg City's BSS, for example, is to serve as transitional tool to private utility cycling, a goal that can be interpreted in the long term as aiming to decrease system TDB. More often however BSS have no explicit or measurable goal.

As some BSS adoptions may be motivated by political gain (Which politician doesn't doesn't desire a sophisticated, self-funding, sustainable, equitable, health improving, congestion reducing transportation system in their city?) and facilitated by provisioners seeking profit through sales, advertising or operation of the service, it's no surprise that a clear goal isn't present. So while some existing goals ignore demographic segments, a secondary concern may be the regularly ignored social detriment associated with advertisement subsidized BSS.

We hope the provided TDB estimations (Table 5.3) initiate discussions within municipalities of precisely what purpose their BSS has. Some of our low performance rated case studies have been previously called a success by media, operators and their municipality, yet, as discussed, BSS often provide limited benefits to health, carbon dioxide emission reductions, road congestion and equity. With low TDB rates, even fewer plausible claims of BSS benefits remain.

Chapter 6

A critical perspective of bicycle sharing system politics, business and purpose

Outline

This chapter describes the growth of bicycle sharing systems (BSS) in Europe and North America from a critical urban sustainability perspective. It discusses how BSS, consisting of multiple collaborating actors with different objectives, can lead to unintended outcomes. Environmental sustainability is often cited as a benefit of BSS yet CO_2 emissions have been shown to sometimes increase as a result. Technological and contractual lock-in of BSS by technology and service providers respectively, constrain municipalities from expanding or locating stations where they desire. Politically, BSS are being used to promote cities as being cosmopolitan externally while increasing citizen pride in having a sophisticated and modern technology that is a supposedly sustainable, healthy and equitable form of transport. The rapid and global dispersion of BSS has been facilitated by their many positive associations. Yet many of BSS' promoted benefits are unproven, limited or inconsistent. In addition many systems are subsidized by advertising, promoting consumption and even car ownership. While BSS do have some concrete benefits, these are disproportionately gained by the already privileged classes.[1]

6.1 Introduction

Bicycle sharing systems (BSS) appear to be easily implementable solutions with many benefits for relatively little expenditure. Existing literature, however, has largely focused on quantitative analysis (Fishman, Washington, and Haworth, 2013; Ricci, 2015) and optimal rebalancing (Erdoğan, Battarra, and Calvo, 2015; Forma, Raviv, and Tzur, 2015) but very little on critical analysis of the validity and distribution of BSS benefits.

[1]This chapter is based on a working paper.

While operators and decision makers regularly state BSS' many benefits, clear goals are rarely provided with their adoption, making claims of success, using arbitrary statistics, questionable. Additionally, BSS deployments requires multiple actors with different priorities, sometimes deteriorating their efficacy. Comparing BSS performance as a metric (Chapter 5) provides a relative measure of success, but this too can be criticised as being too narrow. Analysis of BSS politics in the context of sustainability and justice raises existential questions regarding the purpose of these systems in cities, regardless how much the the systems are used.

The reported benefits of BSS, which we strongly differentiate from goals or purposes, are many and varied: cycling modal shift increase, economic and travel time savings for users, reduced congestion and emissions, physical and mental health, normalizing cycling, a complementary and alternative transportation mode, convenience, leisure and social equity (Fishman, Washington, and Haworth, 2013; Ricci, 2015; Shaheen, Guzman, and Zhang, 2010). While many of these are plausible, they first depend on BSS having a certain level of use and stations being present for a variety of demographics, which is rarely the case (Chapter 5).

The recent growth of BSS coincides with the study of new technologies being promoted as solutions to societal and environmental concerns while being capitalized upon to attract funding, pacify conflicts and increase urban value (Kenis and Lievens, 2015; Krueger and Gibbs, 2007; While, Jonas, and Gibbs, 2004; Whitehead, 2003; Wilson, 2015). The problem with these technological or policy solutions is that while they may provide social, environmental and economic benefits, gains are not equitably distributed. With ongoing deregulation, city or urban governments are becoming more independent, important and responsible in shaping urban living. A selective process of social and sustainability policies, increasingly privatized, conceal underlying goals of economic growth for some citizen classes over others (While, Jonas, and Gibbs, 2004; Wilson, 2015). Urban sustainability literature criticizes technocentric projects, similar to BSS, that provide 'green fixes' through green policies (Long, 2015; While, Jonas, and Gibbs, 2004) in other sectors (energy, transport, waste, building). Similarly, 'sustainability fixes' have predominantly focused on implementing policies specifically reducing CO_2 emissions, among a wider set of issues, through measurable means rather than potentially more effective, but less quantifiable, alternatives (While, Jonas, and Gibbs, 2010).

Many BSS stated benefits, publicized as objectives, are unproven and in some cases undermined. The three most commonly promoted benefits of BSS relate to the equity, health and the environment. For most cities however, users are more likely be white, male, younger, wealthier and own a bicycle and a car (Fishman, 2015). The likely cause of gender inequity is that cycling infrastructure, which at the very least appears unsafe or unenjoyable, is more commonly used by men (Garrard, Handy, and Dill, 2012; Goodman and Cheshire, 2014). The health benefits of BSS are controversial as well. A study in London showed increased benefits for men as women tend to have a greater number of accidents (Woodcock et al., 2014). Cycling is a healthier alternative to driving, certainly, and some forms of public transport, but it likely reduces the health benefits of those who previously walked (Fishman, Washington, and Haworth, 2015; Murphy and Usher, 2014;

Case study	Luxembourg	Munich	Minneapolis	New York City	Seattle
Technology	JCDecaux	nextbike	PBSC	PBSC	8D/Arcade
Operation	JCDecaux	PTA	NRM[b]	Motivate	Motivate
Tech. owner	JCDecaux	PTA	NRM	Motivate	City
Manager	City[a]	PTA	NRM	City	City
Sponsor	-	-	BCBSA[c]	Citibank	Alaska Airlines

[a] Economic disincentives by operator for certain station locations.
[b] Nice Ride Minnesota, a non-profit.
[c] Blue Cross Blue Shield Assoc., among many others.

Table 6.1: Types of bicycles sharing system actors and case study examples.

Woodcock et al., 2014). Public transit use is not necessarily reduced by a BSS's presence, it may replace some trips but also encourage increased use by trip chaining (Ricci, 2015). The decrease in car usage as an alternative is minor in user surveys and no work has yet measured actual behaviour change, only self reported (Ricci, 2015). Likewise carbon emissions reductions are questionable, especially as most BSS use conventional trucks for rebalancing bicycles, in some cases increasing overall emissions (Fishman, Washington, and Haworth, 2014). The many claims of BSS benefits are overestimated.

A BSS consists of multiple actors. Technology manufacturers, sometimes multiple, provide the physical infrastructure, point of sale technology and operational software required for a functional BSS. The maintenance and repositioning of bicycles is often contracted out to a private company. System management, dictating operational goals and station location, is often handled by municipalities but to varying degrees handled by operators. The technology owner tends to be the operator, municipality or a non-profit. The municipality is present if BSS require the use of public land for stations, but some types of systems do not require stations and therefore omit governmental involvement. Mayors occasionally play important roles in BSS deployment, championing and finding sponsors. Sponsors are prevalent in North America and the UK in subsidizing BSS. Users and residents are the final actor. Individual BSS have diverse combinations of actors, some of which hold multiple roles (Table 6.1).

Over the last decade BSS have been aglow with positive associations encouraging their rapid growth. Throughout this evolution negative aspects have not been documented. The broad diversity of operation and ownership models have evolved, with different actor combinations, making generalization and comparison difficult. Interactions between actors with different goals has led to conflicts, contradictions and co-opting leading to alternative outcomes than those promoted. This chapter reveals and discusses these so further work can focus on these facets.

The chapter begins by presenting methods (Section 6.2) before critically describing narratives in Europe and North America (Section 6.3), followed by a series of discussions on key issues (Section 6.4) that arose from the narratives before finally concluding (Section 6.5).

6.2 Methodology

A total of 19 in person or telephone interviews where carried out between 2013 and 2015 with municipal decision makers, BSS professionals, operators and cycling non-profits in a variety of cities in North America and Europe (Dublin, Luxembourg, Vienna). Larger BSS in North America were targeted for interviews, which at the time there were still few of. Fewer European interviews were completed simply due to time constraints. Three interview question sets were completed by email responses. English and French media articles from North America and Europe were also studied to complement interviews. We quote the transcribed interviews in this chapter but maintain anonymity while providing the organisation type, role, such as elected council member or city manager, and whether their relevant BSS is in Europe or North America.

Our semi-structured interviews were tailored to three interviewee types: municipal, operator and cycling organization. This research evolved from a suspicion that operators and municipalities were prematurely calling their BSS a success. Cycling organizations were chosen for an external opinion having expert knowledge in effective cycling strategies. Interview questions served as guidelines for discussion rather than fully structured. The purpose of the interviews was to understand the motivation, adoption and evolution of BSS (Appendix D.1).

6.3 A critical history of BSS evolution in Europe and North America

Bicycle sharing systems are most common in Germany, France, Italy and Spain in Europe. Although contiguous, their outcomes are summarized differently. Germany's systems haven't been recognized as successful (Parkin, 2012; Tironi, 2011). To understand why it's necessary to return to Germany's alternative BSS evolution.

In 1998 three students developed the Call-a-bike, station free, BSS in Munich with about 1200 bicycles in the city centre (Nitschke, 2015). Following financial difficulty in 2001, the system was taken over by Deutsche Bahn (DB) and spread to over 50 other German cities. Germany due to this had a much earlier and more dispersed BSS presence, although this typically consisted of one station adjacent to train stations. Around the time Lyon's system launched, in 2005, a second technology named nextbike emerged and began spreading across Germany. The system was also station free with virtual station areas where bicycles could be parked. With a presence in over 30 cities, some municipalities, such as Munich, now had two BSS present. Because these systems did not use stations they did not require municipal involvement for the use of public space to place stations nor did they have the same visual presence as systems with stations (Nitschke, 2015). These systems as a result were not integrated into larger cycling or transportation initiatives and not promoted by municipalities.

The presence of Call-a-bike and nextbike likely reduced the integration and development of BSS as part of larger cycling initiatives in Munich (Nitschke, 2015) and other German cities. With Munich's public urban space fully allocated, increasing cycling infrastructure further meant taking space from other transport modes, likely cars, something that politicians were reticent about. The development of more comprehensive station based BSS was easily disarmed by the existing presence of existing less visible and smaller BSS. Eventually decision makers' use of alternative station based BSS, popular cycling initiatives and perhaps the desire to market themselves as a liveable city, motivated the development of a station based system managed by Munich's public transport authority. While Berlin adapted their systems to become station based most other German BSS remain station free or exceptionally small.

Italy while having a few large and well used systems, largely has many very small systems with little use. Spain had a rapid expansion throughout the country, and still has many highly used systems, but many smaller systems closed following the 2008 economic downturn. France has a variety of systems in terms of size and usage mostly operated by JCDecaux. Overall Europe's new BSS deployment peaked between 2007 and 2010.

Existing BSS development is often privatised and associated with advertising. This contrasts with the earliest know BSS. Amsterdam's 'White Bikes' was conceived in 1965 by Luud Schimmelpennink during his time as a member of the Dutch anarchist *Provo* movement as a response to air pollution and consumerism (Teun Voeten, 1990; Zee, 2016). The freely accessible bicycles, provided by volunteers and painted white for use by all, did not last long. Many where quickly removed by police due to a bylaw requiring bicycles be locked but more generally out of resistance against Provo's initiatives to provoke the police (hence the name) (Beatley, 2000). Schimmelpennink, however, continued to shape the BSS landscape to its current form.

The White Bikes would have many imitators in Europe and North America until the 1990's. Most experienced a similarly short fate with perhaps the exception of La Rochelle in 1976, who's mayor strongly supported the initiative. While Amsterdam's Provo movement was short-lived, Schimmelpennink, after being elected to Amsterdam's city council, proposed a similar BSS concept a few years later. This was rejected due to the bicycle being viewed as a thing of the past and the car as the future (Zee, 2016). In 1995 Schimmelpennink helped develop Copenhagen's 1995 coin-operated and station based, second generation, BSS. In operation until 2012, it was so popular that finding a bicycle was sometimes difficult (Beatley, 2000). It is to date the longest know running system. After another attempt in 1999 to develop a modern BSS in Amsterdam (Beatley, 2000; Teun Voeten, 1990), Luud Schimmelpennink assisted JCDecaux in 2002 in developing Vienna's third generation BSS, with an automated and secure checkout system linked to user's credit cards, solving earlier generations' biggest problem, anonymity (Zee, 2016). So while Amsterdam's White Bikes were born out of an anti air pollution and anti-consumerism movement, many of Europe's BSS are now funded by advertisements promoting consumption and often cars.

Advertising being paired with BSS can be traced back to Rennes' 1998 call for street advertising offers where Clear Channel, an American advertising company, offered a third generation BSS as an addition to their bus shelter and advertising offer and won. The previous contract holder for bus shelter advertisement, French company JCDecaux, unhappy with the outcome vindictively removed all bus shelters, leaving Rennes' citizens in the rain (Meignan, 2007), and contested the tender process in the courts. The court ruling crippled Rennes' new "Vélo à la carte" BSS by disallowing any expansion of the system. To the detriment of citizens Clear Channel and JCDecaux have repeatedly challenged outcomes of street furniture and advertising provisioned BSS contracts since this event (Girard, 2005).

Unsurprisingly, JCDecaux quickly began development of Cyclocity, their BSS brand, in 1999 (Lundahoj, 2014) at their headquarters outside Paris, deploying their first systems in 2003, following the assistance of Luud Schimmelpennink, in Vienna, Cordoba and Gijon. The first large test of JCDecaux's new BSS technology however was in 2005 when Lyon, France's third most populous agglomeration, requested offers for a BSS in exchange for street furniture advertising. This time JCDecaux was prepared to challenge Clear Channel and won the contract, creating the worlds largest BSS at the time (Parkes et al., 2013) and demonstrating their ability to offer advertisement subsidized BSS for large cities.

Paris had carefully watched Lyon's BSS developments. In a hurry to deploy their system for the summer before municipal elections, Clear Channel and JCDecaux were both involved in defining the tender, guaranteeing that their products would best fit the request for proposals while alternatives would not (Tironi, 2011). JCDecaux lost the bid to Clear Channel which had offered more bicycles. Unsatisfied JCDecaux once again contested the outcome in court and, thanks to a technicality, annulled the outcome resulting in a second round of proposals which JCDecaux finally won by offering more bicycles. The absurdity continued however, with Clear Channel also taking the outcome to the courts but only succeeded in temporarily preventing an expansion of Paris' future BSS into adjacent municipalities (Paris, 2008). With the deployment of 750 new stations and thousands of bicycles in Paris would also be implanted many new advertising billboards. As the leftist party was responsible for the BSS, the green party attempted to protest the privatisation of public space but found the complexity in untangling free bicycles from advertising too complex to communicate to voters (Tironi, 2014). The contention regarding advertising would however follow JCDecaux in other municipalities such as Brussels and Namur.

Paris' BSS, associated with sustainability, health and decreased congestion, was a huge boost in image for JCDecaux (Le Goff, 2009) following allegations and convictions of corruption (Marketing Week, 2000; Rydberg, 2007; Strategies, 2003). After Paris, JCDecaux experienced a rapid growth in the number of BSS deployments until 2011 (Figure 6.1). It's unclear if the decline is due to market saturation, most large cities now having a BSS, decreased demand for advertising coupled with a BSS, or a decline in billboard advertising prices. Regardless, JCDecaux has no interest in running BSS as a service independently of advertising and did not bid for London's operator contract because revenue was not linked with advertising (Le Goff, 2009).

While some municipalities purchase BSS infrastructure and others operate it, for advertiser provisioned BSS all the infrastructure belongs to the company and will remove it at the end of the contract. Some municipalities view this as a benefit as the tech-

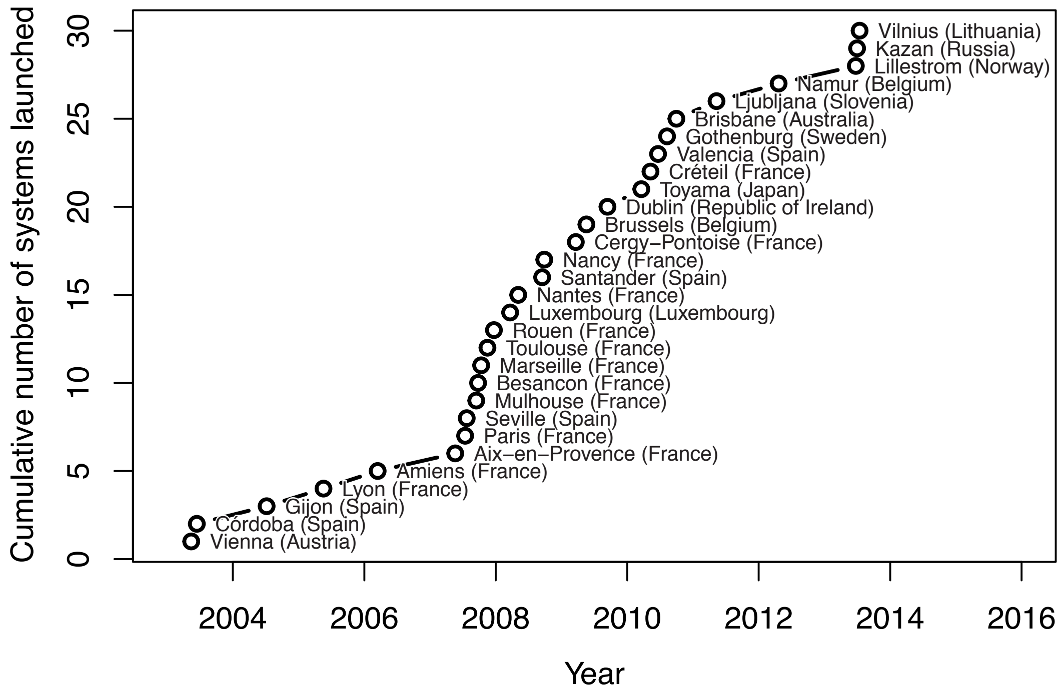

Figure 6.1: JCDecaux bicycle sharing system deployments.

nology is still evolving rapidly. There is however a more nefarious side to this. System expansions require new negotiations between operators and municipalities. Placing new stations where the advertiser has no interest in placing advertisements creates problems relating back to these companies having no desire to simply run a BSS. A good example is present in Luxembourg.

Luxembourg City's BSS, operated by JCDecaux and deployed in 2008, is the largest in the country with 73 stations. As an important usability factor of a BSS is the station coverage area, The greater the area covered enables a larger proportion of the population to access more destinations. Luxembourg City is peculiar for having two BSS directly adjacent but using incompatible technologies. While JCDecaux may provide added stations in exchange of advertisements billboards, they ask for payment for stations at locations undesirable for advertising. The reasons for Bertrange's distinct BSS, adjacent to Luxembourg City, is due to their discovering that the cost of purchasing *electric* bicycles, docks and station infrastructure was cheaper than purchasing conventional infrastructure from JCDecaux. This results in fragmented BSS, decreasing their utility.

Municipalities using advertiser operated BSS are locked-in. While initial contracts typically define stations, bicycles and service to be provided in exchange for advertising rights, adding further stations and bikes causes problems for a few reasons. Advertisers wish to have stations in high visibility areas, preferably of a certain demographic. If the municipality insists on a station being in a location the advertiser has no interest in, they discourage this with high costs for multiple reasons. Advertisers have no interest in operating a BSS and placing a price on BSS service. This exposes advertiser's black box of costs and revenue. So to impede undesirable station locations the operator may charge high costs justified by the 'high cost of operating the service'.

Returning to our earlier statement that advertising operators have few incentives to maximise BSS usage, this creates a particularly interesting situation. Municipal BSS promoters, often mayors or other elected decision makers, who have bootstrapped their reputation to this symbol of sophistication and sustainability, cannot easily claim their BSS to be a failure lest it reflect poorly on them as well. Although there exists no quantifiable evidence of advertiser operators offering lower quality service than others, it's plausible, and encourages a situation of potential collusion in calling a BSS successful.

Advertisements are not inherently bad, but many provide more than just information and are unethically using sophisticated techniques as an "ultimate influencer" (JCDecaux, 2012) rather than to inform. The most commonly promoted benefits of BSS are health by increased activity, decreased road congestion, emission reductions and general sustainability. Advertisements generally push for consumption and even car-dependent lifestyles (Figure 6.2).

Europe's conventional BSS development was spurred by an advertising innovating to remain competitive in outdoor advertisement. The visibility and associated reported benefits of BSS made them attractive to politicians, happily provided by advertisers at no cost to municipalities. We have seen however, how in Europe the coupling of advertisement and BSS brings legal conflicts and delays to the introduction of the service. Advertisers' goals also differ from municipalities', which is locked in with the technology,

Figure 6.2: Car advertisements on bicycle sharing system station billboards in Luxembourg City.

creating in some cases fragmented BSS of decreased utility.

Europe's BSS development influenced North America (Parkes et al., 2013). The Portland Yellow Bikes developed in 1994 were inspired by Amsterdam's White Bikes. The motivation to develop Yellow Bikes however was simply to have free and convenient bicycles available. While the system gained a lot of publicity, the maintenance required and thefts rapidly put an end to the system. A few other systems in North America also dabbled in early generations of BSS or small conventional systems, such as Washington's SmartBike DC, but it wasn't until 2009 that Montreal's Public Bike System Company (PBSC) deployed the BIXI (BIcycle taXI) BSS, with 300 stations and 3,000 bicycles, that larger systems began to appear.

The rapid deployment of BIXI technology in North America may be due to Washington's 2008 SmartBike experience discouraging the use of advertising companies. Clear Channel deployed a small 10 station 100 bicycle system as part of a street furniture contract but had no interest in developing it further when the municipality desired to do so (Klein, 2015). At an impasse, the system was abandoned and BIXI and Alta Bicycle Share collaborated to provide the modern, flexible and potentially less constrained Capital Bikeshare (CaBi). Four BSS launched in 2010, Denver and Minneapolis, both operated by non-profits, Washington, operated by ABS, and Mexico City, run by Clear Channel, after which advertisers have had little success in North America. The absence of advertisers from North American cities is due to two additional factors. Many mayors expressed dislike for advertisement linked with street furniture and the demand and value of street advertising decreased sharply following the 2008 economic crises, reducing advertisers' bidding for such contracts.

Using BIXI technology Alta Bicycle Share (ABS) became North America's regular operator for large cities, serving Washington (2010), Boston (2011), New York City (2013), Chicago (2013), San Francisco (2013) and Seattle (2014). A second technology supplier, Trek/BCycle, has been present in many more cities but typically for smaller systems and often operated by non-profits. An interviewed American BSS professional states ABS' success is due to having applied PBSC technology, "the golden standard" of BSS, and being "fortunate to have good staff"[2]. Likely, ABS having an experienced staff offering to manage systems while selling trusted technologies was responsible for their rapid growth. More recently operator CycleHop has grown rapidly using various technologies, one of which, Social Bicycles, is particular for being a flex system, similar to those present in Germany, but with optional stations.

In 2012 PBSC made a decisions which caused disruptions and opportunities for North American BSS development. Believing they were being overcharged they terminated early their relationship with 8D, the company providing BIXI with all the technical components, and began developing a new solution internally. Besides the 26 million dollar lawsuit filed by 8D, later dismissed (Martineau, 2012), BIXI's replacement technology was inadequate causing Chattanooga's system significant difficulties and motivating New York City's (NYC) launch to be delayed (Sadik-Khan and Solomonow, 2016). Mismanagement by Alta Bicycle Share and PBSC's misrepresentation regarding the state of their newly developed technology led to delays and complexity for NYC's BSS deployment, almost to the point of being scrapped entirely (Sadik-Khan and Solomonow, 2016). In early 2013, with NYC still to launch, Alison Cohen, ABS's president, left the company to later found Bicycle Transit Systems (BTS) with other important members of ABS (Andersen, 2014). When NYC finally launched in late May 2013 some problems were still present but the system was considered a success (Sadik-Khan and Solomonow, 2016). Meanwhile PBSC was struggling with delayed repayments and the destruction of uninsured assets caused by Hurricane Sandy. PBSC filed for bankruptcy in January 2014. Shortly after, ABS formed an alliance with 8D to provide alternative BSS technologies. A Montreal investor purchased PBSC and restructured it over the following year, causing BIXI technology shortages during that time.

Unlike many other BSS in North America, NYC's bicycles and other infrastructure were owned by ABS rather than the municipality. The delays caused by PBSC's technological complications and the invested capital in NYC caused ABS to be financially strained by early 2014 (Flegenheimer, 2014). To worsen their situation, in April 2014 ABS lost the Philadelphia BSS contract to BTS which now had some of their key former employees (Andersen, 2014). Until then ABS had dominated service provisionment for larger BSS deployments in the United States. In addition to this, ABS's 2013 contract to provide BIXI bikes for Vancouver's 2014 system fell apart due to PBSC bankruptcy. These factors deprived ABS of needed capital and in October 2014 investment group Bikeshare Holdings bought the company, changing its name to Motivate (Chappell, 2014).

Similar to Europe's advertiser lock-in, many North American BSS using PBSC technology found themselves locked in with no technology provider available following the bankruptcy. System expansions were delayed in San Francisco, Chicago, Washington, New York City (NYC) and other cities (CBS SF Bay Area, 2014; Goodyear, 2014). Motivate, now with new capital and desiring to expand many of its systems was con-

[2]New companies have since entered the market and others upgraded their technology.

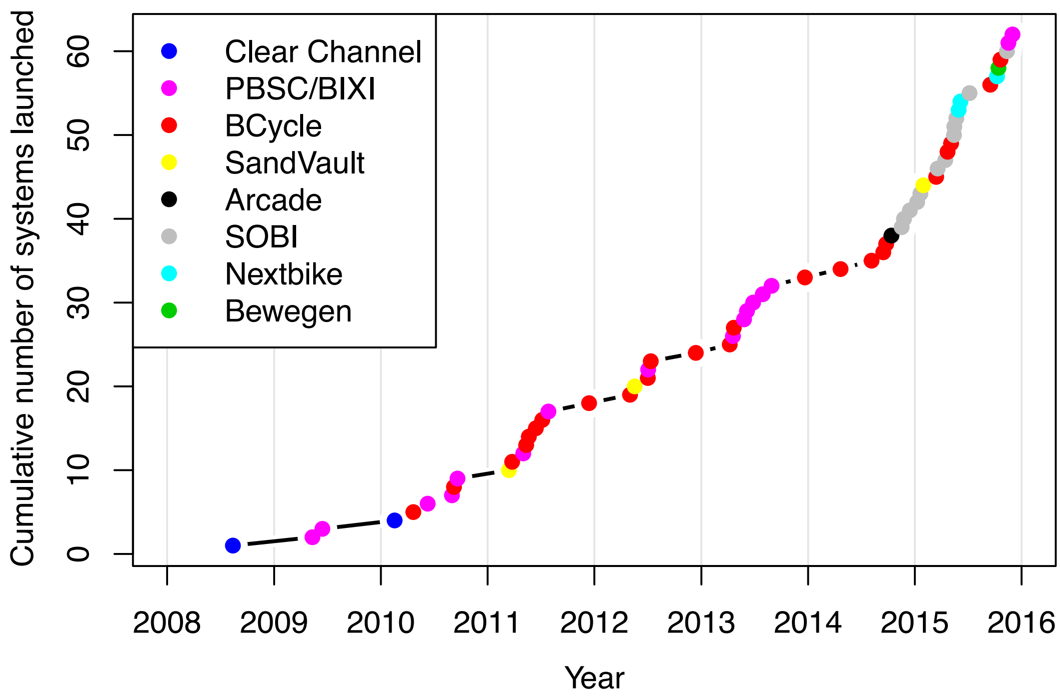

Figure 6.3: Bicycle sharing system deployments in North America according to technology provider.

strained. Motivate replaced NYC's software with 8D's in early 2015 to improve BSS usability, reliability, management and diagnostics (Miller, 2015) and had new bicycles and docks manufactured in China and Detroit (Peters, 2016) despite the expected patent infringement lawsuit from PBSC (Baril, 2015).

In terms of BSS deployments, North America is at least five years behind Europe, 2015 being the largest year so far (Figure 6.3). Despite the common perception promoted that BSS have been successful in North America, with rare exceptions such as Seattle, Canada and the US both have grounds to re-evaluate this perception. All Canadian BSS have had difficulties. Vancouver's BSS initially planned to launch in 2012 has been repeatedly delayed until its progressive launch in the summer of 2016. Ottawa closed their Bixi system and changed to Social Bicycles in 2015. Toronto's system stuttered due to a mayor who viewed cyclists as a nuisance, changing operator to Motivate following PBSC's collapse and unable to expand due to obsolete technology (Spurr, 2015). Montreal has been consistently well used but at great cost to its tax payers following its bankruptcy and failure to repay $15 million in loans (Bleiberg, 2014; Vailles, 2014).

Meanwhile the US has many BSS with low usage, such as in Fort Worth, San Antonio, Chattanooga, Fort Lauderdale, Boulder, Charlotte, Nashville and Houston (Chapter 5). Seattle is perhaps the first system to attract much media attention as it came to the brink of bankruptcy before being purchased by Seattle. The cause of the deficit has been claimed to be unmet expectations of financing, debt repayments, insufficient income from low membership counts and governance structure (Bush, 2016; City of Seattle, 2016b; Westneat, 2016). The City of Seattle BSS managers claim the system should have been publicly owned rather than by a non-profit (City of Seattle, 2016b) that then sub contracted to a for-profit operator. City staff comments hint that hilliness may be a factor and are exploring electric bicycles in the 2016 request for proposals (City of Seattle, 2016c). Surprisingly there is little mention of Seattle's helmet requirement as a cause for low use.

So while BSS started as an ineffective protest to car pollution, anti-consumption and part of the sharing economy, it has been popularized in Europe by advertising companies. Meanwhile in North America, the 'gold standard' of BSS tech, PBSC, developed by a non-profit subsidized by the City of Montreal, went bankrupt, costing the municipality millions, only to be purchased by a real estate developer. Alta Bicycle Share, founded by cycling enthusiasts and operator of larger BSS, suffered from PBSC's collapse leading to their purchase by an investment firm. The evolution of BSS can, as a result, be summarized as the corporatization of a democratic concept initiated by non-profits and cycling enthusiasts.

6.4 Discussion

There exists extremely little critical or qualitative analysis of BSS. White papers have effectively summarized the large recent developments of quantitative analysis (Fishman, Washington, and Haworth, 2013; Fishman et al., 2015; Ricci, 2015) with minor mention of BSS existential issues. The analysis of Paris' BSS development and underlying conflicts of privatisation and capitalization of public space (Tironi, 2011; Tironi, 2014) present the complex reality between between political party beliefs and the ability of the public to comprehend them, leading to political parties forced to support policies, such as advertising, they disagree with. Nitschke (2015) provides a much needed description of German BSS, largely ignored in the literature, and focuses on the development of Munich's most recent system while well articulating conflicts of interest between BSS actors.

In this section we further discuss the issues raised through the European and North American case studies presented. We begin by looking at BSS reported benefits, purpose and success metrics before focusing on some specific issues relating to equity, lock-in, advertising, public participation, rebalancing and helmets. Finally we discuss how politicians and businesses use BSS for ulterior outcomes than true pro-cycling initiatives.

6.4.1 Benefits, purpose and success

Bicycle sharing systems are promoted based on benefits but often not given a distinct purpose. Without a clear purpose definition or goal the claim of a system being a success cannot be questioned. From interviews many stated potential benefits of BSS were reoccurring:

- Provide alternative transport mode to the car.
- Economic and environmental benefits.
- Air quality improvements.
- Normalize the image of cycling.
- Increase mode shift to private cycling.
- Reintroduce the joy of cycling.
- Increased accessibility.
- Transport resilience and convenience.
- Decrease road congestion.
- Reduce overcrowding in buses and subway.
- Complement other modes of transport.
- Health.
- Promote tourism and recreation.

As we mentioned in the introduction, some suggested benefits of BSS are negligible, inconsistent or unproven. With large amounts of data tracking every trip's distance[3] and duration, operators can and do interpret aggregate sums to promote and support their system. An American operator states "a lot of the stats we report, like calories burned and miles travelled, [are] an extrapolation based on formulas not real actual data, it's our best guess." Claims of success based on estimates reflect positively on decision makers, operators and advertisers associated with the system. A closer look at the interpretations of many of these data press release statistics however reveal an ignorant or deceitful conversion of data to measurable benefits.

Miami Beach's operator claim CO_2 reductions of almost four million metric tons in two and a half years (Decobike, 2013), equivalent to the total emissions of Uganda in 2011 (The World Bank). The ludicrousness of the claim is better revealed when normalized by distance travelled yielding CO_2 reductions of 270 kg per kilometre or 1.2 metric tons per trip. Boston's celebration of four years of service is similarly fictional with CO_2 reduction estimates of 0.924 metric tons per trip and 412 kg per km travelled (Hubway, 2015). These values make Luxembourg's exaggerated CO_2 reductions of 830 g per trip and 208 g per km travelled trivial (JCDecaux, 2011). Using an optimistic 20% of trips replacing car use (Fishman, Washington, and Haworth, 2014) with an emission rate of

[3]Most BSS do not have a GPS and do not track path, only trip origin and destination.

140 g CO_2 per kilometre yields emissions of 56 metric tons rather than the 415 suggested by JCDecaux for Luxembourg. This emission reduction estimate discounts rebalancing vehicle exhaust which in some cases exceeds reductions (Fishman, Washington, and Haworth, 2014).

Bicycle sharing systems are susceptible to the same technocentric 'green fix' problems as other sectors (Long, 2015; While, Jonas, and Gibbs, 2004). The simplification of environmental sustainability to CO_2 reductions creates demand for measurable solutions rather than potentially more effective but unquantifiable methods. The use of metrics encourages measurable gains, independently of the quality of their impact (While, Jonas, and Gibbs, 2010). So rather than be effective at their stated goal, they represent a proxy. In the context of a BSS promoting emission reductions, number of trips and overly optimistic tons of CO_2 saved are quoted while trips largely only replace public transport, walking (Fishman, Washington, and Haworth, 2013). Similarly, a BSS promoting health benefits will quote calories burned while already healthy and active people use the system. Bicycle sharing systems by their nature of digitizing individual urban transportation create large amounts of data allowing estimates of CO_2 emission reductions and calories saved, among others, to be used for promotion by decision-makers. Likewise however, this same data can show how overstated benefits may be.

Bicycle sharing systems should be *part* of a strategy to increase cycling modal share and not a strategy in itself (Beroud and Anaya, 2012). In some situations, especially politically, BSS appear to be used as stand alone promotions of cycling and its multitude of benefits. The last two American Democratic National Conventions in 2008 and 2012 funded BSS deployments in Denver and Charlotte (Marshall, Duvall, and Main, 2015). Tironi (2014) mentions Paris' system deployment was rushed before the election and the adoption may have related to political motivations rather than from a cycling promotion strategy. London's former Conservative mayor, Boris Johnson, consistently associated himself with the system despite it being initiated by the former Labour mayor Ken Livingstone. When mayors look to provide a BSS, advertisers, such as JCDecaux or sponsors such as Barclays, Santander or Citibank, are happy to facilitate it in exchange from the profits of associating their brand and their clients' with, mainly, environmental sustainability.

While increasing cycling in London is mentioned as one of Transport for London's (TfL) goals of their BSS, over 200 million pounds was spent on their system in two years (Hill, 2012), money that was otherwise largely meant to be spent on cycling infrastructure improvements. Perhaps this is politically a wise investment as it supports cycling without the political disruption that equal investment in cycling infrastructure would have caused due to parking or lane reassignments. Similarly, the 2009 adoption of a new BSS in Munich was blocked, partially due to the politically infeasibility at the time to suggest reductions in car parking (Nitschke, 2015).

One of the main signs that BSS are being used as symbols of municipal sophistication and sustainability awareness is the pervasiveness of small systems with very few bicycles and stations. Just like having one bus line does not constitute a transit supportive government, neither does a small BSS demonstrate an authentic cycling and mode shift initiative.

Bicycles sharing systems imply 'sharing' and being part of the sharing economy. The sharing economy is a broad democratic resource sharing concept of reuse, community and sustainability outside traditional economic transactions (Matofska, 2016) with many similarities to promoted BSS benefits. Comparing a traditional bike rental service to a BSS, the duration and frequency of use differentiate them, yet the transactions are much the same. Many BSS are devoid of sharing. No individual provides belongings for common use without expectation of (economic) reciprocity, ownership is often by a capitalist corporation expecting something in return. Advertiser operated BSS are strongly capitalistic, profit seeking and encouraging consumption. Alternatively, the original Amsterdam White Bicycles was very much part of the sharing economy as individuals provided bicycles to be freely shared with other residents for the greater common good in order to reduce pollution and consumption. According to Belk's (2010) definition of sharing, advertiser operated BSS are a commodity exchange, at the opposite extremity of sharing, while systems owned by non-profits and municipalities fall somewhere in the middle as aspects related to revenue generation and advertisement make BSS inclusion into the sharing economy, and associated benefits, fuzzy.

How interviewees measured BSS success is of much narrower scope than the benefits:

- Transportation alternative.
- Economic, breaking even.
- Number of memberships, trips per day or trips per day per bicycle.
- User satisfaction through surveys.
- Normalizing cycling as a mode of transport for all, beyond lycra and messenger niches.
- User demographics to mirror city demographics.

What defines a BSS' success depends on the municipality stating clear goals. When asked the purpose of their system, a European city's system manager responded "That's a very good question. I don't think I've been asked that before and I've done a lot of interviews." before describing some of the benefits, cycling modal share, equity and congestion. This exemplifies well how BSS are perceived as bundles of benefits rather than tools for a specific goal. A BSS may be helpful in popularizing a mayor but this is unlikely to be a published goal. As it's easy to promote the many potential benefits of cycling and BSS, governments may prefer, and find it safer, to advertise possible benefits rather than goals. Some BSS do have clear goals such as those defined above, but we argue that many of these goals are not in-line with a larger environmental and social sustainability initiatives or senseless on their own. Being economically self sustaining has little purpose without a larger aim. In the case of NYC's BSS which has the goal of providing a transport alternative (La Vorgna, Marc et al., 2013), the system's simple existence suffices in calling it a success. This is similar to an official calling their system a success at launch (Zazueta-Castro, 2015).

The number of trips or trips per day per bicycle is regularly used by operators and media as a measure of success (Bialick, 2013; Cripps, 2013; Goodyear, 2013; Paris.fr, 2013). Similarly flawed to user satisfaction as a measure of success, these metrics are fundamentally inadequate due to who the service is most helping. In the case of BSS it is more commonly wealthier young white men, not reflective of the population distribution (Buck, 2012; Fishman, Washington, and Haworth, 2013; Goodman and Cheshire, 2014; Murphy and Usher, 2014; Ogilvie and Goodman, 2012; Ricci, 2015; Woodcock et al., 2014), while advertising to all residents or using public funds, often both, to offset costs. So while Chapter 5 reveals some high performing BSS, they may still be unjust by providing further advantageous to the already privileged.

If many of the proposed BSS benefits are unfounded or inconsistent and targets for success (goals) irrelevant or unjust, the question arises as to what purpose remain of these systems. There are some indisputable benefits however. Non-cyclists worry about bicycle theft, maintenance and therefore unsurprisingly have more positive feelings towards BSS use than private cycling (Curto et al., 2016). As BSS negate private cycling fears, it provides an effective option for lowering the barrier to utility cycling for non-cyclists. These systems also clearly increase the visibility of bicycles on the street, even if only docked at stations, and encourage a more casual use with riders wearing unspecialised clothing, helping normalize the image of cycling.

Bicycle sharing systems are also convenient, but as we said, particularly for some demographics more than others. Further more, analysis of BSS operations, specifically rebalancing, shows that disproportionate resources are spent supporting commuter behaviour rather than BSS as a convenience (Chapter 4). Rebalancing facilitates but also generates new trips. Extensive rebalancing between transportation hubs and CBD encourages a costly dependence that is not offset by membership fees. Commuter BSS use is offset by other members and alternative income sources such as advertising. Were BSS to be used as tools of convenience, with reduced rebalancing and costs, alternative revenue sources would likely be less necessary or decrease the need to target wealthier demographics to balance costs and perhaps be more just.

Many municipalities that now have large BSS have previously abstained from the large cycling marketing that now surrounds these new systems. Claims that BSS lower the barrier to cycling (Curto et al., 2016) may simply be the result of marketing. Had similar effort been made promoting private utility cycling along with investment in infrastructure rather than a new technology, perhaps a similar outcome would have resulted with greater environmental and social benefits and less privatisation of public space and advertising. So while BSS has some benefits it is unclear if the opportunity cost would have been more effective spent on regular cycling initiatives.

Bicycle sharing systems are not necessary to developing large cycling modal shares, as has been shown in the Netherlands and Denmark. Cycling initiatives and infrastructure can be largely attributed to this outcome. While BSS can be catalysts for cycling modal shift for a privileged demographic, safe and comfortable infrastructure is required to broaden its potential. A more just success of a BSS is dependent on effective political support encouraging funding of necessary and equitable infrastructure improvements among many other societal issues. Fundamentally some demographics "have no access to healthy food, so there's a large obesity epidemic in these neighbourhoods. So you can't expect these people to hop on a bike ... it's a societal issue." (American BSS consultant)

6.4.2 Equity, health and public participation

Beginning in the 1890's bicycles provided a mode of transport enabling social and gender equity (Horton, 2006). Any mode of transport that reduces the ease or cost of travel has similar outcomes. The car's twentieth century rise to dominance effectively privatised large amounts of public space by requiring personal vehicles to use roads. Alternative modes of transport, such as trolleys, cycling and even walking, were relegated in importance or actively degraded or destroyed, decreasing equity. Currently in the US, BSS are regularly being promoted as increasing equity[4]. This being effective relies on system stations being available in areas of lower income residential areas and near places of employment, having comfortable and safe routes to travel along and a reasonable distance.

Due to accessibility to city centres having become popular and increasingly expensive in the last few decades, lower income groups are located in lower density areas farther from the city centre and effective transportation. In the case of Washington "because of transit access ... metro rail corridors are very expensive to live in. Therefore you only have well-to-do people living in these corridors." (American BSS consultant) Accessibility has value and is capitalized upon. As BSS usage intensity relies on higher population and employment density, lower income areas are less likely to be provided stations (Duarte, 2016). These communities, as a result, do not have the same opportunity to use BSS regardless of whether demand exists. The exists in fact the danger that BSS stations placed in lower-income neighbourhoods increase property values and rents displacing vulnerable residents.

A comprehensive effort in Minneapolis has shown that ongoing investment and effort to promote BSS use has had limited benefits (Kretman Stewart, Johnson, and Smith, 2013). Placing stations in lower income areas has little effect as there exist many other barriers, such as having a credit card and internet-access, street safety and ability to carry groceries or children (Kretman Stewart, Johnson, and Smith, 2013). A few BSS also require smart phones with data plans to use the service. In some lower income communities cycling is associated with children and being unable to afford a car, making demand for BSS utility cycling very low. Analyzing online crowdsourcing for station suggestions, (Piatkowski, Marshall, and Afzalan, 2015) shows that less input is provided by areas with higher Hispanic and African-American residency rates. It is however not clear if this is due to lack of access to the technology or due to reduced interest.

Some lower income communities, such as Portland, home to Alta Bike Share, protest

[4] Social equity in relation to BSS is much less discussed in mainland Europe.

the development of cycling infrastructure in their neighbourhoods (Benesh, 2014). They oppose the investment as they perceive it to serve outside interests, likely increasing the rate of gentrification, while their community has been starved of investment that locals desire. The problem stems from investment need being decided by wealthier political, media and business leaders, who do not have stakes in lower income communities (Benesh, 2014; Mercier, 2009).

Density and distance to employment make BSS ineffective in areas lower-income residents are often present, making these systems ineffective in increasing equity. Besides the further privatisation of public space, BSS which are privately funded and operated reduces likelihood of effective equity initiatives. Rebalancing analysis (Chapter 4) has shown that service quality is more allocated to income generating areas. Additionally, many American cities purchase BSS assets using federal grants while often stating that no public money is used. This results in social subsidy of a service, often operated by a private company, facilitating urban transport of a privileged class.

Aversion to public spending in the United States (US) for public transport and advertiser BSS provisioners requires membership fees to be higher than in Europe in order to cover costs. These higher membership fees further impact equity goals. Some BSS, such as Chicago, Boston and Washington, offer discounted memberships that do not require credit cards, one common barrier to membership for lower income individuals, among others (Kretman Stewart, Johnson, and Smith, 2013). While other factors we mentioned are a barrier to use, the low number of equity memberships purchased (Buck, 2012) suggest there is an effort to increase equity but limited demand. Boston provided subsidized memberships at system launch in July 2011. By December only 72 of 600 $5 memberships were claimed (Buck, 2012). This raises the question of what the needs of socio-economically deprived areas are. Residents may have more utility for other forms of transit such as more frequent bus service.

While municipalities speak of reversing inequalities, some BSS operations create them. Many employees of Chicago's system where employed with irregular or short work shifts intentionally resulting in part time status, denying employees of full-time benefits (Steinberg, 2014). These practices limit worker income equity, stability and potentially health. As a result workers from some of the large American BSS, such as Boston, Chicago, Washington and New York City, unionized. Miami's BSS, which does not actively promote equity, is operated by a private company in areas of high revenue while hiring from a low income area (Buck, 2012).

So the fundamental difficulty in reconciling BSS with socio-economic equity is that system use, related to revenue, relies on higher density of residences, employment and services (Duarte, 2016). Something that over the last few decades has been increasingly in demand, expensive and exclusive, resulting in lower income, and associated ethnicities, having reduced access to the systems. Bicycle sharing systems are best for distances beyond walking comfort but not so far as to exceed the free period, typically of 30 minutes, or when bus or rail travel is faster and easier. There exists some exceptions to this however, Montreal's system seems to provide better service to lower income areas (Fuller, Gauvin, and Kestens, 2013).

Figure 6.4: Helmet solutions for Brisbane's and Vancouver's bicycle sharing systems (Photos by Julia Affolderbach and Pascale de Rotrou).

While we discuss mainly socio-economic equity, gender inequality is also present. Women are less likely to use BSS for utilitarian travel (Beecham and Wood, 2013; Goodman and Cheshire, 2014; Ogilvie and Goodman, 2012) as they are more risk averse but also more susceptible to accidents (Woodcock et al., 2014). The imbalance in BSS use likely results from unappealing or unsafe cycling infrastructure (Garrard, Handy, and Dill, 2012).

Helmet requirement laws have been partially blamed for low BSS usage in Australia (Fishman et al., 2014). Seattle and Vancouver, which launched BSS in late 2014 and mid 2016 respectively, are the only other known instance of having a system operating with a helmet requirement law present. Seattle's system has experienced low usage despite providing free clean and accessible helmets. Vancouver's system provides a simpler helmet solution by having the helmets attached to the bicycles similarly to what is done in Brisbane (Figure 6.4). This solution appears to defuse the issue without actually solving the problem as it's unlikely people will use the provided helmets due to hygiene or dampness.

A recent North American study focusing on BSS safety found users less likely to be injured than when riding a private bicycle (Martin et al., 2016). The reasons suggested relate to the sturdiness and slowness of the bicycles preventing fast or risky behaviour, riders typically being more careful and improved cyclist visibility and lighting. As BSS users typically wear helmets less often, helmet use was not a found to be a factor in reducing injury rates (Martin et al., 2016). Mexico City, which launched in 2010, the same year as Brisbane and Melbourne, clearly felt helmet legislation would be a barrier to BSS use and annulled the requirement. No BSS with helmet requirement law has had usage of more than one trip per bicycle per day (Chapter 5). If BSS with helmet requirement laws consistently under perform, it's unclear what purpose their adoption and investment has in Seattle and Vancouver.

In July 2016 a woman, wearing a helmet, was the first BSS confirmed fatality in the US (Strum, 2016). There has been one fatality in Montreal, wearing a helmet (Shields, 2014), and two in London. All these women were killed by drivers of large trucks (Richards, 2015; Strum, 2016). One of the London fatalities was on a designated Barclays Cycle Superhighway (Cycling UK, 2013), suggesting just how inadequate some sections may be in providing safe and efficient travel in London. The other North American fatality was in Mexico City, a man was run over by a bus (Monroy, 2014). Helmets were not consistently worn but would not have helped in any of the cases above due to the size of the vehicles. A helmet may have prevented the only other recorded North American fatality, in Toronto, where a BSS rider attempted a stunt in a skateboard park (Kauri, 2013).

It's unknown how often fatal accidents occur to BSS users in the rest of Europe, but they happen with much greater frequency in Paris than all of North America combined (Le Figaro, 2014; Le Nouvel Observateur, 2009; Le Parisien, 2015). There were 7 fatalities within the first two years of Paris' BSS launch (Le Nouvel Observateur, 2009). Across both continents women tend to be the major victims, killed by drivers of large trucks or buses and the inadequacy of existing cycling infrastructure.

6.4.3 Public participation

Residents suggesting BSS station placements through workshops or public participation geographic information systems (PPGIS) (Sieber, 2006) is common in North America since Washington's 2010 system launch. Online maps typically allow the submission of locations, voting for other people's recommended locations and commenting on the quality of locations. Many systems have been using these not only for initial deployment but for system expansions as well (e.g., Washington, New York City, San Francisco). The use of PPGIS or workshops in Europe is unheard of, resulting in typically faster deployments.

An interviewed American BSS non-profit director was critical of PPGIS input, much preferring workshops or direct contact with resident or business associations to build support for implanting stations in neighbourhoods. Additionally, Piatkowski, Marshall, and Afzalan (2015) found that BSS public participation doesn't equally represent city demographics. An additional critique is whether PPGIS and charrettes are simply tools to promote forthcoming BSS, satisfy resident's desires to be consulted and potentially pacify or disarm would be NIMBY complainers (Sadik-Khan and Solomonow, 2016). Bicycle sharing systems require a dense structure of stations already constrained by urban availability and underground utilities. The extensive public outreach in NYC was instrumental in supporting the city for a multitude of lawsuits filed against the city regarding station location (Sadik-Khan and Solomonow, 2016). It's unknown whether dissatisfied residents attended workshops. Regardless of citizen input, city planners in interviews remarked they generally found optimal locations to be obvious without public input due to density and public transport.

Figure 6.5: Protest to advertising billboards at Namur's BSS launch.

6.4.4 Advertising and lock-in

Given there is little evidence to date that BSS provide net environmental benefits (Ricci, 2015), many systems have traded this expectation for increased public advertisement. Advertiser integration into street furniture has created complications for municipalities, caused resident protests (Figure 6.5) and negative impacts on BSS.

Los Angeles' planned 2013 launch was cancelled after realizing that planned revenue through billboards would not be allowed with pre-existing street furniture contracts present (Nelson, 2013). In New York City, where Citibank is the system's main sponsor, locating a large stations adjacent to Madison Square Garden, the main indoor arena for professional sport and entertainment events, was denied due to Chase Bank being a sponsor and competitor to Citibank.

Another aspect of linking advertisement and BSS is the placement of stations. As advertisements are typically located on the back of kiosks, it raises the question of whether stations are optimally placed for advertising or BSS use. This is a complex issue beyond our scope, but it is unlikely optimal station placement and advertising placement have the same criteria. A non-quantitative observation of station locations in Luxembourg City exemplifies this possibility as stations are mainly adjacent to busy thoroughfares and infrequently in denser and quieter residential areas.

How important station visibility is to residents is unclear. Residents are more familiar with their neighbourhoods and learn where stations are or use familiar maps to find stations in less frequently visited neighbourhoods. For tourism and business visitors station visibility is likely of greater importance if they are one of the target users. Station location on main streets may however help promote the normalization of cycling. A Canadian city project manager called their BSS “the best kept secret” due to having to place stations off main streets, on side walks and having no mayoral support.

The operation of BSS in exchange for advertising rights operate as black boxes where BSS costs and advertising profits are hidden. These are clearly lucrative contracts considering how contested they are. The lack of interest by advertisers, who already have the BSS experience and technology, in bidding for independent operating contracts, such as in London, suggests that the revenue from advertising are of a higher magnitude and better investment for capital, no matter how much advertisers complain of BSS expenses (DeMaio, 2009). Additionally, BSS membership and usage fees in Luxembourg, Paris, Dublin and others, all operated by JCDecaux, provide little or no revenue to the operator. This means JCDecaux has little incentive to see more people use their systems as this would only increase their maintenance and service costs. It’s not difficult to imagine how this creates a situation where service level agreements need to be very firmly established and monitored.

While in some cases advertisers compete for BSS contracts, the popularity of the systems, particularly among mayors (DeMaio, 2009) created strong demand. In 2006 Aix-en-Provence agreed to a contract of paying 800,000 Euros a year in addition to advertising billboards. After four years of lethargic use and recognizing that they had been taken advantage of in the contract, they closed the system (Cycle Sud, 2009; Cycle Sud, 2011).

Barcelona is an oddity where Clear Channel operates the system independently of any advertising contract (DeMaio, 2009). Perhaps, similar to JCDecaux in Paris, this provided an opportunity for Clear Channel to demonstrate their ability to operate a world class BSS as a loss-leader and enter new advertising markets. In 2010 Clear Channel launched Mexico City’s BSS, the second largest in North America. Generally, advertisers’ behaviour strongly suggest they only use BSS as tools to enter markets.

Advertiser operated BSS combine contractual and technological lock-in. Bicycle sharing systems run by advertisers who manufacture, own and operate the system can simply refuse to expand the system, as happened with Washington’s system by Clear Channel (2008 - 2011), or make it prohibitively expensive, as occurred in Luxembourg. For non-advertiser BSS technological lock-in is still present. Stations, docks and bicycles purchased by municipalities have physical and electrical communication standards, many of which are patented. This prevents the selection of alternate providers if the cost is considered unreasonable or the company is unable to provide components, as was the case with PBSC following its bankruptcy.

The rental of BSS technology, as is the case for advertiser provisioned BSS and a few others such as New York City, has some advantages. As BSS technology continues to evolve some become obsolete. Toronto had such an issue with their purchased technology being a hybrid between BIXI and 8D, something that no longer existed following their conflict, delaying a desired expansion of the system (Spurr, 2015). When interviewing municipalities, in 2013, some appreciated the experience of ABS but were concerned by the monopoly of operations. The PBSC technology was seen as superior to BCycle by some originally, but now fear being locked-in with buggy technology following the split between PBSC and 8D, preventing future expansions.

When the City of Seattle was deciding whether to purchase their ailing system owned by a non-profit and operated by Motivate, they considered the lock-in effect of purchasing technology that may be incompatible with future potential expansion plans, such as smart or electric bikes (City of Seattle, 2016b). Desiring to expand the system, the lock-in required that future offers greatly outweigh purchasing more of the same technology. Their alternative option was to try selling their unique system (City of Seattle, 2016b), passing the lock-in burden to another municipality.

Having different and incompatible BSS types creates problems for adjacent municipalities adopting different systems, decreasing the potential benefits to citizens relative to a homogeneous system. Despite this obvious outcome the occurrence is increasingly common. Luxembourg, Sao Paulo, New York City, Los Angeles and Santiago (Figure 6.6) are some of the cities where multiple BSS technologies are in proximity to the detriment of the users (Bloom, Heilman, and Brien, 2015; Linton, 2015). This is also very common in Germany due to nextbike and Deutsche Bahn's Call a Bike being present in many cities, however most of these systems have no stations, using free floating bicycles, and therefore not susceptible to this problem.

Santiago, Chile, although outside our case study area, is an interesting example of where technological incompatibility may be intentional. The system provided by Clear Channel is located in Las Condas, a wealthier commune of Greater Santiago, while the other system, from BCycle, largely surrounds it, creating a transportation barrier.

An import factor for municipalities to protect against lock-in would be the selection of BSS technology with an open standard or that belongs to a consortium of competing companies with corresponding components.

6.4.5 Politics and business

Bicycle sharing systems in North America appear to take longer to deploy than those in Europe. This is likely due a more participatory process, an aversion to advertiser provisioned systems, the search for sources of sponsorship and funding and coordination between multiple actors. Advertiser operators interact directly with municipal planning, have little interaction with the public and provide the technology themselves. Paris' BSS launch with 750 stations occurred on July 15, only four and a half months after signing the contract on February 27, 2007 (Paris, 2008).

Although many BSS in the USA claim to not use public money, this is often not true. Municipalities may not use local funds but often receive national grants. Despite public transportation and roads being heavily subsidized, American cultural aversion to public spending and transport subsidy creates a necessity for BSS to be economically successful

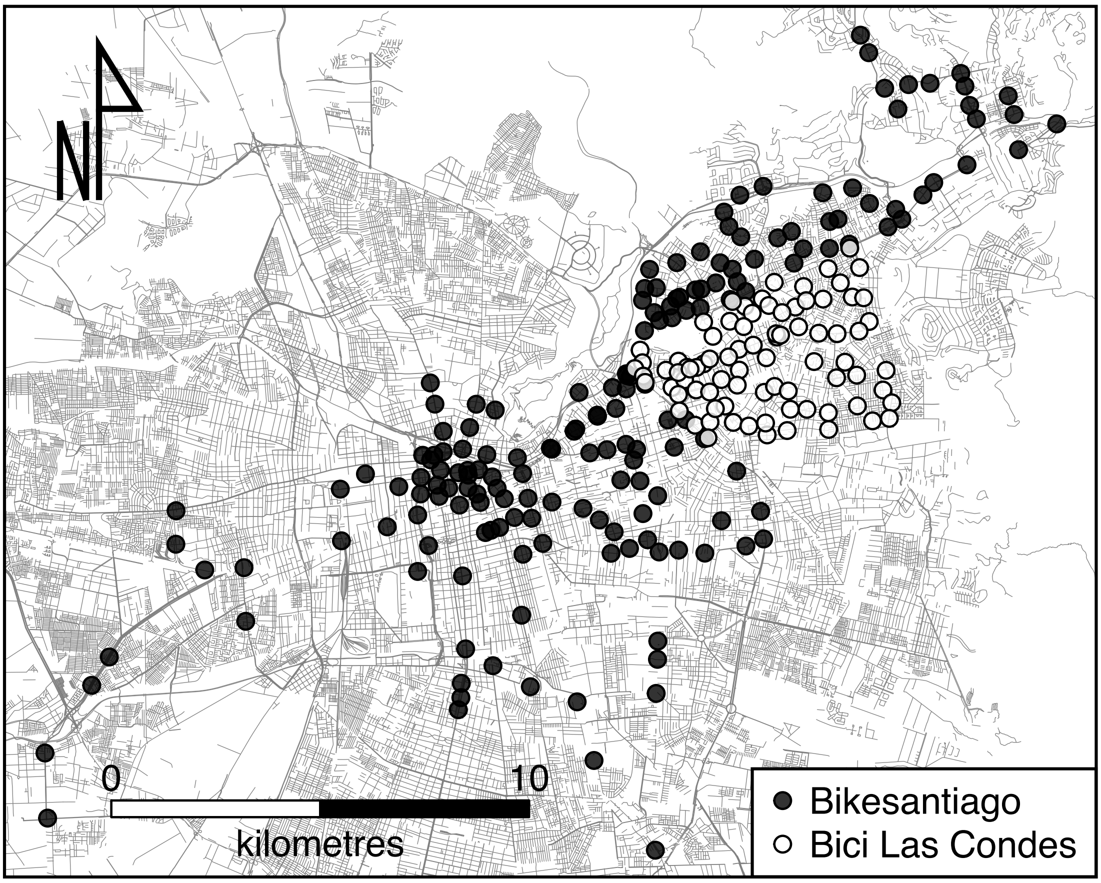

Figure 6.6: Santiago's two exclusive bicycle sharing system coverage areas.

and greater media attention of system performance. Meanwhile European BSS are more likely to be criticised for allowing advertisements into urban spaces. As advertisement pays for BSS, it appears that on both continents the subsidization in one manner or another of these systems is unpopular.

With existing globalization, the 2014 creation of a North American specific BSS association (NABSA) rather than a Western or global organization, is perhaps indicative of barrier to communication between the two continents. North American operators collaborated as they encountered similar problems and technology. Due to many European operators being advertisers which manufacture and operate there own product there likely exists little reason to collaborate.

In Europe and North America some mayors champion their BSS. This has important benefits in promoting use, securing sponsorship funding and developing cycling infrastructure improvements. London's sponsorship was the result of Boris Johnson's personal contact with the head of Barclays (Donovan, 2013). The direct association of mayors to BSS initiatives may be mutually beneficial however. Mayors of Lyon, Paris and London where all re-elected following BSS deployments during their previous terms. The use of BSS for self promotion using the many celebrated benefits is prevalent. Mayors draw on conventional societal problems of health, environmental sustainability, congestion and equity but also build citizen's pride. A good example is Portland's Bureau of Transportation director calling their planned BSS "the largest smart bike share system in North America" (Maus, 2016). Where a 'smart bike share system' contains the IT technology in the bicycle rather than the station. A month later Vancouver responded with an almost identical claim of getting "the largest smart-bike system in North America!" with 1500 smart bikes (City of Vancouver, 2016). Portland, not to be outdone later claimed to be developing "the world's most sustainable bike share system" (Newcomb, 2016; Portland Bureau of Transportation, 2016). This game of technicalities tries to inspire pride locally and advertise sophistication continentally, while factually many other North American 'smart station' systems are of equal potential and much larger (Chapter 5). So BSS are not only used to market themselves as liveable cities (Nitschke, 2015) but compete in sophistication even if it is mundane.

Mayors, operators and technology providers actively promote citizen hubris through superlatives associated with BSS. The CEO of Bewegen, a new eBSS technology provider, pandered to Baltimore during the system announcement (in front of a large parking) stating "the City's residents and visitors deserve the very best. The City's forward-thinking mindset, which will bring pedelec (electric-assist) bikes to its streets makes Baltimore a leader worldwide." (Bewegen, 2016).

McCann (2013) defines *policy boosterism* as a form of policy marketing to promote city policies externally, popularize decision makers associated with policies and polish city image while potentially attracting economic investment. Applying this framework to BSS we see all the same attributes. Paris' BSS initiative, among other cities', has been boasted about and 'exported' internationally (Parkes et al., 2013). Mayors of Paris, London and NYC have strongly associated themselves with their city's BSS. Finally governments and media promote proudly the arrival of BSS and their associated benefits, pridefully suggesting membership of an exclusive club.

As McCann (2013) explains, there are municipalities which supply policy boosterism and others, *extrospective*, which desire to consume policies proved elsewhere due to budget and time constraints. While some BSS deployments appear as part of overall cycling initiatives, such as NYC, the pervasiveness of smaller BSS, of limited geographical coverage in their municipalities, suggest the desire for "quick fix" outcomes rather than a larger locally adapted solution. "In some cases the municipality will put funding into bike-sharing even before they have a sufficient bike infrastructure network. That's not the best way to do it." (American BSS consultant) Bicycle sharing systems are less controversial than cycling lanes and the associated removal of on-street parking or road lanes. Whether decision-makers select BSS as a tool to build support for cycling, lowering future barriers to the necessary cycling infrastructure, or an end in itself, is unknown. Without adequate cycling infrastructure BSS usage is likely be biased towards more experienced and risk averse riders, but fundamentally, unjust.

Whether effective or not, BSS are being used to promote cities externally. In Minneapolis, some system sponsors see BSS as helping develop a more vibrant urban core leading to better recruitment of talent by attracting Millennials. New York City's Mayor Bloomberg, at the 2013 launch of their BSS, stated their system would "help to sharpen NYC's competitive edge versus other global cities like Washington D.C., Paris and London" (Bloomberg, 2013) and department of transportation Comissioner Sadik-Khan declared "Mayor Bloomberg has brought NYC streets into the twenty-first century and prepared them for the century to come" (Bloomberg, 2013). These comments suggest BSS adoption was partially extroverted in an attempt to promote the appearance of NYC as a modern city and perhaps attract economic investment as well.

A modern city is becoming associated with having a BSS (Ó Tuama, 2015). In an ongoing effort by cities to appear sophisticated and innovative, a simple BSS may no longer suffice as we can see by Portland and Vancouver's play on semantics to extract value from a no longer innovative technology. We may as a result see a shift to BSS with electric BSS (eBSS). JCDecaux and PBSC, the two largest BSS technology providers in Europe and North America, have recently developed eBSS. The push for eBSS is not pushed by operators but as a response to cities looking to distinguish themselves further by appearing more sophisticated and environmentally sustainable. Some cycling advocates do not see electric bicycles as a beneficial mainstream option for urban transport (Colville-Andersen, 2014). As we have seen, BSS are not consistently implemented out of desire for a transition to sustainable mobility but to increase local pride and international reputation.

We have discussed how administrations benefit from association with BSS, but businesses also ride the sustainability promotion wave. Technology providers promote environmental benefits of their systems, stating they "transform drivers into cyclists" (PBSC, 2016). Advertiser provisioned BSS allow the greening of the operator, such as JCDecaux, but also the association of sustainability and health with companies advertising through sponsorship, such as Barclays or now Santander (London) and Coca Cola Zero (Dublin), or ads directly on bicycles. Operators explicitly market the association of advertiser brands with a “healthy, sustainable and community-based project” (Hamilton Bike Share, 2015). Nitschke (2015) summarizes well the core problem of advertisement associated BSS as “being a premium infrastructure developed by private companies on public space in order to capitalize on an ‘urban elite’, facilitated by narratives of a sustainable city within the sharing economy” (p. 41). In addition to this is the privatisation of a new public transport system operating on public space, with no debate as to whether the service should even be run by a public organization.

While BSS can serve as mechanisms to promote a mayor and administration, a reciprocity exists where system users develop an expectation from government. Cycling organizations in Dublin strengthened their demands to government for decreased speed limits and cycling infrastructure to take better care of potentially vulnerable BSS users that the administration had created (Ó Tuama, 2015). So BSS could also be seen as Trojan horses to cycling infrastructure. Whether some cities adopt BSS as part of policy boosterism but are then coerced into providing the infrastructure socially, environmentally and economically required is an exciting question.

6.5 Conclusion

There exists a large variety of bicycle sharing system (BSS) structures consisting of different actors with contrasting motivations, funded publicly, privately or by advertising. Generalizing critiques of BSS becomes difficult as a result. While the many benefits of BSS are constantly promoted, a purpose or goal is less consistently present or nebulous, such as providing a new transportation alternative. The fundamental problem is that surveys in the literature have consistently shown BSS users to typically be younger, male, white and wealthier individuals. User demographics are not representative of their municipalities, making public expenditure and allocation of space benefit the already privileged.

The sustainability of BSS is regularly promoted. Yet the term sustainability is so pervasive and without opponent that it is has become apolitical, mainly serving as a banner to validate any initiative with rosy outcomes of environmental, social and economic benefits. This panacea becomes vague however when specifying who will gain from these initiatives. Bicycle sharing systems are no different. Investment firms operate BSS with the sole purpose of increasing investor wealth. Wealthier white males are the predominant users of these systems. Public space is utilized, and privatized through advertising, for this new exclusive form of transportation. These systems serve as symbols of sophistication, aiming to attract talent and investment. Meanwhile residents without access to the service, either due to safety or income, are subject to increased advertising and public expenditure on an exclusive service. Most residents of a city with a BSS will be minimally but negatively impacted. The pacification of residents is carried out by building pride through the use of superlatives in describing their BSS by operators and decision makers or association with world class cities, while reminding of their sustainability.

Land use prioritizing cars is exclusive as it typically requires a private vehicle. The bicycle greatly facilitates accessibility and lowers the barrier to relatively rapid transport. As a result bicycles were originally a symbol of female independence and, following the first world war, socialism. Most BSS now however provide an exclusive service. Bound to be economically viable, due to hypocritical resistance to public transport subsidy, BSS are located in dense urban cores, best suited for efficient BSS usage. The limited safety of urban cycling due to limited cycling infrastructure combined with BSS location results in wealthier white male users being largest user demographic.

So while BSS are used predominantly by one segment, they are often accompanied with advertising, occupying public space and promoting consumption and car dependent lifestyles, opposing the promoted environmental sustainability, emission and congestion reduction benefits. The many suggested benefits have served as vehicles for advertising to enter urban cores and capitalize on public space.

The sharing economy is a concept of mutual benefit through decreased consumption and expenditure of material goods by joint use. Bicycle sharing systems appear to fit the definition yet the profit generation aspect present for many systems counters this. Systems managed by municipalities, however, are more part of the sharing economy despite their unjust demographic imbalance in use.

The phenomenal increase number of BSS in European and North American in the last ten years can be partially explained by policy boosterism. Early cities such as Paris saw the potential in using BSS to market themselves as an innovative and progressive, sustainable city, addressing local air quality and congestion concerns, while popularizing their mayor. Other municipalities imitated Paris and New York City by importing 'tried and true' BSS as quick solutions to address similar concerns but also health and equity. Aside from some BSS promoted benefits being contested, many of these systems are too small to provide much change. Politicians use this new technology to provide a solution to environmental challenges, rather than encouraging societal change, such as removing parking spaces or a larger reallocations of urban public space to be inclusive with equitable transportation options.

Justification of the continued existence of BSS requires a larger goal benefiting all sectors of society while decreasing expenditures towards exclusive use. Bicycle sharing systems lower the barrier to the discovery of cycling as a sensible mode of utilitarian transport. To be equitable this requires BSS be part of larger cycling initiatives that increase cycling infrastructure quantity and quality while reducing BSS operations facilitating their use as a commuter service and more as a convenience, and finally, decoupling advertising from operations.

Once proper infrastructure is present and decoupled from profit generation, BSS can ethically serve as catalysts for private utility cycling for a broader demographic. The danger is that if BSS continue to be used as symbols of change rather than tools of change their acceptance and potential will be tarnished.

Chapter 7

Conclusion

This thesis research explores bicycle sharing systems (BSS) through quantitative metrics and qualitative analysis. Due to existing BSS metrics being incomparable we devised a metric from open data to create a measure of success. By determining a system is a failure advances discussions towards effective cycling infrastructure beyond the promotion of a symbolic technological solution to larger societal problems. Interviews in Europe and North America and media analysis provide a description of BSS developments outside the golden success narrative promoted by technology providers, operators and municipalities.

The following section summarizes the results from our trip estimation (Chapter 3), rebalancing in practice (Chapter 4), the performance of existing BSS and determinants of use (Chapter 5) and finally, from an alternative perspective, the existential problems facing BSS as a result of political and business interests (Chapter 6). This work's contribution is then situated and future work is described before closing remarks.

7.1 Findings

7.1.1 Democratizing success measurements

Formalization of station level data furthers the understanding that it not only contains bicycles being checked in and out, but also rebalancing and collisions. While some previous literature has accounted for rebalancing in station level data gathering, interaction collisions which sometimes exceed rebalancing, are not taken into account. The combining of trip data and level data allows the extraction of rebalancing data. Something that has only been theoretically analysed through optimal routing research.

The second contribution comes from models estimating the number of daily trips. By exploring the relationship between openly accessible level data and the typically private number of trips, we were able to define multiple translation methods. Having a manner of estimating the number of daily trips allows the democratisation of BSS usage in order to move beyond the constant political rhetoric of success. This allows more effective pro-cycling alternatives to be considered if necessary.

7.1.2 Rebalancing and operator behaviour

Bicycle sharing research has grown extremely quickly in the last five years. Many articles have analysed the large amounts of data that are generated by station levels and trips. This insight into travel behaviour, previously constrained to surveys or having to provide GPS devices to users, has allowed a large amount of analysis. While this data represent a portion of flow where stations are available, even within these service areas any analysis of trips as a representation of demand is biased by the strong impact of rebalancing operations in determining which trips can occur. Our rebalancing analysis reveals the strong impact operators have on determining which trips do and do not occur based on service level agreements and operator goals which may be distinct from those of the municipality.

This rebalancing analysis shows that rebalancing, the mere redistribution of bicycles so that stations are not full or empty, can be carried out in a variety of manners with different outcomes. Municipalities often contract the BSS operations to private companies without a clear understanding of the control operators have in gaming service level agreements while trying to maximize profits. There is not one type of rebalancing. Rebalancing behaviour is dictated by a goal. The multiple actors involved in a BSS have different goals but operators have the most control while somewhat constrained by service level agreements that do not necessarily encourage the municipality's desired outcomes. We have provided recommendations for rebalancing strategies related to various goals, it remains for municipalities to clearly define what goal their BSS has.

7.1.3 Performance and determinants of use

Applying our trip estimation work to 75 of the larger BSS in Europe, North and South America and Australia, we provide a first large scale global comparison. Performance values, in terms of trips per day per bicycle, show that a third of our sample's bicycles are used less than once per day. There exists no clear value for concrete success, but low usage will have few of the promoted health, congestion and CO_2 benefits that are promoted. Performance is one measure of success, for those BSS actively striving for social equity or alternate goals, other measures apply.

Using these values we relate BSS and urban attributes, such as cycling and other transport infrastructure, as well as geographic features and weather. We again created multiple models, this time to determine which factors increase BSS performance, finding that station density, cycling infrastructure and population increase their use, while helmet requirement laws and other expected variables were barriers to use. This work's important finding however was that the number of stations does not increase performance. This contradicts the status quo 'network effect', promoted by the BSS industry, stating that exponential growth in performance is achievable with linear growth in number of stations. Besides the likely outcome of selling further BSS technology, the network effect is likely more palatable to decision-makers over the reallocation of public space for further cycling infrastructure.

7.1.4 Politics and purpose

Bicycle sharing systems (BSS) are new addition to urban pubic transportation. This alternative mode provides added ease and resilience to moving about the city. By abstracting BSS to a transportation technology alone most systems can be considered similar but surrounded by unique varieties of actor constellations in different geographical settings. It is the interactions between these actors however that fundamentally impact how BSS serve citizens. Seraphic BSS benefit many of the actors involved by association, profit or both. There are however many limitations. The literature overwhelmingly shows that user demographics are whiter, younger, more educated, wealthier and more likely male than the local population. Additionally many of the suggested benefits such as health, CO_2 emissions and increasing social equity are greatly oversold. Much like roads create exclusive spaces where only cars can travel in comfort and relative safety, BSS use public space and often public funds for a service that favours one class of citizens. Regardless, due to physical limitations BSS can only serve so many people concurrently and consecutively, especially when considering that most users travel during similar periods in similar directions, requiring intensive rebalancing to afford more trips. These systems are largely operated to service commuters rather than as a convenience and lowering the barrier to (re)discovering cycling. Only private utility cycling can achieve the many proposed benefits of BSS in a sustained manner. This however requires safe and enjoyable cycling infrastructure with secure parking availability, something that is controversial and politically extremely challenging. Currently bicycle sharing systems prove to be an easier and popular alternative but less effective and, more fundamentally, unjust.

7.2 Contribution and future work

This thesis contributes to existing BSS analysis literature but also in the fields of optimization research, urban transportation and critical urban sustainability. The formalization of station level data, reveals rebalancing and collisions, which many publications have not taken into account in their analysis. Developing a technique to estimate the daily number of trips and rebalancing quantities allows extensive new analyses to take place. Existing optimal rebalancing research has ignored operational aspects. Chapter 4 analysis should strengthen future models and allow consideration of alternative goals than preventing outages, such as maximizing trips, profits or other BSS purposes. While analysis revealed two different types of rebalancing, new station characterization techniques were created, and well appreciated by practitioners, providing new means for future analysis. This rebalancing work also showed that any BSS trip analysis *must* take into consideration rebalancing which selectively alters bicycle and free dock availability and therefore usage patterns. Finally, in the interest of municipalities and residents, my work reveals that rebalancing affects BSS outcomes rather than simply being an objective task.

Estimates of trips show that most researched case studies have less than two trips per day per bicycle, meaning that providing equivalent bicycles to daily commuters could have similar outcomes with much lower expenditure. These little-used case studies will have very little of the promoted benefits further challenging that these BSS are a wise expenditure. Further, analysis of factors affecting performance strongly challenge the practice of increasing system size to increase performance, showing in multiple manners that this is an unproven outcome.

Finally, this work describes the conflict surrounding BSS that negatively impact their usefulness and how a good example of shared economy initiative was transformed into projects of commercialization and privatisation of public space. We show how BSS serve economic interests but also improve perceptions of companies, advertisers and politicians. While some municipalities exploit BSS adoption for personal image and quick fix solutions we also found they are exploited by entering in contractual and technological lock-in, negatively impacting residents, of which they appear to have little awareness of until experiencing the constraints. Overall this work should encourage further analysis and raise scepticism regarding BSS benefits and the outright calling of case studies as successful.

The contributions of this work raise many new possibilities for future work. Performance estimates, lower than expected for many systems, raises many existential questions for BSS. As we showed in Chapter 5, some BSS are well used and appreciated, despite social justice concerns, and therefore do have some value. The critical questions is therefore whether the opportunity cost would have been potentially more beneficial and equitable if allocated differently. A comparison of whether cycle track investment and general cycling promotion are more beneficial than current BSS developments could undermine recent BSS adoption trends.

Little work exposing the controversy and conflict surrounding BSS exists, especially in North America where discussion are mainly regarding equity. A deeper analysis of who benefits, besides the users, economically and politically has interesting potential. While BSS are promoted as a new form of public transport, whether these systems, which have largely already been privatised, are a form of public transport at all has yet to be discussed. While many European BSS are affordable, many in North America are not. Public transport should be suitable for all users yet bicycle sharing systems are not for a variety of reasons: their cost, the safety and comfort of existing cycling infrastructure and the relatively small areas that they service. Despite this, and contrary to what is repeatedly stated especially in the US, BSS are regularly subsidized.

Spatially there remains other questions related to actor motivation. While a few publications have discussed optimal placing of stations there remains the question of how location relates to other purposes such as advertisement. As stations often serve as billboards and directly for the BSS, for advertiser operators whether compromises are made in order to maximize ad revenue over system use that typically is contracted to receive no revenue from. Further, while we described how the intensity of rebalancing undermines environmental goals, the question of what maximum potential a BSS can have while still being environmentally beneficial.

Finally, we have shown many reasons discouraging BSS adoption due to their level of use but it may be that they have wider impacts on cycling policy. While some politicians may ride on the popularity of these systems it may have unintended consequences where the public then demands suitable cycling infrastructure to accompany a rare pro-cycling policy by many administrations. Similar to a trojan horse, BSS may promote broader changes to cycling policies. Looking at countries that have very hgih rates of cycling, such as the Netherlands and Denmark, we can find only one BSS in Copenhagen but that has low performance. What is prevalent in these countries however, typically at train stations, are long-term BSS (LTBSS), where bicycles can be used for days at a time and returned at the origin. This clearly raises questions of whether the wrong type of BSS is currently being deployed or BSS are not necessary in achieving high cycling rates.

7.3 Closing

This thesis began by discussing conventional car dominated urban transportation problems in Western cities. This research evaluated whether BSS are beneficial to local municipalities. Sadly it appears that in most cases BSS do not help reshape urban transportation. Broader intentional restructuring of urban transportation is required and many existing BSS are being applied as ineffective ‘quick fix’ solutions. Existing BSS have not become the solution to the multitude of urban transportation problems caused by car dominance. A new technology has been adopted with salesmanship rather than carrying out effective but difficult policies for real change. Bicycle sharing systems require density yet existing car dependence has created large suburbs of low density housing for which these systems are not adequate. So BSS may serve in higher density areas, but this geometric problem restricts these systems to a small proportion of residential areas, typically already with good subway service, especially in North America. So while BSS is promoted as a sustainable alternative it may in fact detract from effective, yet not novel, socially, environmentally and economically alternatives such as cycling infrastructure.

Academics have been excitedly researching BSS’ new sets of data and theoretical aspects, such as rebalancing, without thoroughly and critically analysing what purpose it serves. Portions of this research likewise focus on BSS issues that from an alternative perspective, such as social justice, may make anything but existential discussion void. So while our rebalancing chapter criticises optimal rebalancing research for ignoring the purpose of BSS, our quantitative work may be perceived as hypocritically by focusing on aspects of metrics and determinants of success, comparable to discussing acceptable rates of road fatalities.

This research evolved from questioning whether BSS were being run effectively or as empty symbols of sustainability, the danger being that if so, this enjoyable and useful new form of transport (for the author), with potential for increasing cycling, would be tarnished. This research aimed to also provide a qualitative perspective to predominantly quantitative work. Through interviews and study of critical urban sustainability literature the existential issues surrounding BSS became apparent, to some degree undermining discussions of success. These existential aspects however, are more likely to be downplayed by actors opposed to their conclusions, in which case this quantitative work of success and determinants has a vital function in recognizing inefficient systems and the limited outcomes of promoted benefits.

Finally, it is extremely hard to generalize and state that all BSS are unjust or not worthwhile, but certainly many are. We hope that this work initiates more research critiquing such systems and refocuses municipal energies to the development of more socially and environmentally sustainable and effective cycling infrastructure.

Appendix A

Chapter 3 notes

A.1 Chicago validation

The DAM, IAM and SAM applied to the Chicago station levels data saved for validation yield normalized error rates of 0.35, 0.79 and 0.42 respectively. These poor results are similar to San Francisco in the combined models (Table 3.8) which is expected as both experience similar technical problems which fluctuate station levels continuously, and increasingly often, therefore simulating interactions which our model is dependent on for estimation. The IAM overestimates trip counts the most in response to the anomalous rebalancing quantities while in the first half of Chicago's data span the DAM and SAM closely estimate T_d while glitch fluctuations remain few. Looking at the three model estimates over time in Appendix A.2 we see their accuracy decrease as rebalancing quantities increase in proportion related to trips.

A.2 DAM, IAM and SAM applications

We apply the day, interval and station aggregated models to our eight case studies in the Figures below.

A.3 Culling for improved estimates

In order to strengthen estimates we also explored methods of culling out believed rebalancing values. We iteratively compare the results of two simple culling techniques of absolute $x_{\Delta sdt}$ values. Our first method consists of replacing values greater than the cull limit with zero. While this method seems excessive as it also removes any legitimate interactions it also has the benefit of potentially compensating for rebalancing operations that straddle two intervals and are not culled. The second technique simply replaces the excessive values with the average of the temporally adjacent values. In Figure A.9 we again see that differences in rebalancing behaviour also affects culling success.

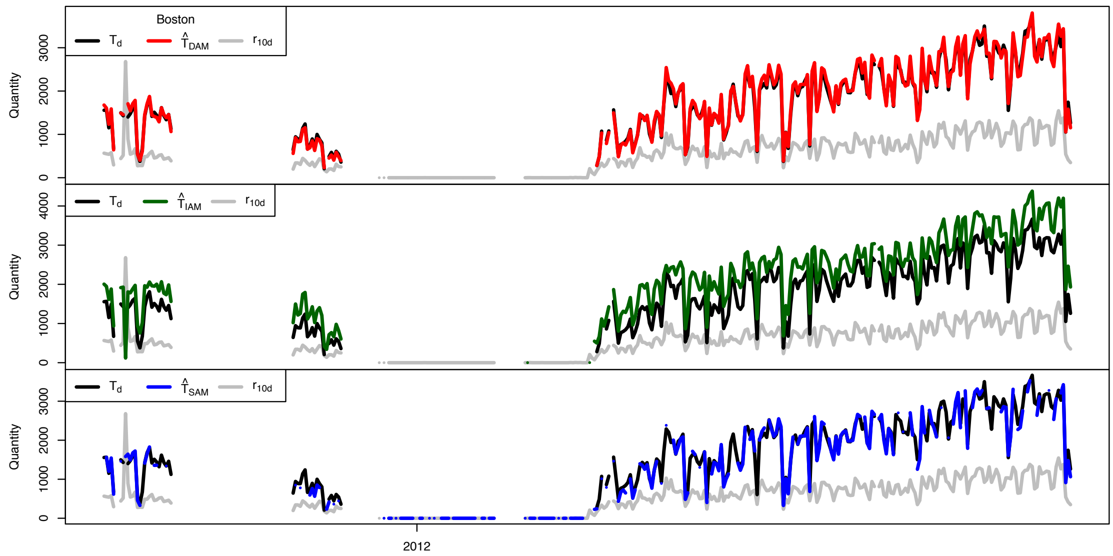

Figure A.1: Boston trip estimates using day, interval and station aggregated models.

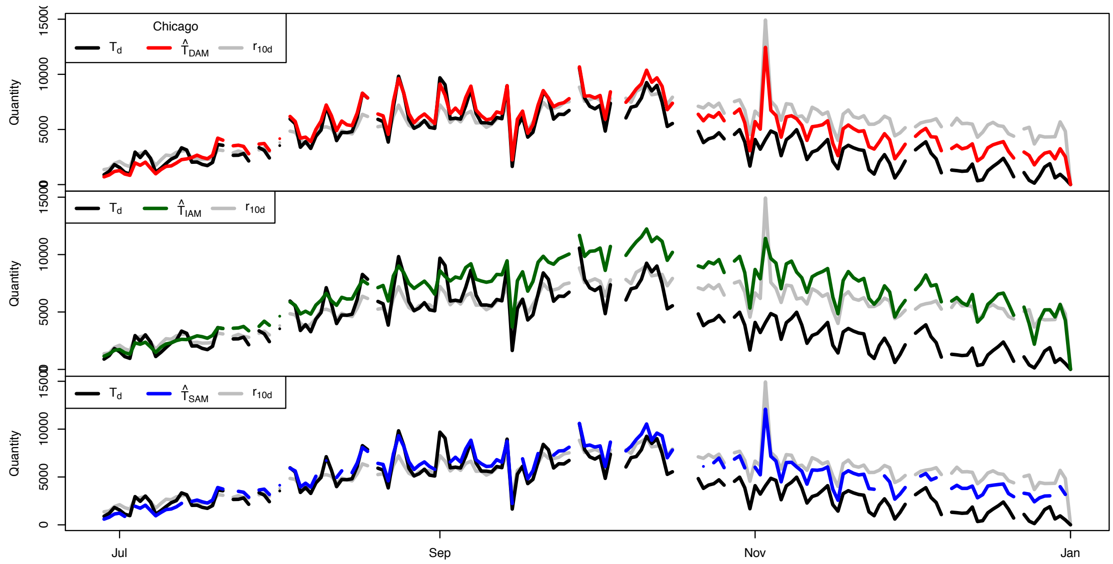

Figure A.2: Chicago trip estimates using day, interval and station aggregated models.

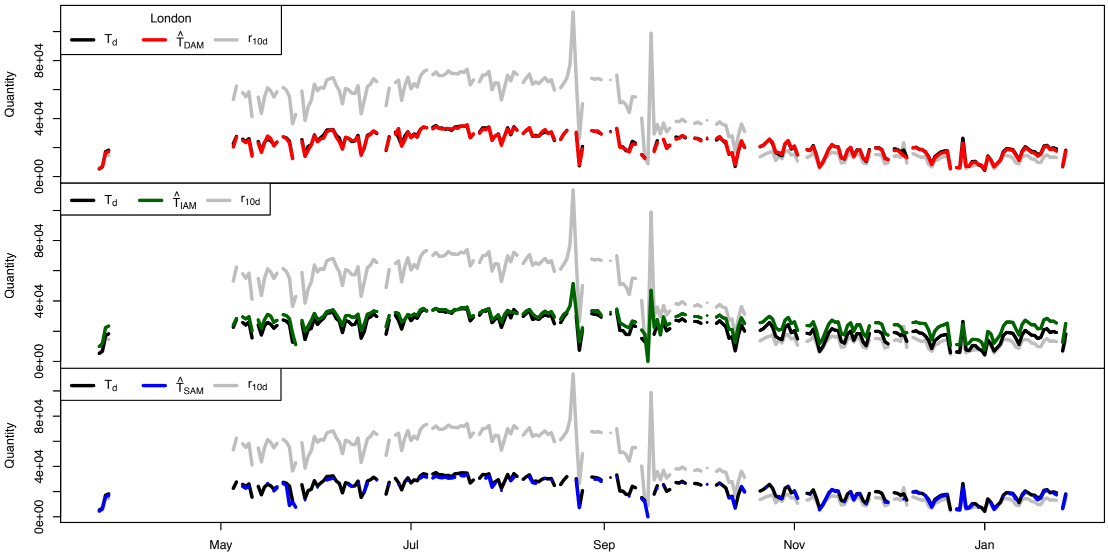

Figure A.3: London trip estimates using day, interval and station aggregated models.

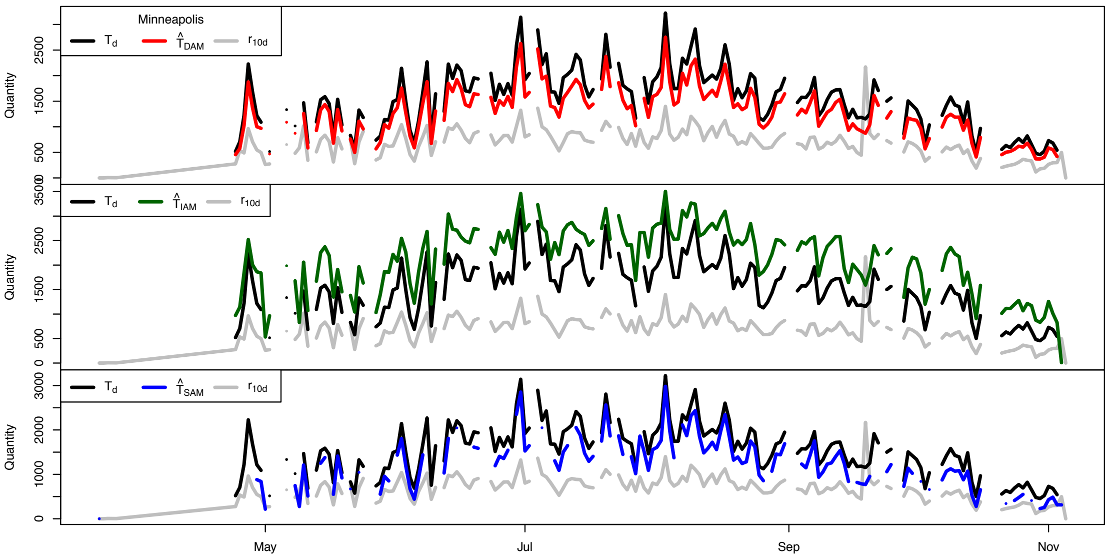

Figure A.4: Minneapolis trip estimates using day, interval and station aggregated models.

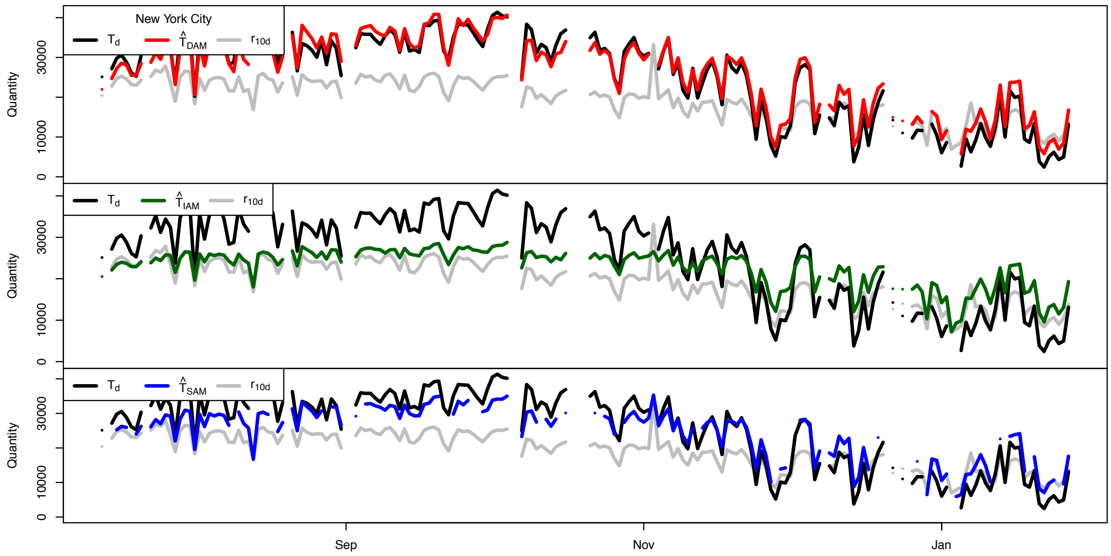

Figure A.5: New York City trip estimates using day, interval and station aggregated models.

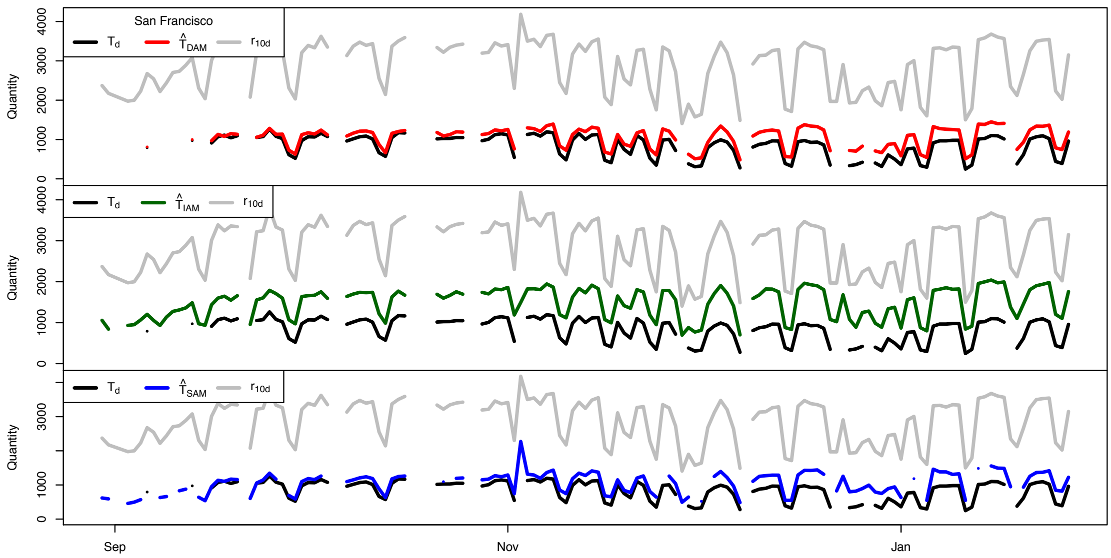

Figure A.6: San Francisco trip estimates using day, interval and station aggregated models.

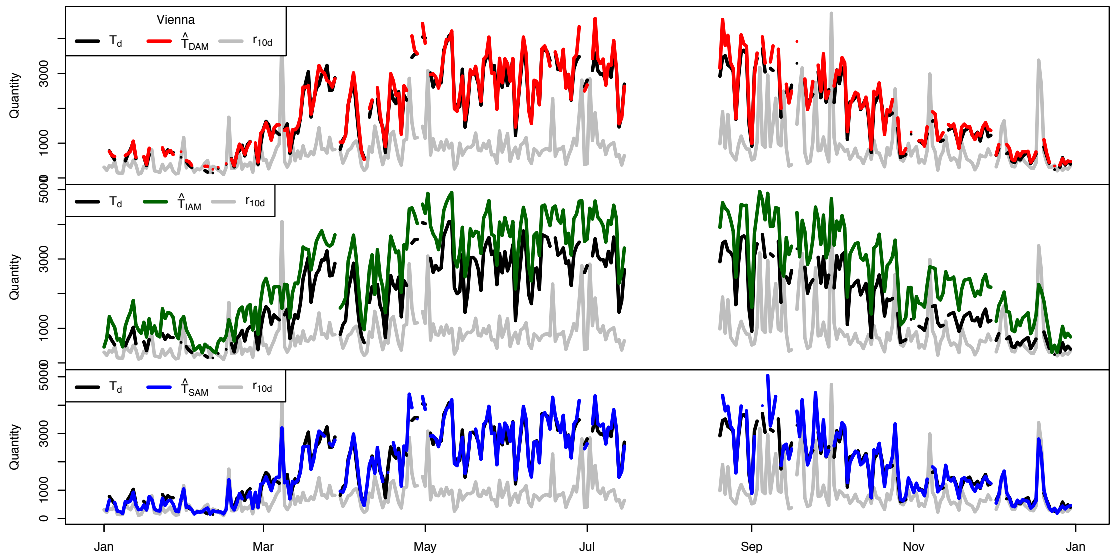

Figure A.7: Vienna trip estimates using day, interval and station aggregated models.

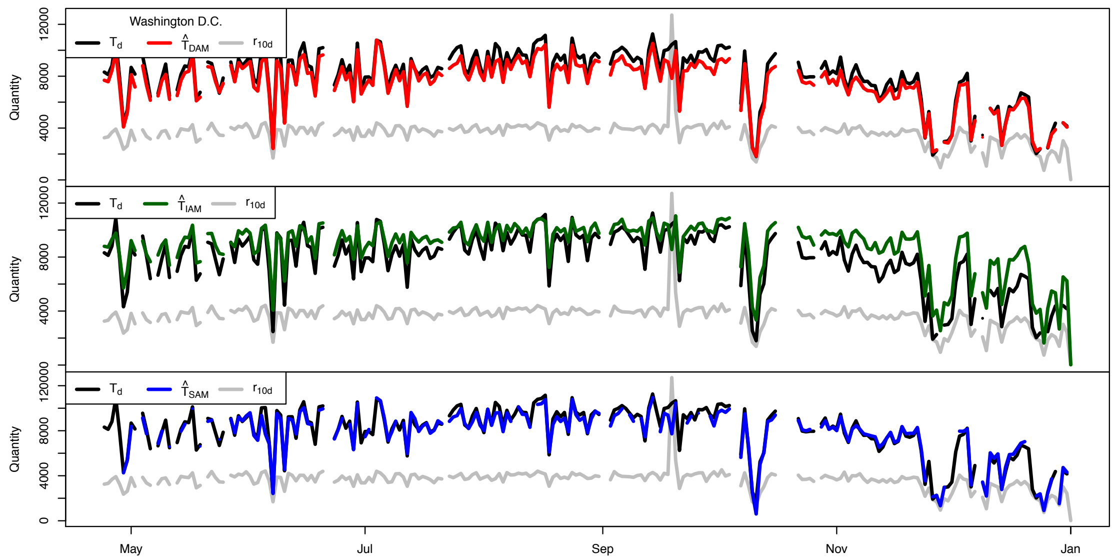

Figure A.8: Washington trip estimates using day, interval and station aggregated models.

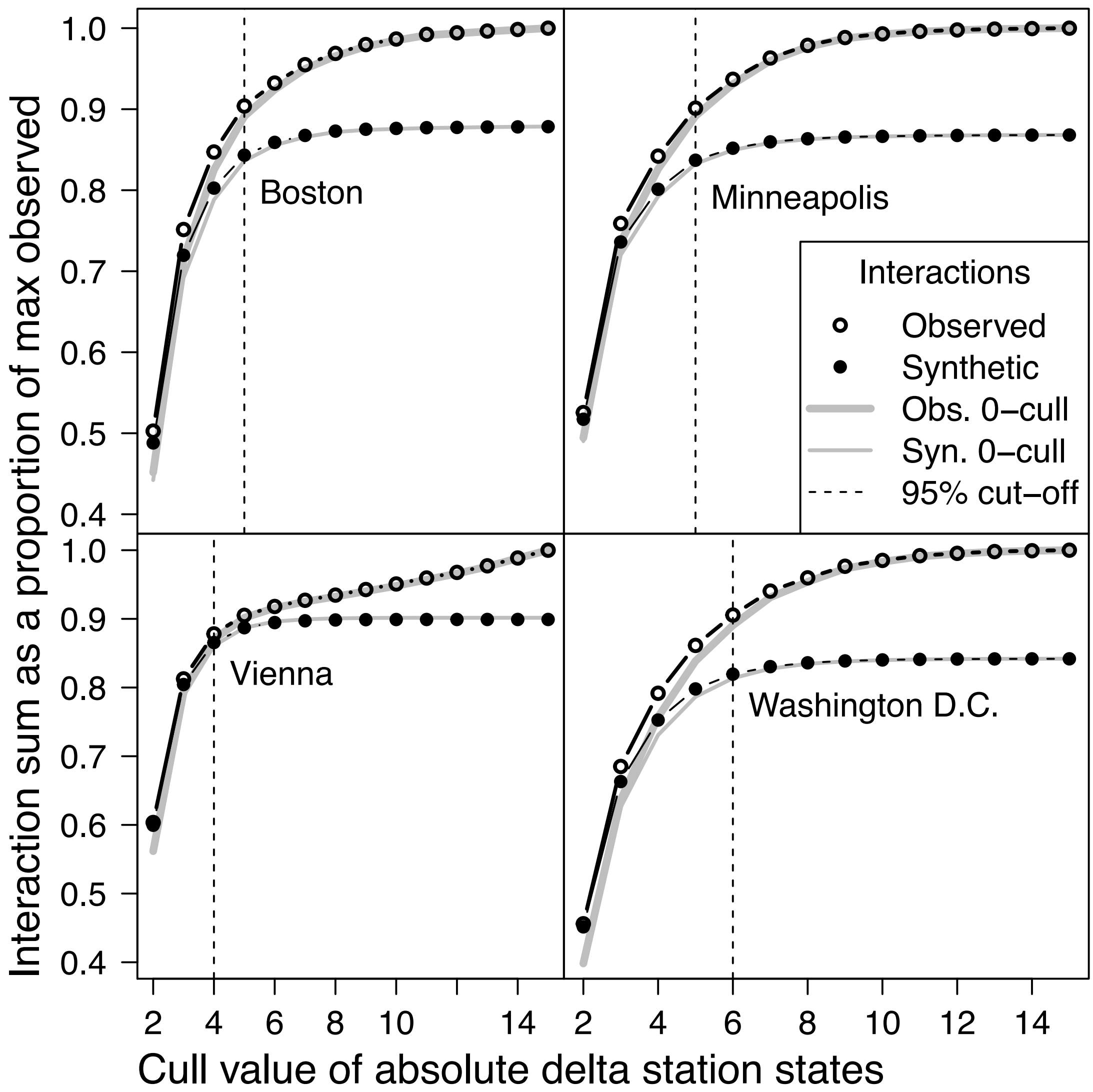

Figure A.9: A comparison of the rebalancing culling techniques on station level data.

Figure A.9 shows the results of applying different culling values to Boston, Minneapolis, Washington D.C. and Vienna. Iteratively replacing x_{10sdt} and z_{10sdt} values greater or equal to the cull value, we compare the sum of interactions within the data sets. Ideally, by perfectly culling rebalancing, the observed and synthetic points in the figure would converge as the cull limit decreases without a reduction in synthetic interaction sum. Vienna again stands out due to its distinctive distribution and has its rebalancing interactions removed most efficiently. The reason for this are the large jumps in bike availability due to technical glitches rather than rebalancing. Interestingly we are able to cull all values greater than three, four and five, depending on the BSS, while maintaining over 95 percent of the interactions. The zero and adjacent mean replacement culling methods showed similar results. We arbitrarily selected a 95 percent preservation of interactions for defining the threshold for a culling limit. Using $x_{\Delta sdt}$ data to apply culling at multiple Δ values yields expected results. Shorter Δ decrease the 95% cull limit value. Applying cull limits allow better assimilation of observed values to the synthetic values which represent actual trips. Keeping with the goal of creating a simple estimation model for public use this method was excluded from the main analysis.

Appendix B

Chapter 4 notes

B.1 Data collection and validation

Rebalancing data collection

Rebalancing amounts can be extracted by combining *station level data* with *trips*. Station level data is the number of bicycles and docks shown available on operator data feeds. Using trips, consisting of date, time, duration and origin and destination, it is possible to create a *synthetic* station level data (Médard de Chardon and Caruso, 2015) that does not contain any rebalancing changes. Subtracting synthetic from collected station levels yields rebalancing quantities. There exists however, some limitations to this methodology.

First, rebalancing quantities are extracted as well as artefacts from technical issues or misreporting from bicycle maintenance or server down time (operator's or data scraping server). A second issue, of importance for spatial analysis, is the occasional tendency for some stations to be geographically relocated (This is more frequent for operators using movable stations) while maintaining the same station identification. This shift is typically less than a few hundred metres but sometimes more. For simplicity we use the location at which stations remained at the longest during our analysis period. We also found that some station locations are incorrectly reported by operators, these were manually updated.

A more important issue is the temporal alignment of trip and station level data. A delay exists between the time of station level data collection requests and the age of the values on the central server providing the number of free bicycles and docks at individual stations. Additionally, every minute, for most BSS, the server combines all the station values into a single file to update the station level data feed. As BSS using BIXI technology are solar powered, stations only notify the server when an event occurs, a bicycle is checked in or out, or, when nothing has occurred, at regular 'heart beat' intervals of what appears to be four to five minutes to conserve energy. The temporal alignment error between trip and station level data creates a divergence when a bicycle return will be reported within the following data extraction period. This error causes

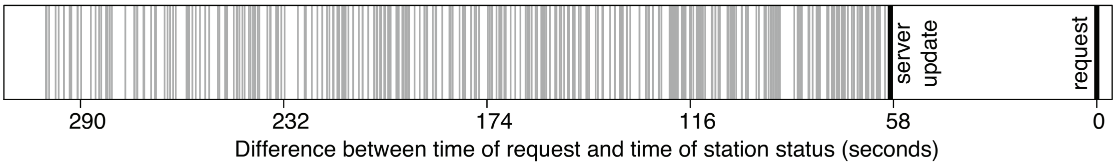

Figure B.1: This example shows difference in time between the request, server update of station states file (60 seconds) and individual station states (mean of 150 seconds).

a tell-tale dip followed by a jump in rebalancing data. As this behaviour is illogical in terms of operator rebalancing and we are confident of the cause, we adjust our data to remove any such matching opposing sequential occurrences and avoid the incorrect identification of rebalancing operations. Given our ten minute extraction intervals, we also remove modelled rebalancing quantities within the range -3 to 3 bicycles.

Figure B.1 shows data collected January 29, 2015 from Washington's BSS data feed and the difference in time between the request and the time of capture of individual station statuses. Figure B.1 illustrates a scenario with almost a minute's delay since the central server has updated the data and an average delay of three minutes for station statuses.

Validation

Temporal validation of our values and rebalancing extraction methodology is completed using monthly reports for New York City (NYCBS, 2015a) and the daily withdrawals and deposits for Boston (Hubway, 2015) and Washington (Capital Bikeshare, 2015b), while spatial validation is achieved by aggregating trips.

Visualizing samples of daily rebalancing amounts for individuals stations we see the alignment error through a withdrawal of one or two bicycles within one interval followed by an equal deposit during the following interval (or vice versa). Occasionally these dips and peaks (or peaks and dips) are of larger magnitude but typically of one or two bicycles. As we are looking at ten minute intervals we expect most rebalancing operations to be moving more than two bicycles. For this reason, combined with the alignment problems we removed all transaction values between -3 and 3, exclusive. Further we scan the data sets for sequential dips and peaks of any values and remove them as well. This methodology has the limitation that any alignment error superimposed on another technical issue or rebalancing operations will not be removed.

While only seven months' rebalancing quantities are available for New York City (NYC), a comparison of error reduction techniques, altering cut limits and the use of the sequential 'dip and peak' cleaning filter, confirmed that our combined approach was optimal. During this period New York City's operators noted that discrepancies existed between the quantities reported by their system, which we use, and those reported by dispatch (NYCBS, 2015b). Except for August and September, the other months achieve a 10-20% error rate. August and September experience error rates of 67% and 30% respectively. Boston and Washington provide daily rebalancing deposits and withdrawals for a limited time span. This finer temporal resolution allows a much stronger validation. Applying the small value extraction and error reduction process to 181 days for Boston and 233 days for Washington, the cleaned data sets yielded mean deposit and withdrawal errors of 21% and 23% for Boston and 10% and 11% for Washington. Our error reduction methods tend to also reduce rebalancing amounts causing our values to underestimate quantities.

The second validation technique uses the fact that the imbalance of trips from a station can only be achieved due to rebalancing. Knowing that the capacity of stations is fairly small, if during a period thousand more trips have ended at a station than started, we know that this is only possible if about one thousand more bikes have been removed, than deposited, by rebalancing. By aggregating the net sum of rebalancing for each station we compare this against the trip departures subtracted from arrivals for each station. Applying this to each case study we see error rates of 3%-12% of total rebalancing amounts. Rebalancing quantities tend to underestimate the actual quantity. This is likely due to our trimming of the data to account for technical errors. The temporal validation error rates for NYC and Washington are higher than their spatial error rates of 9% and 6% respectively. Regardless we believe these two methods sufficiently validate the quality of the data to support our analysis.

We have not found literature stating this relationship between station trip imbalance and net rebalancing quantities or using this method to do any analysis of rebalancing. While having a much simpler methodology than the one we completed, this alternative technique for extracting rebalancing quantities which isolates individual station quantities only functions at aggregated temporal spans. At the very least this methodology provides a measure of validation for any other rebalancing extraction techniques or data sets.

Appendix C

Chapter 5 notes

C.1 Weather's influence on trips

Weather need not be such a strong limiting factor to cycling. Copenhagen cycling rates mildly decrease with colder temperatures but of much greater impact are holidays (Copenhagen Commune, 2016). In Figure C.1 we compare the change in week day cycling rates for a bicycle counter in Copenhagen's Vigerslev Allé and the number of BSS week day trips in New York City. We overlay two years of data for each for robustness. While Easter, summer and Christmas holidays show noticeable cycling decreases for Copenhagen, ignoring these, seasonal weather can be associated with the 25% drop in cycling. Seasonal weather in New York City affects cycling more strongly with a 75% decrease (The September peak is due to system expansion).

As Copenhagen has no publicly available data for it's new BSS we are unable to compare BSS usage in both cities. It could be argued that cycling and BSS usage fluctuate independently due to weather. We therefore also provide a comparison of BSS trips to a bicycle counter, similar to that used in Copenhagen to compare. Seattle's bicycle counter on Freemont Bridge is well outside Seattle's bike-share coverage area, so there is likely only a very small proportion of BSS trips (Pronto, 2016) that are included in the bicycle counter data (City of Seattle, 2016a). Figure C.2 shows a clearly linear relationship between cycling and BSS trips for weekdays and weekends (with linear regression coefficients of 5.9 and 3.1 respectively) over a year.

Based on these figures we can conclude that weather can have decreased impact on cycling and BSS usage if cycling infrastructure, maintenance and cultural norms adapt.

C.2 Open Street Map infrastructure extraction

Applying the criteria from Lovelace (2015) we extracted cycling infrastructure in order to determine if it measurably impacts BSS usage. We present the key value pairs for cycling infrastructure, bus stops and rail stations used in our data extraction.

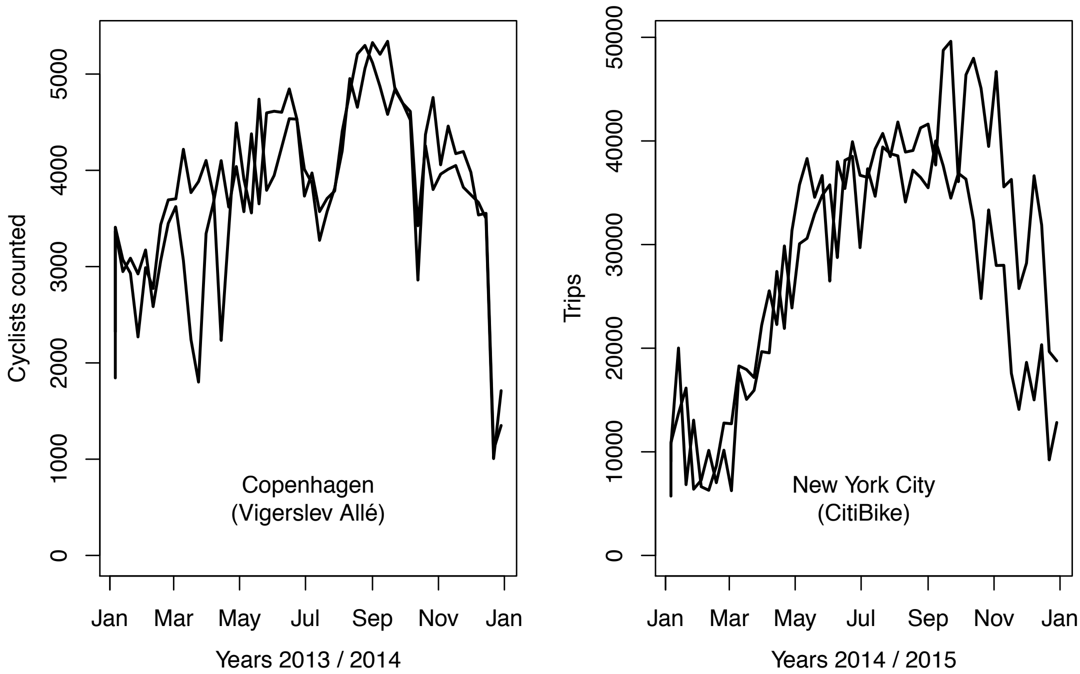

Figure C.1: Annual cyclist counts in Copenhagen (2013 & 2014) and BSS trips in New York City (2014 & 2015).

Cycling	Bus	Rail, subway & tram
`highway = cycleway`	`highway = bus_stop`	`railway = station,`
`bicycle = designated`		`subway_entrance,`
`cycleway = track, lane, shared,`	`# reject`	`tram_stop`
`opposite_lane, opposite_track,`	`disused = *`	
`segregated, shared_lane, yes`	`abandoned = *`	`# reject`
`cycleway:left = lane, track`	`railway = disused,`	`disused = *`
`cycleway:right = lane, track`	`abandoned`	`abandoned = *`
`cycleway:oneside = lane`		`railway = disused,`
`cycleway:otherside = lane`		`abandoned`
`path.bicycle = designated`		`station = disused`

Table C.1: Open Street Map query attributes for infrastructure extraction.

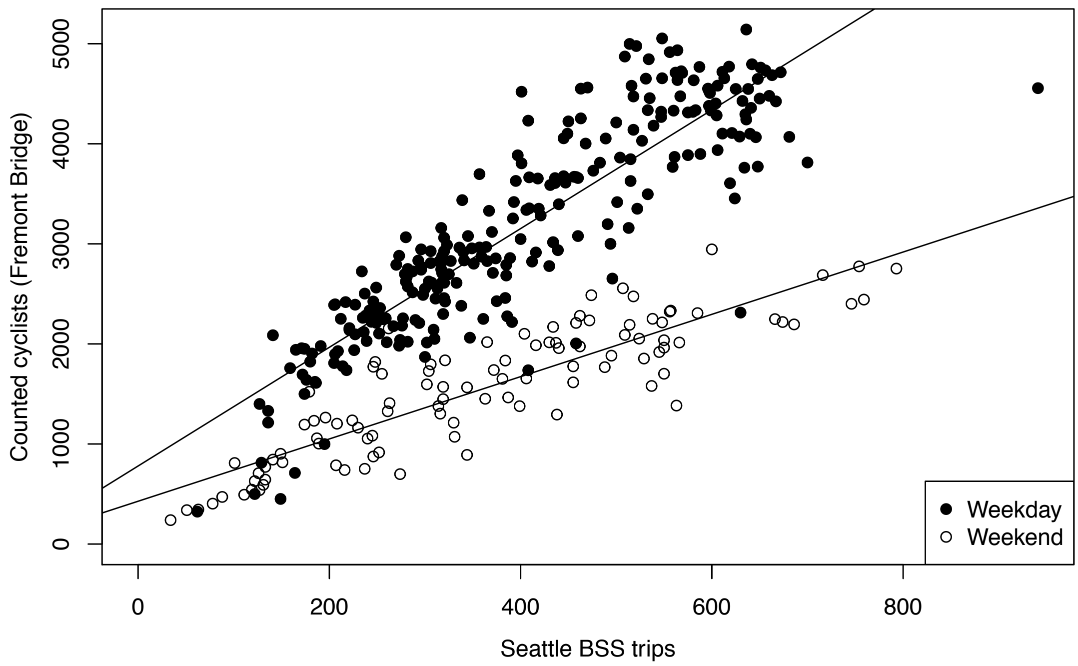

Figure C.2: Observed rate of weekday and weekend bicycle trips to BSS trips in Seattle between Oct. 2014 - Oct. 2015.

Appendix D

Chapter 6 notes

D.1 Interview questions

Below are the structured interview questions used for cycling organizations, BSS operators and municipalities.

D.1.1 Cycling organization

Generally I am interested in the **motivation** to develop a Bicycle Sharing System (BSS), **adoption** and development process, and **evolution** and effects of BSS. I would like to understand what people believe BSS will bring or has changed to urban transport patterns.

General

- What is the role of your organization?
- What has been your role with this BSS.
- What is the history of this BSS.
- Who initiated the adoption of this BSS?

Actors

- What actors/organizations were involved in the process of encouraging or preventing bike-share adoption in this city. What were their roles?
- What do you believe has been the impact of BSS on bike rental shops? Are BSSs competing with their business?
- Who do you think may be negatively impacted by this BSS?

Purpose of BSS

- What is the purpose of a BSS?

- What are the benefits of a BSS?
- What outcomes would you like/hope to see from the BSS?

BSS station locations

- How adequate are the station locations?
- What process determined the location of BSS stations within the city?
- What factors are important in determining ideal station locations and distributions?
- More precisely why were stations located on the curb/parking etc. . . ?
- Do some or all of the BSS stations contain advertising billboards or sponsor names?

BSS Funding

- How is your BSS funded?

Success

- How successful has your BSS been?
- What metrics have you been using?
- What are some fears/problems you foresee about the BSS?

Evolution

- Have there been any unexpected outcomes due to this BSS implementation?
- Are the original BSS supporters still the strongest voice promoting BSS?
- Has your involvement with the BSS changed over time?

Closing

- Where does your funding come from?
- Could you recommend anyone I should contact related to this issue?

D.1.2 BSS operators

Generally I am interested in the **motivation** to develop a Bicycle Sharing System (BSS), **adoption** and development process, and **evolution** and effects of BSS. I would like to understand what people believe BSS will bring or has changed to urban transport patterns.

General

- What is the role of your organization?

- What has been your role with this BSS.
- What is the history of this BSS.
- What type of business model does your company operate under?
- What is the nature of your relationship with the city, county or state that contracted your organization to operate this BSS?

Actors

- With what organizations does your organization interact? Public, Cycling organizations...
- Purpose of BSS
- What is the purpose of a BSS?
- What are the benefits of a BSS?

BSS station locations

- What process determined the location of BSS stations within the city?
- Was a computer model used to determine station locations?
- What factors are important in determining ideal station locations and distributions?
- Do some or all of the BSS stations contain advertising billboards or sponsor names?

Rebalancing

- What is the purpose/goal of your rebalancing?
- How do you do it?
- How many bikes to you rebalance per day?
- What are your main constraints to rebalancing?
- Do you have a service level agreement (SLA) with the city? What does it stipulate?
- Has your method evolved over time?
- Do you use software or observe need visually or is it routine - the same sequence everyday?
- How many trucks with how many spaces are in operation for what portions of the day?

Success

- How successful has your BSS been?
- What metrics have you been using?
- What are some fears/problems you foresee about the BSS?

Evolution

- Have there been any unexpected outcomes due to this BSS implementation?
- Are the original BSS supporters still the strongest voice promoting BSS?
- What will happen when your contract with the provisioner expires?
- What are your thoughts on a pedelec BSS?

Closing

- Could you recommend anyone I should contact related to this issue?
- Do you have any documentation, data or press releases that you could make available for research purposes?

D.1.3 Municipalities

Generally I am interested in the **motivation** to develop a Bicycle Sharing System (BSS), **adoption** and development process, and **evolution** and effects of BSS. I would like to understand what people believe BSS will bring or has changed to urban transport patterns.

General

- What has been your role with this BSS.
- What is the history of this BSS.
- Who initiated the adoption of this BSS?
- Why was this BSS provisioner chosen to manage the system? Why was this business model selected?

Actors

- What actors/organizations were involved in the process of encouraging or preventing bike-share adoption in this city? What were their roles?
- What do you believe has been the impact of BSS on bike rental shops? Are BSSs competing with their business?
- Who do you think may be negatively impacted by this BSS?

Purpose of BSS

- What is the purpose of a BSS?
- What are the benefits of a BSS?
- What outcomes would you like/hope to see from the BSS?

BSS station locations

- What process determined the location of BSS stations within the city?
- Was a computer model used to determine station locations?
- What factors are important in determining ideal station locations and distributions?
- More precisely why were stations located on the curb/parking etc. . . ?
- Do some or all of the BSS stations contain advertising billboards or sponsor names?

BSS Funding

- How is your BSS funded?
- What options were explored?
- Will public money be spent on the BSS? Why is this different than transit or car infrastructure?

Success

- How successful has your BSS been?
- What metrics have you been using?
- What are some fears/problems you foresee about the BSS?

Evolution

- Have there been any unexpected outcomes due to this BSS implementation?
- Are the original BSS supporters still the strongest voice promoting BSS?
- What will happen when your contract with the provisioner expires?

Closing

- Could you recommend anyone I should contact related to this issue?
- Do you have any documentation, data or press releases that you could make available for research purposes?

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List of Figures

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List of Acronyms

AIC . . . . . . Aikake information criterion
API . . . . . . Application programming interface
BIC . . . . . . Bayes Information criterion
BSS . . . . . . Bicycle sharing system
CBD . . . . . . Central business district
DAM . . . . . Daily aggregated model
GBFS . . . . . General bike feed specification
GIS . . . . Geographic Information system
HOV . . . . . . High occupancy vehicle
IAM . . . . . . Interval aggregated model
IS . . . . Information system
IT . . . . Information technology
NAB . . . . . . Normalized available bikes
OD . . . . Origin-destination
OLS . . . . . . Ordinary least squares
OSM . . . . . . Open Street Map
REU . . . . . . Rebalanced effective usage
PBSC . . . . . Public Bicycle Sharing Company
PPGIS . . . . . Public participation geographic information system
RMSE . . . . . Root mean square error
SAM . . . . . . Station Aggregated Model
SER . . . . . . Station expansion rebalancing
SLA . . . . . . Service level agreement
TDB . . . . . . Trips per day per bike
TfL . . . . Transport for London