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TRC-2015-05
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Infrastructure and Technology for Sustainable Livable Cities

FINAL REPORT

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16. Abstract

Providing access and mobility for key installations and businesses located in cities become a challenge when there is limited public transport and non-motorized facilities. The challenges are significant in cities that are subjected to severe winter weather conditions. Improving access to sustainable mobility choices is a key aspect of developing livable cities. This project scope is limited to identifying methods and infrastructure to promote walking and cycling. With regards to cycling, bike-share program development and use of location-allocation models as planning tools are presented. To minimize exposure to adverse weather conditions, underground and above ground pedestrian systems are provided. These two infrastructure options are explored during this study. Providing energy efficient lighting systems to make pedestrians and cyclists feel safe to travel within cities is paramount to improve mobility. Energy efficient lighting systems, cost of implementation, and planning tools are discussed. In winter cities, providing snow and ice free streets and walkways promote walking and cycling. Technologies used for such endeavors and implementation case studies are presented. Electricity needed to operate kiosks at bike-share stations, pedestrian lighting, and snow melting systems can be generated through renewable sources. Solar and wind are two such resources discussed in this report. Also, a few tools that can be used for identifying optimal locations for placing solar and wind sensitive infrastructure are presented.

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1 INTRODUCTION

1.1 OVERVIEW

Providing access and mobility for key installations and businesses located in cities become a challenge when there is limited public transport and non-motorized facilities. The challenges are significant in cities that are subjected to severe winter weather conditions. According to Neilsen (2014), 62% of millennials prefer to live in urban centers. APA (2014) indicated that 56% of millennials and 46% of active boomers prefer to live in walkable, technology-enabled cities where they have affordable and convenient transportation options regardless of the size of the city. In addition to alternative affordable transportation options, 81% of millennials and 76% of active boomers prefer non-motorized vehicles over cars for their daily activities. Fifty six percent (56%) of millennials want to see improvements to sidewalks and bike lanes to enhance safety. Lack of mobility can significantly affect the small and medium size cities economically due to migration of millennials to larger cities around the country. Arlington, New Orleans, San Francisco, and Denver reported an 82%, 71%, 68%, and 57% increase in the millennial population from 2007 to 2013, respectively. In general, millennials are more likely to move into more walkable urban areas than to suburbs.

The size of a city is determined based on the population. According to RCEP (2007), a large city has a population of more than 250,000. A medium city has a population ranging from 50,000 to 250,000 and a small city has a population ranging from 10,000 to 50,000. Many large and small cities around the world have utilized infrastructure and technology to promote mobility and sustainability. A majority of large and medium size cities uses rapid transit systems, metro bus systems, different types of ride sharing programs, and automated people mover technologies, etc.

The latest technology for enhancing mobility, although beginning development in the 1950's, is the automatic people mover system (Sproule 2004). Major cities in Canada and North America have developed automated mover technology for the city dwellers. For example, Detroit People Mover (DPM) was launched in 1987 by connecting thirteen stations in Downtown, Detroit with 41 ft long (Mark I) cars. Automated Light Rapid Transit (ALRT) technology was also initiated to run the same program at the same time in Toronto (Scarborough) and Vancouver. In addition to developing mass transit systems, the personal rapid transit (PRT) system is now widely

used to carry 2-4 persons with luggage for different purposes along defined routes within cities (Muller 2007). The most recent effort is to develop bike-share programs to enhance mobility within cities.

Many cities with extreme weather conditions such as Toronto in Canada (with cold winter) and Oklahoma City in the United States (with windy conditions) have developed Underground Pedestrian Systems (UPSs) through a network of pedestrian tunnels by connecting several buildings in downtown area. Similarly, the UPS in Montreal (Canada) provides a passage between several office buildings, shopping centers, and transportation systems. Winnipeg (Canada) is another city with a UPS that links all four corners of the city's main office district. In addition to using underground and covered facilities, several other alternatives have been proposed or used around the world – a floating bike path for the city of London and an elevated cycle "freeway" in Melbourne, Australia. Every project does not necessarily yield the expected benefits. As an example, the monorail system in Las Vegas is not widely used by the public; whereas the 'Personal Rapid Transit system' in West Virginia has been a large success. It is therefore vital to explore alternative infrastructure options implemented in various cities in order to understand the motivating factors for implementation, methods of funding, and documented implementation and maintenance challenges. It is important to understand the planning aspects to identify the methods of integrating selected infrastructure within the current layout and future plans of a city. Proper planning allows pedestrians to enter a downtown area at entry links near car parks, bus stops, bike sheds, railway stations, and so on. Non-motorized traffic in underground pedestrian systems could be increased by integrating shopping streets, entertainment facilities, or public transport systems. Moreover, educating the public, winning their support, and getting them involved throughout the process is vital for successful implementation.

Another aspect of developing sustainable livable cities is the use of renewable energy sources for lighting, heating, cooling, and operation of infrastructure. In 2009, International Energy Agency (IEA) compiled a report with a review of state-of-the-art technologies, methods of identifying local renewable energy resources, and strategies to overcome implementation barriers (IEA 2009). The technologies listed in the report include district heating and cooling (i.e., integration of heat and power renewable energy sources at a relatively large scale); distributed generation mainly from solar, wind, geothermal and biomass; smart metering; intelligent networks; and biofuel production. Also, Droege (2010) developed a report on *100% Renewable Energy and*

Beyond for Cities. Since every city is different in many ways, learning from global and local efforts to utilizing renewable energy is needed to adopt such technologies for the betterment of a specific city. While some cities had success in integrating such technologies during the initial phase of city development, other cities had to integrate technology by making necessary modifications to the existing infrastructure. In both cases, successes and failures are documented. It is imperative to document such implementations, and communicate with the officials who are involved in such efforts to provide necessary information and guidance for adopting such technologies and developing sustainable livable cities.

1.2 PROJECT OBJECTIVE AND SCOPE

1.2.1 Objective

The objective is to synthesize infrastructure and technology for improving access to non-motorized traffic and mobility within cities while enhancing sustainability.

1.2.2 Scope

Improving access to sustainable mobility choices is a key aspect of developing livable cities. As shown in Figure 1-1, this project scope is limited to identifying methods and infrastructure to promote walking and cycling. With regards to promoting cycling in cities, bike-share program development and use of location-allocation models as planning tools are presented. In many cities with adverse weather conditions, underground and above ground pedestrian systems are provided to encourage walking and cycling. Hence, these two infrastructure options are explored during this study. Providing energy efficient lighting systems to make pedestrians and cyclists feel safe to travel within cities is paramount to improve mobility. This report provides information on energy efficient lighting systems, cost of implementation, and planning tools. In winter cities, providing snow and ice free streets and walkways promote walking and cycling. Technologies used for such endeavors and implementation case studies are presented in this report. Electricity needed to operate kiosks at bike-share stations, pedestrian lighting, and snow melting systems can be generated through renewable sources. Solar and wind energy are two such resources discussed in this report. However, effective implementation of solar and wind powered systems require identifying the optimal locations for such technologies within the city environment. Hence, this report presents a few tools that can be used for planning purposes.

Figure 1-1 is a graphical representation of the overall project scope. The figure shows the role of energy sources, infrastructure, and technology in promoting livability and sustainability.



Figure 1-1. Scope of the project

1.2.3 Project Tasks

In order to accomplish the objective, the project is organized around the following tasks:

Task 1: Review the state-of-the-art and practice

The infrastructure and technology implemented in cities that are listed by various agencies as green, walk-friendly, bicycle-friendly, etc., are reviewed. In addition, available funding sources, technical support, and other resources are reviewed and documented.

Task 2: Survey planners, engineers, and other identified key groups and individuals

City planners, city managers, engineers, and other relevant groups are contacted to gain access to available resources such as the existing infrastructure details, maps, development plans, specifications, cost, and funding resources and mechanisms. The responses is used to document implementation challenges and lessons learned.

Task 3: Synthesis of Infrastructure and Technology for Sustainable Livable Cities

Based on task 1 and 2 outcome, needs and current trends, implementation case studies, successes and lessons learned are synthesized and documented.

1.3 REPORT ORGANIZATION

The report is organized into 7 chapters:

- Chapter 1 presents an overview, objectives, and scope of the project.
- Chapter 2 presents the key aspects in planning, implementation, maintenance, and evaluation of a bike-share program. This chapter also presents technology and infrastructure needed to develop a successful program. A summary of lessons learned from already implemented programs is presented. Also, a summary of an implementation case study that is developed for the city of Kalamazoo in Michigan and presented in appendix B.
- Chapter 3 presents an overview of underground pedestrian systems (UPSs), motivation factors or demands for an implementation, a review of existing UPSs, and a summary of lessons learned from already implemented systems.
- Chapter 4 presents an overview of aboveground pedestrian systems (APSs), motivation factors or demands for an implementation, a review of existing APSs, and a summary of lessons learned from already implemented systems.
- Chapter 5 presents an overview of technology for improving sustainability and resilience of small cities. This includes pedestrian lighting, snow melting systems, and planning tools for identifying optimal locations for implementing solar panels and wind turbines.
- Chapter 6 includes a summary, conclusions, and recommendations.
- Chapter 7 includes the citation list.

The report appendices include the following:

- Appendix A: Abbreviations
- Appendix B: Case Study: Bike-share station locations for the city of Kalamazoo.

2 BIKE-SHARE SYSTEMS

2.1 OVERVIEW

Environmental impact due to use of fossil fuels and health impact due to lack of physical activities and pollution demand implementing less costly and more environmentally friendly transportation modes. Hence, research and implementation of greener alternatives are the focus of many countries and cities worldwide. The explorations and implementations are primarily initiated by city officials and planning committees who are seeking alternatives to make their cities greener and more resilient. One such effort is to improve mobility within cities by enhancing non-motorized facilities, integrating various transportation modes, and implementing other alternatives such as ride-share, bicycle-share, etc. The information presented in this chapter is limited to bike-share.

Recently, the use of bicycles has drastically increased within cities (Firestine 2016). The underlying reason is the typical short trips that are taken by city residents. Bicycles offer the users with a chance to complete their first/last mile trips and modify the trips to meet their individual needs. The advantages brought to city residents and employees are not limited to transit stops and schedules. Additionally, cycling offers health, financial, and environmental benefits. Thus, many cities started expanding non-motorized facilities, promoting bicycle use within their jurisdictions, and developing bike-share programs.

A bike-share program makes bikes available at stations throughout a well-defined project area for shared use to individuals on a short-term basis. This provides another choice of transportation and extends the existing transportation system by providing access to destinations off of existing public transportation routes. Based on the Bureau of Transportation Statistics (BTS), as of August 2015, a total of 46 bike-share systems are being operated by one or more cities with a total of 2,655 bike-share stations in total of 65 U.S. cities (Firestine 2016).

This chapter presents the key aspects in planning, implementation, maintenance, and evaluation of a bike-share program. Use of location allocation models as a planning tool to identify the optimum number of bike-share stations for a given jurisdiction is discussed. Further, technology and infrastructure needed to develop a successful program are presented. A summary of lessons learned from already implemented programs is presented. Also, a summary of an implementation case study developed for the city of Kalamazoo in Michigan is presented.

2.2 PLANNING

Prior to launching a bike-share program, up-front planning and consideration must be made. Even though planning methods are not the same among all cities and communities, at least the following steps need to be considered when conducting feasibility studies:

- Define a goal (such as promoting physical activities, reducing traffic jams, providing access to underserved communities, etc.) Defining a goal is important to successfully perform a feasibility study, and to evaluate the impact and success of a program once implemented.
- Define initial service area by using heat maps.
    a. Identify dense areas such as areas with high population, job rates, commercial/ retail activity, and pedestrian activities; and the areas that are located at close proximities to colleges or universities, touristic attractions, recreational facilities, and hospitals.
    b. Identify number of short trips within and between these dense areas.
    c. Identify available bicycle infrastructure (bike lanes, shared-use paths, etc.)
    d. Identify social equity such as low income housing, percent living in poverty, and percent of non-English speakers.
    e. Identify areas with slope no greater than 4%
- Evaluate possibility of transit intermodality
    a. Identify connectivity with other modes of transport.
- Evaluate appropriateness of a bike share system for a jurisdiction. Surveying residents of communities is key to learning the interests, needs, and acceptance of such a program. In addition, the following information can be collected through a survey:
    a) Willingness to pay for the service
    b) Typical mode of transportation
    c) The level of knowledge about bike share systems
    d) Origin and destination of typical trips, time of day, and day of week
    e) Age of trip makers
    f) Purpose of the trips
- Define the most appropriate operation model and funding mechanism

a) Jurisdiction owned and managed
b) Non-profit
c) For profit

- Define possible locations for stations: on-street, sidewalk and/or off-street.
- Select suitable equipment and bicycles.
- Estimate associated costs such as capital cost, launching cost, operational cost, and administrative cost.
- Develop marketing strategies, and
- Develop strategies to prevent theft and vandalism.

2.2.1 Stakeholder Involvement

The implementation of a bike-share program is likely to involve a variety of stakeholders. Involving them early in the process helps building support and defining goals. The likely stakeholders and their potential roles are listed below:

- Politicians: provide required resources, enact regulatory changes (if needed), and ensure cooperation between municipalities.
- Planners: ensure integration of the system with bicycle infrastructure and ensure integration of the bike-share system with public facilities.
- Transportation authority: ensure integration of bicycle infrastructure with public transit infrastructure and promote the use of bicycles to current transit users.
- Parking authority: provide space for bicycle stations.
- Traffic and roads department: coordinate construction of the stations, make change to road infrastructure, and install signage and signaling to support increased bicycle traffic volume.
- Police: maintain a safe environment for infrastructure, bicycles, and cyclists; and protect the system components from theft and vandalism.
- Community groups and NGOs: build community support, provide bicycle safety education, and promote bicycle use.
- Business associations: build support among merchants, mitigate opposition to removal of parking spaces, and find sponsors.

2.2.2 Service Area Selection

Bike-share service areas are typically located in dense areas (i.e., densely populated areas in terms of employment, commercial/retail activity, and pedestrian activities). Service areas are also located at close proximity to colleges, universities, and hospitals. Other factors that influence the selection of a service area include availability of bicycle infrastructure (bike lanes, shared-use paths, etc.), touristic attractions, recreation facilities, access to other transportation modes, number of short trips that are made by people within a specific service area, and topography. Developing a successful program requires selection of an area that attracts a large number of users and sponsors (FHWA 2012; Alta 2013).

Dense areas are often identified by using heat maps that divide the area to be analyzed into approximate square grids of 1,000 ft^2, and locate the spots where a majority of the population live, work, shop, play and take some form of a transit. Social equity is also located using heat maps. These locations are determined by spatial analysis that identifies the areas with low income housing and percentage of population living under the poverty line. The percentage of non-English speaking population is often considered when planning a bike-share program (Alta 2013). After identifying these dense areas, it is also recommended to conduct a survey. Surveys can help to determine public interests, expected support, and willingness to pay for the service. This information is critical and can help in selecting the most suitable service area. Other helpful information obtained from a survey includes the mode of transportation used and the level of knowledge about a bike-share program (DeMaio and Sebastian 2009). Further, surveys can be used to educate communities about the benefits of bike sharing.

Surveys can be used to collect information about the trips taken by a population of a community on a daily basis. These are called mobility studies. The type of data that can be collected are the purpose, origin, and destination of the trips; time of day and day of a week; the mode of transportation chosen; and the age of trip makers (Bhat and Koppelman 1999). Conducting a survey with a random representative sample of the population, and a population as larger as the budget allows, is recommended. The area of a survey should be extended beyond the dense areas, where bike sharing is most likely to be implemented. This approach helps identifying the potential users that live outside of the dense areas but travel to the area for various reasons such as work or study (DeMaio and Sebastian 2009).

2.2.2.1 Station Locations

There are three commonly used places to locate bike sharing stations (Alta 2013):

- *On-street*: The use of existing no standing/no parking areas are recommended for on-street stations. The consultation with the applicable authority is required to get approval. One vehicle parking space can park up to 8 bicycles. Safety and user's comfort need to be considered when selecting on-street stations. On-street locations are primarily considered for areas with narrow sidewalks (Figure 2-1) (Wine 2012).



Figure 2-1. On-street bike share system (Source: Transitized 2015)

- *Sidewalk*: A minimum sidewalk width of 10 ft is required to accommodate a station and meet ADA requirements. However, most cities often require maintaining at least 15 ft wide sidewalks to accommodate the space required for a station, ADA requirements, and the volume of pedestrian traffic (Figure 2-2).



Figure 2-2. Sidewalk bike share system (Source: Thevillager 2014)

- Off-street: Stations can be located in publically owned or private sites. Public sites may include plazas, transit stations, or parks. These location may have less competition for space but requires more consultation with appropriate authorities. On the other hand, private sites may be more difficult to obtain and will require to have a buy-in from the owners.

2.2.3 Station Density

Bike-share stations are typically located at approximately quarter (¼) to half (½) miles away from each other. This range is based on the distance that a person is often willing to walk to reach a station. They should also be located where the trips will most likely be taken by young adults (between 18 to 35 years old) and places with transit nodes, educational institutions, and major public facilities (DeMaio and Sebastian 2009). However, this distance will be dictated by available funding, and permitting and spacing requirements (FHWA 2012, Alta 2013).

A bike share system with a minimum of 10 stations is typically recommended to provide an effective mix of trip origins and destinations, and justification of operational costs. However, a system with a minimum of 20 stations is desired (Alta 2013). Another factor that affect the distance between stations is the density of the area. As an example, in much denser areas, the

distance between stations is maintained at 1,000 ft to 1,300 ft range (i.e., 25 - 36 stations per square mile) (Alta 2013).

The number of bicycles at each station is a function of the demand. Number of bicycles per station need to be determined to ensure availability at any given time. It is also important to ensure availability of empty docks at any given time for bikes to be returned. A dock-to-bike ratio of 1.5 to 2.0 has been commonly used (Alta 2013).

Once the approximate distribution of stations is determined, following factors need to be considered to more precisely locate the stations (DeMaio and Sebastian 2009):

- Locations with high visibility (e.g., closer to a street intersection)
- Locations with high accessibility
- Locations that do not interfere with other users (e.g., pedestrians)



Figure 2-3. Off-street bike share system (Source: WNYC 2013)

After identifying potential station locations, getting feedback from public and future users is highly recommended. As an example, Alta (2013) used a web-based tool to gather information from the public on potential locations. The tool allowed the users to suggest alternative locations and provide comments.

2.2.4 Business Model Selection

Table 2-1 presents bike share business models, operator, operation procedures, revenue sources, benefits, and potential short-comings.

Table 2-1. Bike-share Business Model, Operator, Operation Procedure, Revenue Sources, Benefits, and Potential Short-coming

Business Model	Operator	Operation procedures	Revenue Sources	Benefits	Potential shortcomings
Jurisdiction owned and managed	An independent contractor	• Services are provided under the supervision of the local authority. • Net revenues are shared by jurisdiction and the contractor. Jurisdiction reinvests the revenue into the program. • Capital funding is provided by the jurisdiction. Equipment and infrastructure is owned by the jurisdiction. • To maximize revenues, contractors are allowed to use advertising and sponsorship. • Jurisdiction is responsible for financing the program. Contractor bears the liability.	• Federal, State, and local grants • Advertising and sponsorship (title sponsor, local businesses, Ads on bike share equipment and communication, etc.) • Membership and usage fees	• Better control over permitting and deployment of stations. • Reinvestment of revenues is controlled. • Uses private expertise to compliment agency skills.	• Funding resources may require more time. • Financially liable. • Sometimes, ads on public space is not permitted. • Contract negotiation skills are required.

Table 2-2: Bike-share Business Model, Operator, Operation Procedure, Revenue Sources, Benefits, and Potential Short-coming (contd.)

Business Model	Operator	Operation procedures	Revenue Sources	Benefits	Potential shortcomings
Nonprofit business	Nonprofit organization	• With the support of a jurisdiction, an entity is created to provide services. • Initial capital is provided by the jurisdiction. Securing additional funding is a responsibility of the nonprofit organization. • Operational costs are primarily provided by the nonprofit organization.	• Federal, State and local grants • Bank loans • Local business sponsorship • Membership and usage fees.	• Financial responsibility of a jurisdiction is marginal • Reinvestment of revenues is controlled. • Revenues are reinvested to improve the system • Public interests are better served rather than interest of advertisers.	• Deployment and expansion of a program can be slower. • Limited supervision by a jurisdiction. • Often lack the necessary expertise for start-up and operation.
Profit business	Independent contractor	• Minimal supervision by a jurisdiction. • Jurisdiction has no financial responsibility. • Public space and permitting costs are paid to the jurisdiction as a percentage of the revenue.	• Private investment • Local investment sponsorship • Ads on bikes and stations • Membership and usage fees	• Implementation and expansion can be quicker • More flexibility to changes	• Minimal supervision by a jurisdiction • Contract negotiation skills are required • Future expansions are likely in profitable areas

Sources: Alta (2013); DeMaio and Sebastian (2009); Shaheen et al. (2010); FHWA (2012)

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2.2.5 Funding Sources

Table 2-2 presents funding sources based on the business model for capital and launch, operation, and maintenance. In addition, the table presents a few comments and considerations.

Table 2-2. Funding Sources: Business Model, Capital and Launch, Operation and Maintenance, and Comments and Considerations (FHWA 2012)

Business Model	Capital and Launch	Operation and Maintenance	Comments and Considerations
Jurisdiction owned and managed	• Federal grants • State/Local grants • Sponsorships	• Membership and usage fees • Sponsorships • Advertisements	• Federal grants may provide long-term dedicated funding. However, the funding agencies will impose stricter timeframes for implementation. Delays are common. • Federal grants can only be used for capital expenses. • When sponsorships are considered, the local ordinance should be consulted to determine if advertising is allowed in public right of way. • When FHWA funds are used, outdoor advertising may be restricted.
Non-profit	• Private foundation grants • Local/national energy conservation and/or health grants • Sponsorship	• Gifts • Sponsorship • Membership and usage fees • Advertisements	
For profit	• Private funding	• Membership and usage fees • Advertisements	

The available funding sources for developing bike share systems are as follows:

- Transportation Investment Generating Economic Recovery (USDOT – TIGER Discretionary Grants 2016)
- Congestion Mitigation and Air Quality Improvement (USDOT – CMAQ 2016)
- Transportation Enhancement Activities (USDOT – TEA 2016)
- Department of Energy (DOE 2016)
- Transportation, Community and System Preservation Program (TCSP 2015)
- Centers for Disease Control (CDC 2016)
- Department of Health and Human Services (HHS 2016)

Some state and local grant opportunities may include:

- Public health grants (FHWA 2012)
- Local transportation funds (FHWA 2012)

Sponsorship or advertising models may include:

- Advertising on street furniture (Alta 2013)
- Sponsorship that involves long-term relationship where stickers, logos and/or statements are put on bike-share infrastructure (bikes, stations, and/or website) (Alta 2013).

2.2.6 Permitting Process

An approval or permission from the public and/or private right-of-way owners is mandatory to locate bike-share stations. This process will often require approval of station plans and preparation of necessary permits. The preparation and approval process can take several months. The steps to be taken are (Alta 2013):

- The station locations, design specifications, and drawings are submitted to the corresponding jurisdiction (i.e. Department of Public Works Traffic Engineer).
- Plans are reviewed and approved.
- Permits are issued.

2.2.7 Bicycle Infrastructure

In the U.S., bicycles are allowed on any street, except freeways and highways. However, when planning to locate bike-share stations, it is prudent to consider bicycle-friendly, safe, and interconnected routes to limit bicycle trips to short distances. Avoiding lengthy and circuitous bicycle routes is recommended (Shaheen et al. 2010). Implementation in communities with already existing bicycle infrastructure is highly recommended. If the community does not have bicycle infrastructure (shared-lanes, shared-use paths, paved shoulders, bike lanes or trails), implementation is not recommended unless the roads are in good condition with adequate width for vehicles to safely pass the cyclists.

2.2.8 Operational Hours and Seasonal Constraints

Operational hours depend on user's travel routines and demand patterns as well as availability of funding. Operational hours include bike service hours and customer service hours.

Typically, non-profits tend to offer service hours from 5 a.m. to midnight and customer service from 8 a.m. to 5 p.m. Operational hours are consistent throughout the week. For profits tend to offer 24-hour service, with customer service from 8 a.m. to 6 p.m. Jurisdiction owned systems also typically offer 24-hour operation (FHWA 2012). Seasonal operation is implemented in winter cities. Typically, the operation is closed during the coldest months. This results in a decrease of operational and maintenance costs (FHWA 2012).

2.2.9 Cost of Implementation

The program implementation costs include:

- *Capital cost* includes the cost of stations, kiosks, bikes, and docks (Alta 2013). Station cost depends on the size (number of bikes per station). Cost of bicycles depends on the features of the bicycles (e.g., availability of gearing systems, independent docks, GPS). The cost can vary between vendors, but typically a station cost ranges from $40,000 to $55,000 (Alta 2013).
- *Launching costs* include hiring employees, storage spaces, bike and station assembly tools, website development, IT setup, marketing, site planning and permitting, bike station assembly, and installation docks (Alta 2013). For example, the launching cost for a system with 35 stations, 350 bikes, and 595 docks is approximately $500,000.
- *Operational costs* include customer service staff salary and benefits, station maintenance (troubleshooting, station cleaning, and snow, litter, and graffiti removal), bike maintenance, bike redistribution, and other expenses (maintaining facility, purchasing tools and spare parts, maintaining IT infrastructure, and maintaining an insurance). These costs depend on numerous factors, but mostly depend on the Service Level Agreement that establishes the operating terms to be met (i.e. how long a station can stay empty, how often bikes are inspected, snow removal policy, etc.) Based on the terms, cost could range from $2,400 to $2,700 per bike per year. Rate of theft and vandalism also affect the operating cost (Alta 2013).
- *Administrative cost* includes costs associated with administering a program (program manager salaries and benefits; and public outreach) (Alta 2013).

2.2.10 Program Marketing

The success of a program depends on how well the communities are encouraged to use and promote a bike-share system. Marketing campaigns have geared their promotion towards 18 to 35 year olds, as this demographic is most likely to use the system. During marketing, it is highly recommended to highlight the health and environmental benefits of using bicycles in general (DeMaio and Sebastian 2009). If a program is marketed during the initial planning stage, more acceptance and support is often seen after launching. Early marketing creates an initial excitement and brings attention to the program. Reaching out to local elected leaders for social rides should be considered to encourage, support, and promote the initiative. During the grand opening, getting the maximum media coverage is recommended to attract the maximum number of potential users. All of these activities will help in building interest and increasing membership (FHWA 2012). Use of highly recognizable and unique brands develops a local identity.

As an example, the city of Montreal conducted a major promotion in fall 2008, before launching the program in spring 2009 (DeMaio and Sebastian 2009). The activities included:

- *Naming contest*: A public contest was conducted through the city of Montreal's website and asked residents to propose a name for the program. The winner was given a lifetime subscription to the program.
- *Demonstration*: Over the course of a month, a demonstration was held in a station and several prototypes were displayed to educate the public. Also, participants were allowed to take test rides.
- *Founding member campaign*: In order to obtain early subscriptions, the public was encouraged to become "founding members". The first 2000 people to obtain an annual subscription received prizes such as limited electronic keys for unlocking the bicycles, tickets to a museum exhibition on bicycles, and other exclusive privileges.

Other means to drive early subscription are to offer pre-sales of discounted long-term subscriptions; offer discounted or free subscription to transit pass holders; and develop collaborative programs with local institutions and business in the form of employer-based health and wellness programs, tourism related, etc., (DeMaio and Sebastian 2009).

2.2.11 User Fee

User fees account for a large percent of operational revenue. The fee structure should be designed to make short one-way trips more affordable while avoiding an all-day use. This is achieved by offering a lower price for short trips while increasing the price as the rental duration increases beyond a predefined time period. This fee structure encourages users to utilize the system as part of the transit trips, and allows the availability of bicycles to everyday users (Wine 2012).

User fees include membership and usage fees. The membership can be issued for a day, week, month, or a year. The usage fee depends on the total duration of a trip. The membership and usage fee ranges are presented in Table 2-3 (FHWA 2012, Wine 2012).

Table 2-3. Membership and Usage Fee

Membership fee		**Usage fee**	
Daily	$8 - $5	0 – 30 minutes	Free
Weekly	$30 - $15	30 – 60 minutes	$1 - $2
Monthly	$60 - $15	60 – 90 minutes	$2 - $4
Annual	$85 - $40	Additional 30 min.	$4 - $6

2.2.12 Additional Considerations

2.2.12.1 Weather

Severe weather conditions (snow, precipitation, etc.) affect the quality of service (FHWA 2012). The heaviest precipitation occurs from May through August. The heaviest snowfall occurs from November through March. As roads and sidewalks are not often cleaned quickly, communities with the least bike share experience are greatly affected (Kenney 2012). In winter cities the system is operated until November and then redeployed in March or April (Alta 2013, DeMaio and Sebastian 2009).

2.2.12.2 Topography

An area with no more than 4% grade along bicycle routes is ideal for implementation of bike-share systems. Users dislike grades more than 4%, and completely evade routes with a grade greater than 8%. Therefore, topography is a critical parameter that needs to be considered during the planning stage. In cities where the grade is greater than 8% empty stations have been found on top of the hills and overflowed stations at the bottom of the hills. Users are willing to ride down

the hill, but refuse to bike up. A commonly used solution is to place a large number of bikes at the top of the hill and implement a redistribution system to bring bikes up the slope. Another more costly solution is to use electric bicycles (DeMaio and Sebastian 2009). Such systems have been introduced on a trial basis in European countries such as Italy, Croatia, Sweden, Spain, and Denmark (Intelligent Energy Europe Programme of the European Union 2015); and in the U.S. (the city of San Francisco, the University of Tennessee, Knoxville, and the University of California, Berkeley). However, the cost is not favorable for developing large programs (Midgley 2011).

2.2.12.3 Potential for Transit Intermodality

Bike-share systems are designed for short trips. Metropolitan transit systems are designed for longer trips and are limited to specific routes. By combining these two systems, it is possible to provide seamless travel between destinations. Also, this helps attract more users to a bike-share system. Further, by offering financial incentives for those who uses both transit and bike-share as a combined service, more users can be attracted to such programs. There are several examples of public systems that have implemented transit intermodality. In German cities such as Berlin, Frankfurt, Munich and Hamburg, the national rail company that operates most of urban commuter rail services has a program called *Call-a-Bike.* Bicycles are located at rail stations and the rail users are offered discounted prices for using bicycles. In the Netherlands, a service is explicitly designed for train commuters to use bicycle with a flat rate per 20-hour block (DeMaio and Sebastian 2009).

2.2.12.4 Accessibility by Minority and Low Income Communities

A bike-share system provides the choice of low cost transportation to communities. Low income and minority communities have the lowest automobile ownership rates and highest dependency on public transit (FHWA 2012). Requirements for bike-share system participation can be a barrier in some low income and minority communities. Certain measures taken to overcome these barrier are as follows (Alta 2013):

- Locate stations where the revenue projections may not be as profitable as others.
- Facilitate the use of phones for obtaining memberships to encourage individuals who do not have access to computers.
- Provide information and services in multiple languages.

- Accept debit cards. Develop partnerships with local financial institutions and banks to assist new users in opening checking accounts and obtaining debit cards.
- Subsidize memberships by securing sponsorships from various institutions and businesses. As an example, coupons with sponsors' advertisements can be printed and distributed to low income residents. Another option is to partner with employers of low-income individuals to encourage participation through a corporate membership.
- Offer introductory rates.
- Provide learn-to-ride classes.

2.2.12.5 Timing

When scheduling a program launching date, adequate consideration needs to be given for the type of equipment and stations selected to avoid delays. Time to procure and install stations, and procure bicycles depends on the type and number of bicycles and stations. For example, the construction related to fixed-permanent stations can take several months. In contrast, locating portable stations may take only a few days (DeMaio and Sebastian 2009).

2.3 MAINTENANCE

2.3.1 Bicycle Redistribution

Bicycle redistribution plays a major role in making a successful bike-share program. Users expect to have open racks to return the bikes and have access to bikes when needed. Full stations with no available docks to return bikes are commonly found in the areas with the highest concentration of jobs, housing, and activity centers. When the topography varies and the grade is greater than 4%, bike rides are primarily generated in the downhill direction. Hence, the frequency of bicycle redistribution need to be determined based on users' travel patterns within a jurisdiction. Once a bike share-system is implemented, additional studies need to be conducted to evaluate the program performance and fine-tune the operational parameters (FHWA 2012).

Redistribution requirements are included in the program's contract to mitigate inconvenience to the users. For example, the contract executed with Capital Bikeshare systems in Washington D.C. requires that stations cannot have all empty docks or all full docks for more than three hours between 6 a.m. and 12 a.m.; and for more than 6 hours between 12:01 a.m. and 5:59 a.m. during any day (Section 3-E 2012). Redistribution methods include trucks/vans carrying

bicycles from one station to another, bike-powered trailers, and recompensing bike sharing system users who manually help to redistribute bicycles (Figure 2-4). The trucks/vans method is used in large bike-share programs, and it is the most expensive mode of redistribution. Irrespective of the method of redistribution, traffic jams during peak hours can affect redistribution (FHWA 2012).



(a) Redistributing van (b) Bike-powered trailer

Figure 2-4. Methods of bikes redistribution (FHWA 2012)

When planning a bike-share program, it is difficult to accurately estimate the cost of bike redistribution. In order to estimate the cost, an understanding of station density (or proximity to each other) and travel patterns are needed (FHWA 2012).

2.3.2 Operational Service Levels and Maintenance

Bike maintenance, removing graffiti on stations, and bike redistribution are part of the services required to develop a successful bike-share program. Level of service provided by a specific program depends on the availability of funding as operational costs. For example, the cost of checking bikes every day to provide a high level of service is more expensive than checking the bikes in every month. If operational costs are covered by using program profits, the level of service is affected by the amount of profit generated. When the profit is less than anticipated, certain services can be postponed to offset the expenses; yet, it will impact the quality of service provided by the program. If operational costs are funded by other means, quality of service is not affected by the profit generated by the program (Alta 2013).

The costs of preventive maintenance can be reduced by allowing users to report bicycles needing repairs at the kiosk with a user interface. It is paramount to maintain an inventory with a detailed and updated repair history for each bicycle. A bike maintenance checklist needs to be developed and used during regular inspections. In order to minimize the cost of maintenance by

eliminating potential duplications, it is important to double check the maintenance checklist at the time of distributing bicycles to different stations.

2.3.3 Prevention of Theft and Vandalism

Reported cases of theft and vandalism are not very common in the United States. Most of the existing bike-share systems have taken measures to prevent theft. These measures include the use of high tech locking mechanisms, integrated GPS transmitters, and the use of specialized shape, size and branding bicycles with unique parts. Besides, some bike-share equipment suppliers provided built-in cable locks on bikes to allow the users to lock the bike when needed during their trip without getting into a docking station (FHWA 2012).

2.4 PROGRAM EVALUATION

Evaluation of program needs, effectiveness, and the impacts on the users is a critical step in developing a sustainable program. During the program planning stage, potential for developing a sustainable program needs to be evaluated. After a program is launched, user's feedback, data collected at Kiosks, data from bike mounted technology such as Global Positioning Systems (GPS) units, or a combination thereof can be used for performance evaluation. Community-based surveys are very useful in evaluating user perspective.

2.4.1 Program Sustainability

The success of a bike-share program depends on its ability to economically self-maintain operational and administrative costs. Due to limited resources and funding available for public transportation, developing self-sustaining programs are not supported (FHWA 2012). The potential revenue sources are user fees, membership fees, grant funding, private foundation contributions and donations, and advertising and/or sponsorships (Alta 2013). It must be kept in mind that bike-share programs typically take a number of years to "mature" and self-sustain. The time it takes to be self-sufficient varies from program to program (Alta 2013).

2.4.2 Program Follow-up

Once a program is launched, user's satisfaction is evaluated aside from monitoring bicycle usage. The first evaluation needs to be performed a year after launching a program. Primarily,

surveys are used for obtaining user feedback. Users can be asked to rate the overall satisfaction based on the accessibility to the community destinations, quality of bicycles, bike-route safety, mobility with bike-route slope, and the suitability of the bike-station location. In addition, the ease of use, available payment methods, cost, availability of bicycles and empty spots at stations, and maintenance could be evaluated based on the user's satisfaction level. The survey responses are instrumental in identifying areas needing improvements and possible expansion of the system. As an example, a year after launching Velib bike-share system in Paris, a survey was conducted with the following questions (DeMaio and Sebastian 2009):

- Did the program allow to make trips that were previously impossible?
- Did the program complement the current transportation options?
- Was the program useful at the beginning or end of an intermodal trip?
- Did the program allow using cars less frequently than normal?

Instead of using questions that require descriptive feedback from the users, a list of questions can be developed to get user feedback as a rating. A sample questionnaire is shown in Table 2-4.

Table 2-4. A Sample Follow-up Survey Questionnaire Form

	Unsatisfied	Moderately unsatisfied	Satisfied	Moderately satisfied	Highly satisfied
Access to community destinations by bikes					
Quality of bicycle					
Bike-route safety					
Mobility with bike-route slope					
Bike-station location					
Available payment methods					
Bicycle fare/User fees					
Maintenance of bike-station					
Availability of bicycles at the station for check out					
Availability of empty slots for bicycle return					

2.4.3 Data for Program Performance Evaluation

Kiosks at bike share stations enable convenient bicycle check-in or check-out. GPS units are mounted on bicycles to collect location and route data. Data collected from kiosks and GPS systems can be used to determine travel patterns and system utilization in order to develop plans for program improvement based on user's perspective. This data can also help track the environmental and health impact to the community by determining the amount of burned calories and carbon offset from the miles ridden by users. Different socio-economic data about the bicycle

users could be assessed based on community surveys. The collected data can also be used to secure additional funding to expand the program. The following is a list of data items that can be used to justify an expansion request (FHWA 2012) based on the user's perspective:

Kiosk-based Data:

- Average Travel Time (hour)
- Average Trip Length (mile)
- Average Delay (hour)
- Type of Membership (monthly/annual/life-time)
- Usage (in peak/off-peak hours)
- Number of trips per day
- Total burned calories/trip
- Carbon offset/trip
- Battery run-out time (of solar powered stations)
- Run-out duration of all the bicycles at a station

GPS-based Data:

- Number of destinations per trip
- Frequently visited routes

Community-based Survey Data:

- Purpose of typical trips
- User's annual income
- User's occupation

Certain programs have made the data available to public. The general public can track the progress, evaluate transparency of a program, and perform necessary analysis to evaluate the overall impact and performance of the program (FHWA 2012).

Jurisdictions need to have access to data in order to evaluate performance and to develop plans for program expansion. User feedback can also be used to measure the effectiveness of marketing initiatives by the decision maker's perspective (FHWA 2012). Bike-share performance can be evaluated in different scales e.g. local jurisdictions, regional planning agency and state wide agency from the view of decision maker's perspective. Planning scenario evaluation, long-term

benchmark, alternatives comparison, and project need with near-term standard are evaluated in terms of different scales for bike-share programs. For example, the local jurisdictions could improve the integrated network planning by maintaining long-term or near-term standard for current bike-share program by reviewing the user's feedback. The local decision makers also could take an initiative whether any alternate scenario is needed for current bike-share program in respect to network planning, project planning, development review or street design; whereas the entire decision would be based on user's feedback. Table 2-5 provides a check list for performance evaluation by local jurisdictions.

Regional planning agency scope includes policy development and funding allocation in addition to network planning. For example, funding allocation by regional planning agencies could be varied (whether it would be long-term, near-term, or alternatives) based on the user's feedback. The regional agency could make decisions for allocating necessary funds based on current project need or planning scenario evaluation; while the correct decision of fund allocation would be solely based on the user's need for the current bike-share program. Table 2-6 provides a check list for performance evaluation by regional planning agencies.

State agency work includes code compliance checking while considering all other indicators as mentioned above in regional agency for evaluating performance of a bike-share program (FHWA 2016). Table 2-7 provides a check list for performance evaluation by state agencies. Different evaluation criterion also could be established based on different land use e.g. urban, suburban, rural, transitional etc., for a bike-share program.

Table 2-5. A Check List for Performance Evaluation by Local Jurisdictions

	Planning Scenario Evaluation	Long-term Benchmark	Alternatives Comparison	Project Need	Near-term Standard
Network planning					
Project planning					
Development Review					
Street design					

Table 2-6. A Check List for Performance Evaluation by Regional Planning Agencies

	Planning Scenario Evaluation	Long-term Benchmark	Alternatives Comparison	Project Need	Near-term standard
Network planning					
Regional policy development					
Funding allocation					

Table 2-7. A Check List for Performance Evaluation by State Agencies

	Planning Scenario Evaluation	Long-term Benchmark	Alternatives Comparison	Project Need	Near-term standard
Statewide network planning					
Statewide policy development					
Funding allocation					
Code compliance					

2.5 PLANNING TOOLS - LOCATION-ALLOCATION MODELS

Location-allocation models are used to identify the optimal location for new facilities such as fire stations, schools, hospitals, and bus stations. In other words, the location-allocation models tend to choose optimal locations from a group of candidates and designate demand to the location based on the demand distribution. The demand locations represent the dispersion of people, employment, and locations of interest. Location-allocation models, depending on the objective of an application, require defining delimited constraints. Commonly used constraints include limited number of facilities (when budget is limited), predefined methods of travel to the closest facility, and predefined impedance cutoff – travel distance or time from demand to a facility or vice versa (Zhang et al. 2013). Location-allocation models designate demand to only one facility; thus, the demand at a certain point is not split or shared by different facilities. Also, any demand that is located outside of the predefined impedance cutoff will not be allocated by the models (Algharib 2011).

2.5.1 Optimization Models

Location-allocation models can be programed into a Geographic Information System (GIS) to develop a decision-support tool for locating critical facilities (ArcGIS 2016; Yeh and Chow 1997; Valeo et al. 1998). ArcGIS software provides a geographic information system tool that is used for network-based spatial analysis to solve complex routing problems. ArcGIS-Network Analyst extension tool contains six location-allocation models that can be used to solve various problems by (1) minimizing impedance, (2) maximizing coverage, (3) minimizing facilities, (4) maximizing attendance, (5) maximizing market share, and (6) targeting market share (ArcGIS 2016).

The minimize impedance model is used to identify an optimum location of a facility, such as a public-sector facility (a library, a health clinic, etc.), to minimize travel time or travel distance.

The location-allocation model that maximizes coverage provided by a facility has been implemented to determine the location of ambulances (Eaton and Daskin 1980), fire stations (Schilling 1976), and rain gauges (Courtney 1978). The other model needed for locating facilities is the one that minimizes the number of facilities to serve a large population with the least number of facilities. The maximize attendance, maximize market share, and target market share models are used for solving competitive facility location problems. Public-sector facilities do not compete with each other, rather they complement each other. Hence, minimize impedance, maximize coverage, and minimize facilities are the three location-allocation models applicable for locating public facilities.

The objective of the study presented in this chapter is to provide a process for developing, implementing, and maintaining a bike-share program. One key aspect of a program is identifying the locations of bike-share stations. This requires defining demand locations, candidate facilities; and a distance and/or travel time matrix. The demand locations considered in this study represent the population density, employment, and locations of interest. The candidate facilities are the predefined locations that are determined based on a set of criteria such as the area of influence, available non-motorized facilities, possibility of intermodality, topography, and the desired walking distance. The distance and/or travel time matrix contains the distances or travel times between demand locations and candidates facilities (Keane and Ward 2002).

Bike-share stations are located to complement each other. Hence, maximize coverage and minimize facilities models are selected as the optimization models. Desired walking distance from a demand location to a bike-share station is defined as the impedance cutoff. Integration of minimize impedance and maximize coverage models helps identifying optimum bike-share station locations to serve a large population while maintaining the desired walking distance.

2.5.1.1 Maximize Coverage Model

This model maximizes the number of demand locations served by a facility. This means that the facility located nearest the high demand density has the preference to be chosen (Algharib 2011). First, the model allows the user to pre-define a number of facilities within a selected area after considering the budgetary constraints. Then, the optimization is performed to cover the greatest demand (Bryant 2013). The maximize coverage model presented by Church and ReVelle (1974) is described below:

$$Maximize \sum_{i \in I} a_i y_i \qquad (1)$$

subject to (s.t.)

$$\sum_{j \in N_i} x_j \geq y_i \qquad (2) \quad for\ all\ i\ \in I$$

$$\sum_{j \in J} x_j = P \qquad (3)$$

where,

I = set of demand locations,

J = set of candidate stations,

P = number of stations to be allocated,

x_j = 1 if station is allocated at j, 0 otherwise,

y_i = 1 if demand is covered at i, 0 otherwise,

S = standard distance (impedance cutoff),

d_{ij} = distance from demand node to candidate facility,

$N_i = \{j \in J | d_{ij} \leq S\}$ set of candidates which can cover demand i,

a_i = demand at node i

Equation (1) maximizes the number of demands covered by a facility. Equation (2) assures that a demand location is covered by at least one facility as long as the demand location is situated within the impedance cutoff (S). Equation (3) calculates the total number of facilities that can be located within a pre-defined service area (Algharib 2011).

Maximize coverage model can be used to locate public-sector facilities such as emergency service facilities. The primary purpose of efficiently locating an emergency facility is to enable the public in the area to have the quickest access to the facility in case of an emergency. The same approach can be used when locating bike-share stations and entry/exit points for underground pedestrian facilities. The main limitation of this maximize coverage model is that it does not consider demand locations situated outside the impedance cutoff.

2.5.1.2 Minimize Facilities Model

Minimize facilities model is used to determine the minimum number of facilities needed to serve a targeted demand based on pre-defined facility locations and impedance cutoff (Bryant

2013; Current et al. 1985). In other words, minimize facilities model aims to minimize the number of facilities needed to serve the demand located within a defined service distance (Church 1984). The difference between maximize coverage and minimize facilities is that minimize facilities model does not allow users to specify the number of facilities to be allocated, rather it is determined through the mathematical process based on the demand and impedance cutoff.

Below is the mathematical formulation of the minimize facilities model as presented by Toregas et al. (1971):

$$Minimize \sum_{j \in J} x_j \qquad (4)$$

s.t.

$$\sum_{j \in N_i} x_j \geq 1 \quad i \in I \qquad (5)$$

$$x_j = \begin{cases} 1 \; if \; node \; j \; is \; a \; facility \; site \\ 0 \; otherwise \end{cases} \qquad j \in J$$

Where,

$N_i = \{j | d_{ij} \leq S\}$ demand covered

S = standard distance (impedance cutoff),

d_{ij} = distance from demand node to candidate facility

i = set of demand

j = set of candidate facilities

Equation (4) minimizes the number of facilities required to serve an area. As per Equation (5) the number of candidates has to be greater than or equal to 1 (Algharib 2011). One of the limitations in the model is that it does not include budget (or the maximum number of facilities) as a constraint. Hence, the number of facilities determined by the model for total coverage may be unrealistic when budget is limited (Chung 1986).

2.5.2 Example: Bike-share Stations for Downtown Kalamazoo

Downtown Kalamazoo is surrounded by a significant population of students, visitors, commuters, and residents making it a suitable place for initiating a bike-share program. Population, employment, and locations of interest were considered as the demands (see Appendix

B Section B.2 for more details). A program size and number of bike-share stations are determined based on the availability of funds and the goals of the program. However, having 10 stations is considered as the minimum to provide an effective mix of origin and destination trips to make a program sustainable (Alta 2012).

ArcGIS is used as the analysis tool and all the required data was uploaded as layers. For this example, the funds and goals of the program were not defined. In order to initiate the analysis, thirty (30) stations were selected as the candidates after evaluating the distribution of non-motorized facilities, bus stations/shelters, topography, and the locations of interest. Figure 2-5 shows the locations of the candidate stations. Additional details on selecting candidate station locations are presented in Appendix B Section B.3.

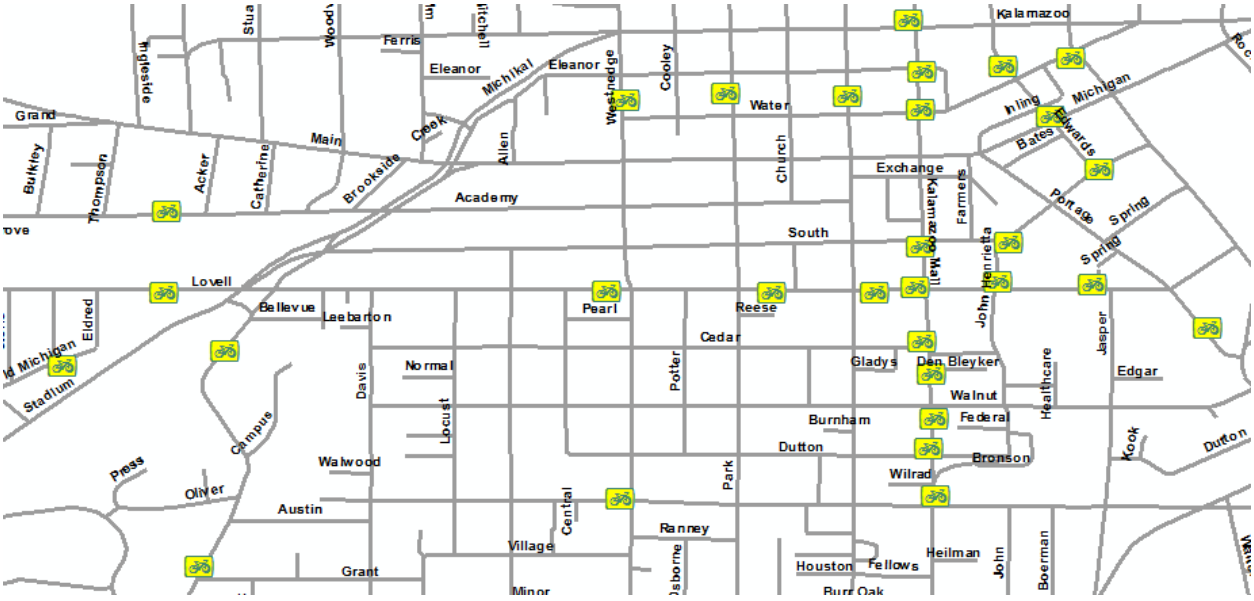


Figure 2-5. Candidate bike stations assigned for preliminary analysis

Maximize coverage and minimize facilities models were selected as the optimization models. Desired walking distance from a demand location to a bike-share station is defined as the impedance cutoff. The maximize coverage model provided the upper bound and minimize facilities provided the lower bound of the bike-share stations for each demand type. Analysis results are presented in Appendix B Table B-1. In order to select a set of optimal candidates that serves each demand type, the station that satisfied two (2) or more demand types was selected as optimal for this analysis. Twelve (12) stations were selected through the above procedure (see Appendix B Section B.4.3 for more details). The main constraint use in the analysis was the

desired walking distance. The final set of optimal bike-share stations for downtown Kalamazoo is presented in Figure 2-6.

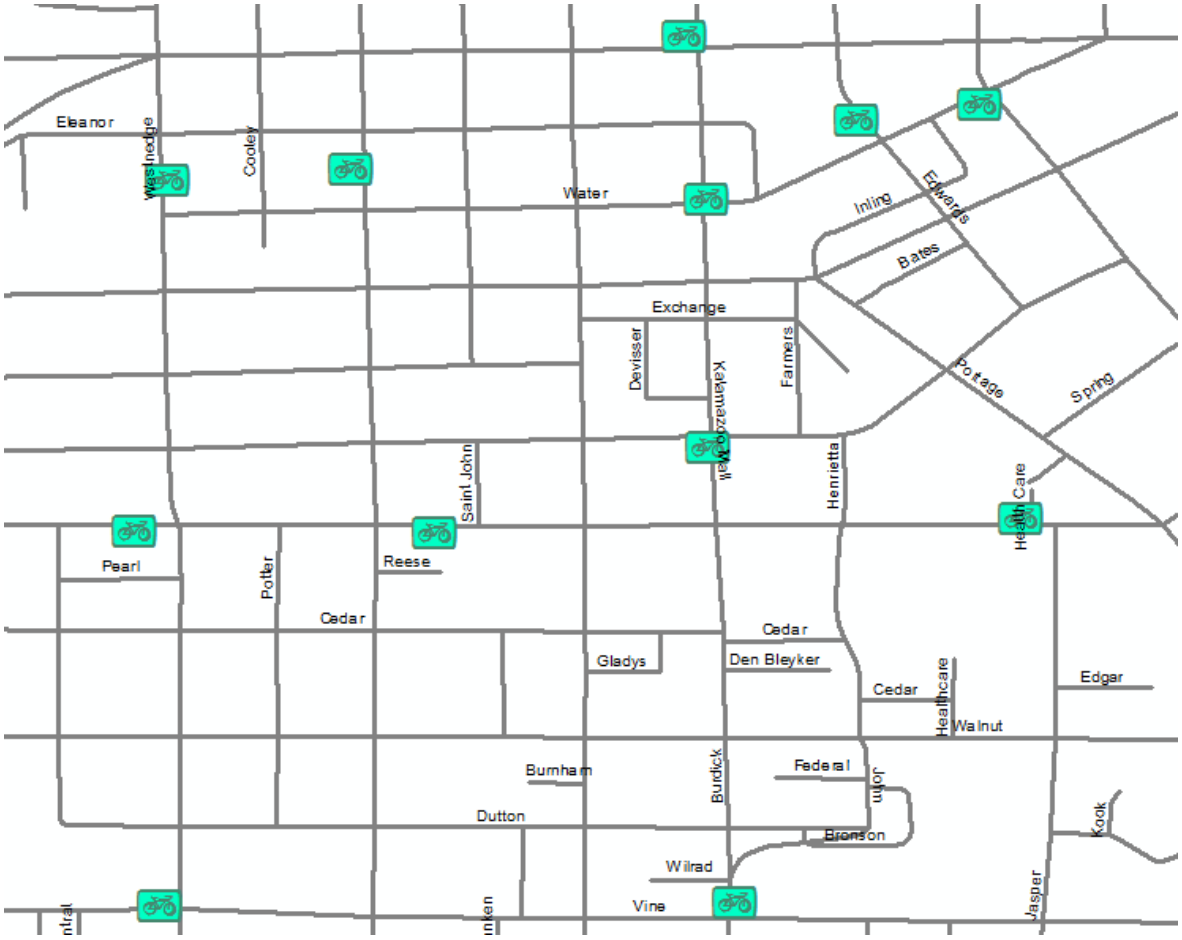


Figure 2-6. The most suitable locations for bike-share stations in downtown Kalamazoo

2.6 TECHNOLOGY AND INFRASTRUCTURE

Developing a bike sharing program seems like an emerging trend; however, it dates back to 1965 and has already gone through four generations over the course of the past 50 years (DeMario 2009). The first generation required no credit card or identification resulting in higher risk of theft and vandalism. The second generation required a check-out deposit; however, the minimal deposit was not enough to significantly reduce theft. The third generation introduced the use of credit card transaction and radio-frequency identification (RFID) chips to unlock the bikes. The user identification and security deposit advanced the program providing accountability against theft and vandalism. Finally, the fourth generation introduced solar powered stations with wireless

communication. The following sections present a brief overview of kiosks and RFID and GPS technology; power supply; and electrical bicycles used in bike-share programs.

2.6.1 Kiosks, RFID, and GPS Technology

The recovery of bike sharing was related to the initiation of technological advancements such as credit card transactions and RFID chips (radio-frequency identification). These advancements allow operators to introduce accountability and reduce theft and vandalism. The credit card transaction are performed by using a kiosk. The kiosks have a software back-end that keeps track of transaction and ridership information. Thus, credit card transaction at the kiosks allows collection of user's identification and deposit.

The RFID chip tags are a remote/self-powered asset tracking technology. Another emerging feature is the use of integrated GPS transmitters that allow for the tracking bicycles throughout the service area. In addition to helping in the rare case that a bike is stolen, this information can be useful both for planning bike-share system expansion as well as overall bicycle network infrastructure improvements (FHWA 2012).

2.6.2 Solar Powered Stations

Typically, grid power is used for the stations and requires hardwiring. Use of grid power requires additional infrastructure and deployment time. Further, it limits the ability flexibility in relocating the stations (FHWA 2012; DeMaio 2009). The most recent development is in a form of a modular system with solar power and wireless communication. The advantage of this modular system is that the stations can be moved, relocated, expanded, or reduced to cope with the demand. The integrated power management programs turn the system into sleep mode after a pre-defined inactive time period until the next user touches the screen to activate the station. This feature helps in saving power for operating the system for an extended period of time (Sherman 2011). When solar energy is inadequate during certain periods, additional rechargeable batteries can be integrated (DeMaio 2009). In winter cities, the solar powered stations can be removed and stored during winter months (Austen 2009).

2.6.3 Other Technologies

Other improvements include incorporating integrated transportation cards, electric bikes, and high-tech bicycle components. The integrated transportation allows the use of one card to ride both bikes and public transportation (Colin 2013). Electric bikes have been introduced in cities such as Knoxville, Tennessee, and San Francisco, California (Colin 2013). Electric bikes have an electric motor that offers several speed setting to assist users to travel in different terrain types. Compared to traditional bicycles electric bikes enable the user to travel longer distances and over hills with less fatigue and sweat. Because an electric bike typically costs twice the price of a similarly equipped bicycle, the electric bike market has not grown as rapidly in the U.S. when compared to other countries (Pro-E-Bike 2015; Dill and Rose 2012; Rose 2012). Figure 2-7 shows components of a typical bicycle.



Figure 2-7. Fourth generation bicycle components (Source: Inhabitat 2013)

2.7 A REVIEW OF TWO RECENT IMPLEMENTATIONS

This section presents an overview of two bike-share programs implemented in two cities in Michigan, USA. The following sections detail funding sources, implementation requirements, power sources for bike-share stations, and program evaluation.

2.7.1 Bike-Share System in the City of Ann Arbor

The president of University of Michigan (UofM) was inspired to initiate a bike-share program after observing the program in the University of Colorado Boulder. At the same time, there was an interest from the city of Ann Arbor to add a program in the community. Clean Energy Coalition (CEC), a nonprofit organization dedicated to promote clean energy technologies as a way to create a healthier environment, was able to bring UofM and city of Ann Arbor together in a partnership to start a program called *ArborBike* (CEC 2016). CEC is the owner-operator of the system. B-Cycle is the equipment vendor. The system includes 14 stations. The majority of the stations are located in downtown Ann Arbor where there are areas with high population and employment densities, including large concentrations of UofM students. The program usually operates annually from April 1st to November 15th (Stanton 2014).

The initial capital cost for launching the program was $750,000. These initial funds were secured from two sources - federal and local. Federal funds amounting to $600,000 were secured from the Congestion Mitigation and Air Quality Improvement (CMAQ) program that is jointly administered by FHWA and the Federal Transit Administration (FTA). A local match worth $150,000 over the first two years was provided by the city. The University is the title sponsor and committed $200k a year for the first three years with a total of $600,000 to help cover operational cost for the first three years. The program is currently in the third year of that agreement. Additional operating costs are covered using ridership and sponsorship revenue. The current sponsors include the title sponsor (UofM) and the community sponsors (Underground Printing - UGP, University Musical Society - UMS, KerryTown Market & Shops, Om of Medicine, and the Uptown of Downtown). The program partners are the city of Ann Arbor, The Ride, the University of Michigan, and Clean Energy Coalition.

Based on personal communication with the program supervisor, it was determined that the city of Ann Arbor did not have to have a specific mileage on non-motorized facilities in the city to get the program started. Increasing bike infrastructure has always been a constant goal of the

city. Although mileage was often increasing, it was not a requirement for the system. During the first year, the number of memberships, rides, and sponsorships, along with just feedback on how well people liked the program were considered as the measure of success. Currently, the city of Ann Arbor is evaluating success based on ridership/membership targets. For example, the current goal is an increase of 15% in membership by the end of 2016.

All the stations are solar powered. When solar power is insufficient, the batteries in the system are replaced with charged batteries. "During the summer, the sunlight is sufficient and hardly ever there is the need to exchange batteries. However, in the early spring and fall, the stations that are not optimally located had been requiring batteries exchange", expressed the system manager, Heather Croteau, through personal communication. Figure 2-8 presents one of the Ann Arbor bike sharing system stations.



Figure 2-8. A bike-share station in Ann Arbor, MI (Source: Rupersburg 2014)

2.7.2 Bike-Share System in the City of Battle Creek

In 2013, the bike-share program in Battle Creek, MI, started with a single station and has added a new station every year since then. To date, there are 3 operating stations and another will

be added during 2016. The initiative started from the Battle Creek Community Foundation, a nonprofit organization, with the purpose of improving personal health and wellness of the community. The system is currently owned and managed by the Battle Creek Community Foundation. The first station was sponsored by the Battle Creek Community Foundation. The 2nd and 3rd stations were sponsored by local institutions such as Calhoun County Visitors Bureau, Bronson Battle Creek hospital, and Kellogg Community College. A few business organizations around the town (Arcadia Brewing Co. and Heritage Chevrolet) also contributed. During the implementation process, the sponsor was involved in selecting a location for the bike-share station and helping with the permitting process.

TeamActive, a local bike shop, maintains the bicycles. *TeamActive* performs weekly routine checks to ensure the bikes are in good condition. *TeamActive* also stores the bicycles during winter and installs a protective cover over the stations (Lewis 2013).

There was no mileage requirement from the city of Battle Creek for implementing a bike-share program. Since there was no defined grant process, the city of Battle Creek did not have any restrictions (Angela Myers, the system manager, though personal communication). The first station was solar powered. Because of the cost of solar powered stations, grid power was used for the rest of the stations to make the cost of installation more affordable to future sponsors. As per the system manager, the kiosks consume very little power and there was no significant cost saving by running the system on solar. A new station can cost about $20,000 including the entire solar system for the infrastructure (Bowman 2014).

The Battle Creek system vendor, *Bcycle*, provides the city of Battle Creek a back-end website to track the usage. So far, the city has not formally evaluated the performance or success of the system. However, the usage increases with the installation of every new station. The goal of the program is to make it self-sustaining. Figure 2-9 shows one of the stations in Battle Creek, MI.



Figure 2-9. A bike-share station in Battle Creek (Source: Kellogg Community College 2015)

2.8 LESSONS LEARNED FROM IMPLEMENTATIONS

Documenting experience in bike-share planning, implementation, operation, and evaluation is vital to enhance performance of the existing systems as well as to make the future implementations more effective. Six lessons learned topics are addressed: (a) theft and vandalism; (b) bicycle redistribution; (c) information systems; (d) prelaunch considerations; (e) station; and (f) system in general. Under each topic, a problem and potential solutions are presented. Table 2-8 provides a summary of lessons learned from the implementations in cities. Table 2-9 presents a summary of pros, challenges, and recommendation from implementations in colleges and/or universities.

Table 2-8. Lessons Learned - City Implementations

Topic	Problem	Solution
Theft and vandalism (Shaheen et al. 2010)	(a) Anonymity when checking out bicycles created a system susceptible to theft.	(a) Third generation bike-share systems introduced smartcard to checkout bikes. The cards recorded user identification and usage. Allocate 8% to 9% of the budget to address theft.
Bicycle redistribution (Shaheen et al. 2010)	(a) Bicycle redistribution is a challenge in high demand areas.	(a) Use of natural gas powered vehicles and trucks for bicycle redistribution. Implement real-time information on bicycle stations (shortage and overcrowding) to increase efficiency and effectiveness in bike redistribution.
Information systems (Shaheen et al. 2010)	(a) Access to real-time information about empty docks and bicycle availability is needed.	(a) Real-time information can be provided through internet, text messages, or calling hotlines.
Prelaunch considerations (Shaheen el al. 2010)	(a) System needs to be flexible enough to adopt to the change in demand.	(a) Implement mobile stations to help relocate based on usage patterns.
Station (DeMaio and Sebastian 2009)	(a) Station is often empty. (b) Station is often full. (c) Station is underused.	(a) Increase redistribution capacity. (b) Increase station capacity, add more stations nearby. (c) Relocate station to a more visible or busier location.
System in general (DeMaio and Sebastian 2009)	(a) System is underused. (b) System is not used in combination with other transit modes.	(a) Reduce membership fees, improve bicycle infrastructure, provide temporary financial incentives, and increase marketing. (b) Advertise on the transit system, provide free or discounted memberships to transit holders.

Table 2-9. Lessons Learned - Implementations in Colleges and Universities (Kenney 2012)

University and Bike share system Name	Pros	Challenges	Recommendations
University of Illinois at Chicago *B-Cycles*	• Program offered flexibility to pick up and return bikes at multiple locations. • Kiosks were used to make the service available during 24 hours/day and 7 days/week.	• High cost incurred for infrastructure and purchase of bicycles. Need for recuperating cost by overcharging to users. • Program was not successful due to issues with paperwork and proper authority. Consequently, program was launched at the end of semester and did not have much acceptance. Also, weather was severe immediately after installation and contributed to low usage.	• Invest adequate time in planning, preparation and marketing.
University of Chicago *Recycles*	• Uses properly labeled impounded bikes from campus to minimize costs • Free for students, faculty and staff when campus ID is used. • Must sign a waiver prior to admission • Multiple locations on campus	• Offers only round trips. Bicycles must check-out and return at same location during working hours. • Hours vary at different times of the year • Program is unable to charge late fee to student accounts. Only when a student owes $200 or more, a hold is put on the account. • $34,000 is required annually to hire a coordinator in its Office of Sustainability to run the program • There was not enough budget to add more bikes. • Hours limited by staffing at each station.	• Students need to be educated about locking the bicycles during member sign up process to prevent theft. • Parking fees can be used as sources of funding. • Program needs to be linked to and payable through a card system.
Loyola University *ChainLinks*	• Students manages the program. • Flexible terms for duration of rental - daily, weekly, monthly, semester basis, and academic year basis.	• Started as student-run organization of volunteers and then changed to paid student laborers. This resulted in higher operational costs • Training students to manage the system and transferring authority between students were challenging. • Additional operational cost was needed to store bicycles during winter.	• Staff support/oversight is recommended to help with the transition between students
University of Kentucky *Wildcat Wheels*	• Two programs: student (students operated) and faculty/staff (department operated) • Used federal grant (CMAQ)	• Residential hall only have two bicycles available for rentals • There is no daily rentals. • More difficult and costlier to maintain.	• TIAA-CREF is a potential funding source to explore for large-scale bike sharing systems.

	• Bicycles can be rented for various durations: weekly, semester-long, and residential hall fleets. • No membership or usage feeds, but requires to sign a waiver. • Uses refurbished bikes	• Bike shop is mainly operated by students making it challenging to train and transition authority between students.	
University of Illinois at Chicago *Illinois Cross-Campus Bicycles*	• Free of charge • Does not require a waiver • Department funded and operated	• Only available for faculty, staff, and paid graduate students of a particular department. • Store during winter season • Not inspected after each use. Difficult to notice problems and fix them, especially overnight.	• Partnering with local bike shops is recommended for maintenance. • Small-scale programs are proven to be successful.

3 UNDERGROUND PEDESTRIAN SYSTEMS

3.1 OVERVIEW

Underground pedestrian systems (UPS) are a series of interconnected tunnels used in several cities with populations of significant size. The systems are typically used to avoid inclement weather and/or to decrease pedestrian density in urban areas. This section presents the motivating factors identified from literature for using underground pedestrian systems, review of two underground systems, and conclusions drawn from the findings.

3.2 MOTIVATING FACTORS FOR UPS IMPLEMENTATION

Cui et al. (2010) reviewed underground pedestrian systems in 51 cities. Table 3-1 lists the name of city, country, and population. In North America, the City of Duluth, Minnesota (MN), has the least population with 86,128. Out of all 51 cities, St. Gallen in Switzerland (CH) has the least population of 73,808.

Table 3-1. Population of Cities with Underground Pedestrian Systems (Cui et al. 2010)

North America			East Asia			Europe		
Duluth	MN	86,128	Kawasaki City	JPN	1,426,000	St. Gallen	CH	73,808
Albany	NY	98,424	Kyoto City	JPN	1,474,000	Geneva	CH	188,634
Rochester	MN	110,714	Nagoya	TWN	2,264,000	Stuttgart	DE	597,939
Richmond	VA	214,114	Taipei	JPN	2,619,000	Helsinki	FI	599,676
Halifax	CN	390,095	Osaka	CHN	2,665,000	Athens	GR	664,046
Atlanta	GA	447,841	Harbin	CHN	3,482,000	Frankfurt	DE	687,775
Vancouver	CN	603,500	Nanjing	CHN	3,642,000	Amsterdam	NL	779,808
Oklahoma City	OK	610,613	Hong Kong	CHN	7,188,000	Munich	DE	1,388,000
Seattle	WA	652,405	Beijing	CHN	11,510,000	Barcelona	ES	1,602,000
Washington D.C.	DC	658,893	Tokyo	JPN	13,350,000	Hamburg	DE	1,734,000
Winnipeg	CN	663,615	Shanghai	CHN	14,350,000	Paris	FR	2,244,000
Edmonton	CN	812,200	Other			Kiev	UA	2,804,000
Dallas	TX	1,258,000	Buenos Aires	AR	2,965,000	Berlin	DE	3,502,000
Philadelphia	PA	1,553,000	Sydney	AU	4,293,000	London	GB	8,539,000
Montreal	CN	1,650,000	Santiago	CL	5,218,000	Moscow	RU	11,920,000
Houston	TX	2,196,000	Singapore	SG	5,399,000			
Toronto	CN	2,615,000	Bangkok	TH	6,355,000			
Chicago	IL	2,719,000						
New York	NY	8,406,000						
Mexico City	MX	8,851,000						

The definition of a Winter City was presented during the 11th World Winter Cities Conference for Mayors – An average temperature below 32 ^{0}F during one month a year and an average snowfall of more than 8 in. of snow in a calendar year (Cui et al. 2010). Considering the above definition, more than half of the North American cities listed in Table 3-1 fall into the category of winter cities. Hence, it can be concluded that cold weather and snowfall are factors that contributed to implementing underground systems. On the other extreme, Oklahoma City has extreme weather events (tornadoes) and suffocating heat which favored selecting a tunnel system. The climate of the city was seen to be the most significant factor when making the decision on whether to invest in an underground pedestrian system in the city or not. When pedestrians are able to walk uninhibited by weather they spend more time outside their homes and apartments and take more trips than they would if they had no tunnel system to shelter them. This helps stimulate the economy as there are more opportunities for spending.

Table 3-2 lists weather conditions, city scale and economic level of a selected number of cities. Along with the climate, the city scale is also found to be a motivating factor for UPS implementation. In cities that have high population densities, the tunnel systems allow reducing crowding at the ground level. As seen from the data presented in Table 3-2, except Oklahoma City and Harbin, all other cities have at a population density of more than 2,590 people/mi^2. The economic level of a city can also be a motivating factor. The higher the per capital income for the city, the more likely they are to build a pedestrian tunnel system. A majority of the North American Cities listed in the table have a per capita income in excess of $20,000.

Table 3-2. Cities and Motivating Factor Information (Source: Cui et al. 2013)

Cities	Weather Conditions			City Scale				Economic Level
	# of Months Below 32°F	Annual Snowfall (in/y)	Annual Average Temperature (°F)	Population (Thousand)	Land Area (mi^2)	Density (People per mi^2)	Year	Annual Per Capita Income (2009, US$)
New York	1	23.6	76	8,392	304	27,687	2009	30,885
Vancouver	0	22	63	578	45	13,818	2006	31,845
Chicago	3	44	72	2,851	228	12,559	2009	27,138
Montreal	4	84	68	1,621	141	11,497	2006	30,142
Philadelphia	1	23.6	76	1,547	136	11,448	2009	21,661
Toronto	4	49.6	68	2,503	244	10,288	2006	33,827
Atlanta	0	2.1	79	541	131	4,134	2009	36,912
Houston	0	0.4	83	2,258	580	3,898	2009	25,563
Dallas	0	3.2	85	1,300	343	3,800	2009	25,941
Winnipeg	5	44.4	65	675	180	3,769	2009	31,942
Edmonton	5	49.6	59	782	265	2,961	2009	39,126
Oklahoma City	0	9.2	81	560	607	925	2009	24,195
Moscow	5	1097.6	61	10,523	418	25,214	2009	177,603
Beijing	3	65.6	77	13,300	529	25,180	2009	4,490
Hong Kong	0	0	85	7,034	427	16,501	2009	31,420
Tokyo	0	6.8	77	12,989	845	15,377	2009	48,597
Shanghai	0	1.6	81	11,346	1023	11,093	2009	4,743
Nanjing	0	1.6	81	5,460	1824	2,995	2009	4,009
Harbin	5	25.2	70	4,747	2736	1,736	2009	2,028

3.3 REVIEW OF EXISTING SYSTEMS

Even though the published data suggests weather and population density at ground level as the motivating factors, several other factors might have contributed to implementation decisions. Also, literature is limited on the significance of the facilities connected through such systems, funding sources and mechanisms, and challenges and lessons learned from such implementations. Hence, this section of the report presents a review of two systems in Oklahoma City and Rochester, Minnesota.

3.3.1 Oklahoma City Underground Pedestrian Facility

As of 2014, Oklahoma City's population was around 610,000. The facility was formerly known as the *ConnCourse*, and is currently named the *Underground*. Figure 3-1 shows the layout of the current system.

The tunnels were originally built in 1931 as a privately funded and owned facility by William Balser Skirvin to connect his *Skirvin Hotel* to the *Skirvin Tower* (Wikipedia 2016). In the 1970's, Jack Conn from Fidelity Bank developed a section of downtown Oklahoma City (OKC) and wanted to connect to the existing tunnels in the city. At the beginning there was no apparent direct economic benefit to be seen for Mr. Conn. Motivation included weather extremes and opportunities for expanding retail business for the city. The cost of an approximately a mile-long tunnel segment in the 1970's reached $1.3 million. Because of Mr. Conn's work in developing the system, it was named as the *Conncourse*. The tunnel system featured retail shops, services, restaurants, and clubs. With the expansion completed, it became very popular and saw daily traffic of 30,000 to 40,000 pedestrians. Expansion of the system continued into the 1980's with multiple smaller connections. Moving through the 1980's and into the 1990's the tunnel system suffered along with OKC. The attractions in the tunnels mostly disappeared and the pedestrians were primarily limited to walkers on their lunch breaks. The system was falling into disrepair. In 1998, the tunnel system was being run by public money and the fire department had determined the tunnel system unfit for use. An organization called the Downtown Oklahoma City, Inc. was created to assist with the tunnel redevelopment. The group claimed responsibility for the system and received assistance from the newly created business improvement district in 2001. The system was renovated in 2007 by integrating art galleries and renamed the *Underground*.

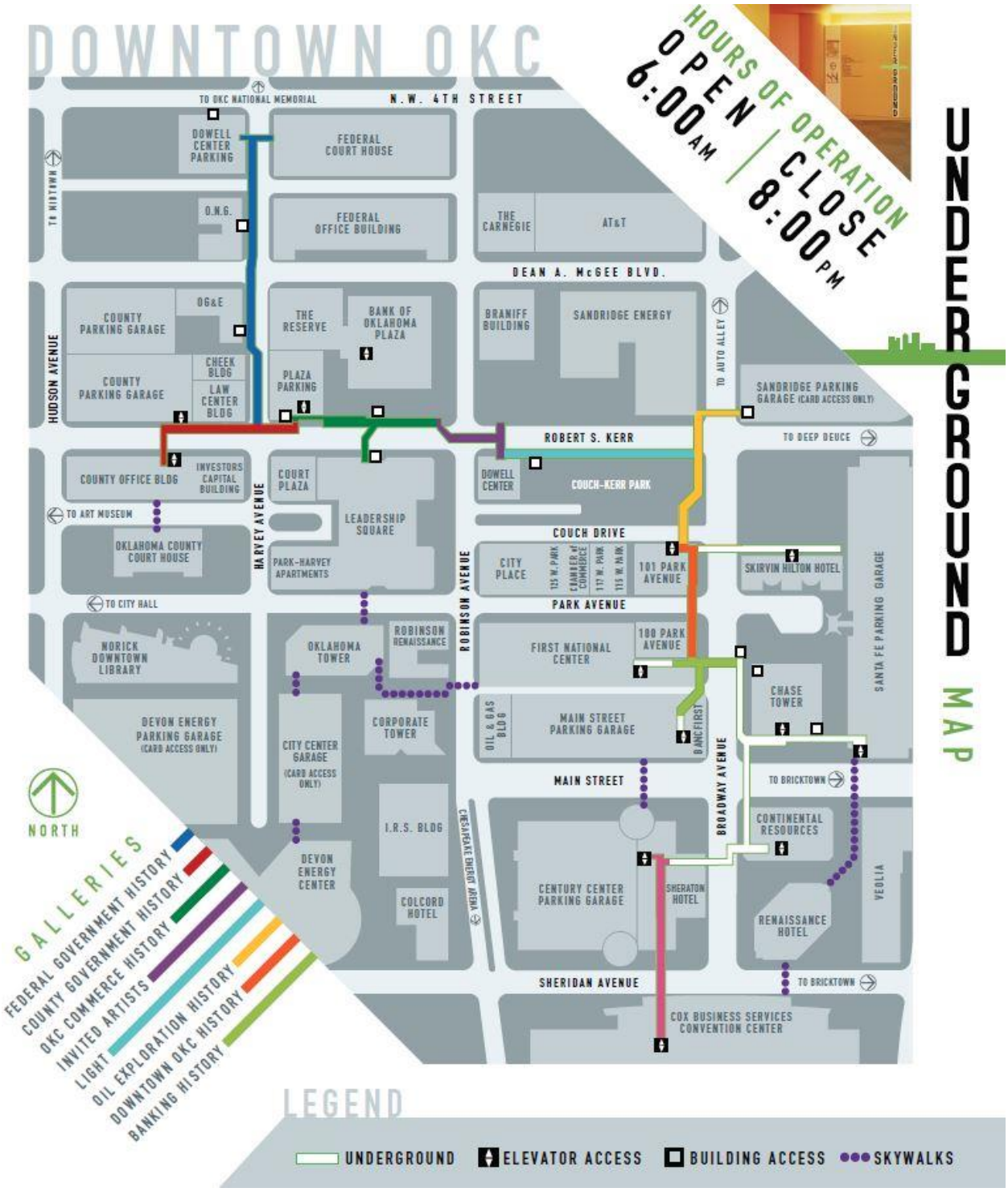


Figure 3-1. Layout of OKC Underground (Source: DowntownOKC 2016)

3.3.1.1 The Facilities Connected through the System

The tunnel system spans 20 square blocks and allows pedestrians to move throughout the business district easily with over 20 access points. The system is open from 6 a.m. to 8 p.m. during weekdays and is useful in times of extreme weather conditions. It also allows downtown workers easy access to parking garages and is a good exercise spot for walkers who want to avoid intersections (Figure 3-2). The tunnel system connects directly into many businesses and parking garages. Table 3-3 lists major facilities connected through the underground system. As shown in the table, it still has its original connections with the Skirvin Hotel and Skirvin Tower (now known as 101 Park Avenue).



Figure 3-2. An interior view of the system (Source: NewsOK 2014)

Table 3-3. Connections to OKC Underground

Hotels	Parking Garage	Government Building	Offices	Bank	Other
101 Park Avenue	Dowell Center Parking	Federal Courthouse	First National Center	Chase Tower	Cox Business Services Convention Center
Skirvin Hotel	County Parking Garage	County Office Building	Continental Resources	Bancfirst	Leadership Square
Sheraton Hotel	Plaza Parking		Oklahoma Natural Gas	Bank of Oklahoma Plaza	Dowell Center/Couch-Kerr Park
	Sandridge Parking Garage		Oklahoma Gas & Electric		

3.3.1.2 Funding Sources

The underground system was originally built by people in the hotel business and extended by those in the oil industry, led by Jack Conn. As time went by, the oil boom ended and the *Underground* ownership was handed over to public agencies. The expansion to the tunnel system was part of a large urban renewal plan implemented in the 1970's. Expansions and renovations

are funded by private entities and through Federal Redevelopment Grants. The maintenance cost of the system ranges from $150,000 to $200,000 a year. About 75% of the funding comes from businesses with direct connections to the Underground. The businesses are assigned a fee based on whether the business has a direct physical connection to the tunnel system or if it sees benefits from being within the proximity of the tunnels.

Sources that work or have worked directly with the OKC *Underground* have stated that developing such a system would not have happened without the initial private funding push for the tunnel system. The initial cost for a system similar to what OKC has would be beyond what most cities of their size could deal with.

3.3.1.3 Challenges and Lessons Learned

Complaints have accused the *Underground* of killing the street life as it brings people underground and off of the street level where many businesses have their storefronts. Some have even gone as far as suggesting the shutdown of the tunnels, although it has not been considered. The popularity of the tunnel system also fell considerably after the last oil boom ended as a result of the depressed economy. Today, the tunnel system has been called a "guilty pleasure" and has become so intertwined with OKC's everyday life that many people would have a difficult time imagining the city without it.

The upkeep and maintenance of the tunnels are challenging tasks. The system has seen flooding due to broken and leaking storm pipes that run overhead the tunnels as well as storm events and construction from street updates above. Unique difficulties are presented by the tunnels such as having to work carefully when constructing above it as well as flood control from storms and storm pipes.

3.3.2 Rochester (Minnesota) Underground Pedestrian System

As of 2013, population of Rochester, Minnesota, was around 110,000. Rochester has an underground pedestrian system which is also known as a subway. The original tunnel system connected the Kahler Hotel and the Mayo 1914 Building, which housed the Mayo Clinic's private medical practice. At that time, the system was primarily used by patients and doctors traveling back and forth from the Mayo medical buildings and the hotels at which they stayed. Expansions for the next 5 years brought the tunnel system to other Kahler owned properties as well as other

buildings such as the Franklin Station power plant and multiple other hotels. As time passed more extensions were added to the tunnel system. In the 1990's, Kahler added more on to the system as a connection from the Marriot Hotel in Rochester to the foyer of the Heritage Hall of the Kahler Hotel. The system was expanded by adding other important connections throughout the city. The final addition was built in 2003 - a 600 ft extension under Center Street. **Error! Reference source n ot found.** provides an overview of the current system.

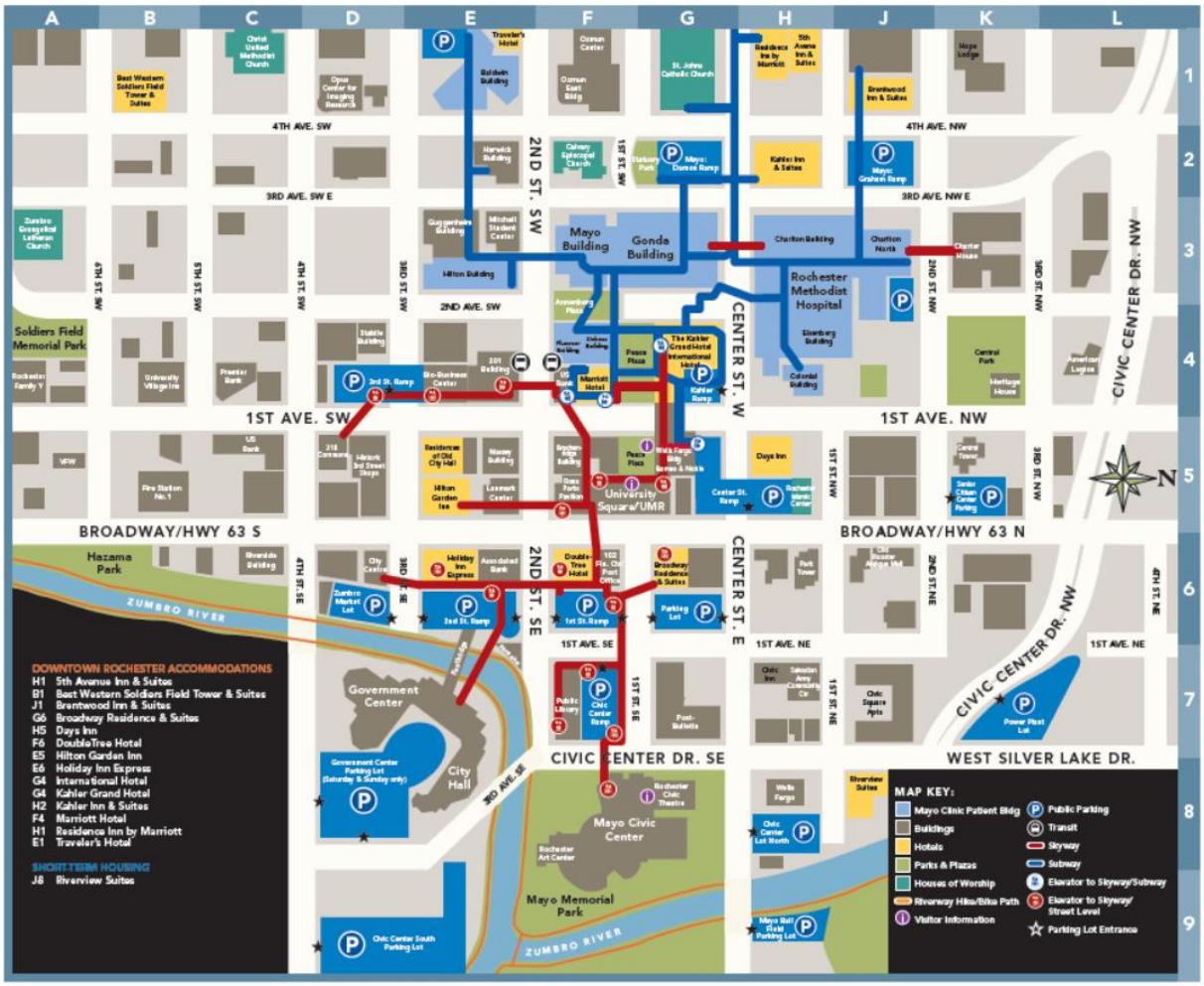


Figure 3-3. Overview of Rochester's subway and skywalk system (Source: Dixon 2016)

Today the underground pedestrian system is intertwined with thousands of hotel rooms, Mayo buildings, commercial buildings, restaurants, and entertainment venues. The walkways above and below ground are well marked and are mall-like with bright lighting and a multitude of

public art among the shopping experience. The Mayo Clinic has connections to nine different hotels (Figure 3-4). This allows patients and visitors to conveniently travel to and from their hotels.



Figure 3-4. Subway connection in the Mayo Clinic Building (Source: Dixon 2016)

3.3.2.1 Facilities Connected through the System

The pedestrian subway system in Rochester serves many Mayo medical buildings in the area as well as many Kahler hotels and properties (Figure 3-5). Rochester's unique distinction with the medical field, the main attractor of pedestrians is the Mayo buildings and their surrounding hotels. Many of these buildings have direct connections to the subway. Table 3-4 list major buildings and other facilities connected to the subway.



Figure 3-5. A view of the busy subway system in Rochester (Source: Baxter 2013)

Table 3-4. Connections to Rochester's Pedestrian Subway

Hotels	Parking Garage	Medical Facilities	Other
Kahler Grand Hotel	Mayo: Baldwin Ramp	Baldwin Building (Mayo)	Feith Family Statuary Park
Rochester Marriott Hotel	Mayo: Damon Ramp	Harwick Building (Mayo)	St. John's Catholic Church
Broadway Residences & Suites		Hilton Building (Mayo)	
Kahler Inn and Suites		Mayo Building	
Double Tree Hotel		Gondola Building	
Hilton Garden Inn		Mayo Clinic Hospital	
Holiday Inn Express			
Residence Inn by Marriott			
Brentwood Inn & Suite			

3.3.2.2 Funding Sources

Rochester had its tunnel system started by Mayo and it is still privately owned by Mayo and Kahler.

3.3.2.3 Challenges and Lessons Learned

Primary maintenance concern is flooding as shown in Figure 3-6.



Figure 3-6. Flooding of the Rochester subway (Source: Sederstrom 2013)

3.3.3 Review Summary of Two Case Studies

The cost of building an underground pedestrian system can run 3 to 10 times beyond the cost of a similar project at grade level (Cui et al. 2010). The initial costs of a tunnel system is very expensive and could result in difficulties in getting residents' support for using public money. Oklahoma City and Rochester underground pedestrian facilities were developed with private funding. In Oklahoma City the tunnel system was started by private hotel owners and expanded by Jack Conn later. Eventually private funding support was lost and the reliance of the OKC downtown residents on the system resulted in public entities taking over as they had grown

accustomed to the tunnels. Rochester had its tunnel system started by Mayo and it is still privately owned by Mayo and Kahler.

Along with the initial private funding, it would be important to consider both the prior cases to be out of the norm for the size of population that both have. Many cities that implement pedestrian tunnel systems do so for easing densities as well as weather avoidance, although they have much more money at their disposal than smaller cities. The average population of a North American city listed in **Error! Reference source not found.** is 1.7 million, 1.1 million more than O klahoma City and 1.5 million more than Rochester. In both cities, the UPS has provided many positives (inclement weather avoidance, relief of pedestrian density, etc.) as well as unique design and upkeep issues (flooding, high maintenance costs, etc.).

3.4 EVALUATION OF A SMALL CITY FOR A UPS - CITY OF KALAMAZOO

Downtown Kalamazoo, MI, is considered as a case study. First, the motivating factors relevant to Kalamazoo are compared with those of cities that have UPSs. Then the similarities and differences between Kalamazoo and the two previous case studies of Oklahoma City and Rochester are analyzed. Finally, conclusions and suggestions for downtown Kalamazoo are presented.

The main motivating factors for cities to implement an underground pedestrian system are climate, size of a city (in terms of population, land area, and population density), and economic level. Climate was the driving factor in North American cities. In analyzing climate, focus is on whether the city is a winter city and the amount of snowfall or precipitation that it receives. Table 3-2 is updated with relevant data for Kalamazoo and presented as Table 3-5.

Reviewing the table from left to right, it appears that Kalamazoo has climate conditions that favor having a UPS - an average temperature below 32 ºF for 3 months and an average snowfall of about 62 in. per year. The average yearly temperature in Kalamazoo is about 48 ºF (NOAA 2016).

Downtown Kalamazoo has the least population and the least land area compared to all the cities listed in Table 3-5. Because of the smaller land area, the city has a very high population density. With these numbers it is difficult to justify having a UPS.

Finally, the per capita income is the lowest among the North American cities listed in the Table 3-5. Lower economic levels mean less money to put forth into an underground pedestrian system that requires great initial investment and high maintenance.

Underground pedestrian systems in Oklahoma City and Rochester were initially developed with private funding. Kalamazoo Bronson Methodist Hospital also has an underground pedestrian system that connects all the hospital buildings. However, none of these tunnels are connected to downtown streets. In addition, a section of downtown streets have a snow melting system. Having a snow melting system encourages at grade pedestrian activities.

Further, several privately owned skyways are located in downtown Kalamazoo connecting hotels, parking garages, and offices. The purpose of providing skyways in Kalamazoo is to minimize street crossings and exposure to inclement weather. These skyways are used solely by pedestrians and do not have shops located within them. It appears to be redundant to offer skyways and UPSs in Kalamazoo. Overall a UPS can be a benefit to the city and its residents but it has costs beyond that of a similar construction at grade. At this point it appears that Kalamazoo would have a difficult time justifying a pedestrian tunnel system outside any private investments.

Table 3-5. Comparison of Kalamazoo against the Other Cities having UPSs

Cities	Weather Conditions			City Scale				Economic Level
	# of Month Below 0°F	Annual Snowfall (in/y)	Annual Average Temperature (°F)	Population (Thousand)	Land Area (mi^2)	Density (People per mi^2)	Year	Annual Per Capita Income (2009, US$)
New York	1	23.6	76	8,392	304	27,687	2009	30,885
Moscow	5	1097.6	61	10,523	418	25,214	2009	177,603
Beijing	3	65.6	77	13,300	529	25,180	2009	4,490
Hong Kong	0	0	85	7,034	427	16,501	2009	31,420
Tokyo	0	6.8	77	12,989	845	15,377	2009	48,597
Vancouver	0	22	63	578	45	13,818	2006	31,845
Chicago	3	44	72	2,851	228	12,559	2009	27,138
Montreal	4	84	68	1,621	141	11,497	2006	30,142
Philadelphia	1	23.6	76	1,547	136	11,448	2009	21,661
Shanghai	0	1.6	81	11,346	1023	11,093	2009	4,743
Toronto	4	49.6	68	2,503	244	10,288	2006	33,827
Atlanta	0	2.1	79	541	131	4,134	2009	36,912
Houston	0	0.4	83	2,258	580	3,898	2009	25,563
Dallas	0	3.2	85	1,300	343	3,800	2009	25,941
Winnipeg	5	44.4	65	675	180	3,769	2009	31,942
Nanjing	0	1.6	81	5,460	1824	2,995	2009	4,009
Edmonton	5	49.6	59	782	265	2,961	2009	39,126
Rochester	3	54	46	110	55	2,026	Varies	30,977
Harbin	5	25.2	70	4,747	2736	1,736	2009	2,028
Oklahoma City	0	9.2	81	560	607	925	2009	24,195
Kalamazoo	**3**	**62.8**	**49**	**76**	**25**	**19,943**	**Varies**	**19,064**

4 ABOVEGROUND PEDESTRIAN SYSTEMS

4.1 OVERVIEW

Aboveground pedestrian systems (AGPSs) comprised of very short pedestrian bridges as well as extensive networks of above ground facilities (skywalks) that helps getting non-motorized traffic moving from one point to another. The structural systems and architecture used in these facilities can range from very expensive elegant structures to very simple bridges. In the 1960's and 1970's, approximately 20 to 30 cities in the United States adopted the idea of implementing skywalk systems in their cities (Cornwell 2006). Skywalks may be enclosed and climate controlled, offering protection from extreme weather such as heat, freezing conditions, thunderstorms, and snow storms. Less expensive skywalk segments are open and provides less protection than enclosed segments. Some skywalks may not even have a roof. Figure 4-1 shows an example of a simple bridge.



Figure 4-1. A bridge crossing a freeway (Source: Pinterest 2016)

4.2 MOTIVATING FACTORS

In the 1960's and 70's, many cities throughout the United States incorporated skywalks. This became popular due to the newly formed shopping malls that offered a complete indoor shopping experience. It is expected that skywalks would help attract people to downtown areas and offer a more urban feel. Although specific reasons for implementing a skywalk network in a city may differ from one to another, city development is the primary reason for implementing a skywalk network. When covered skywalks are connected to office buildings and businesses, an

increase in business activities are observed because office workers are more likely to go out during lunch break irrespective of the outdoor exposure conditions.

Skywalks offer safe passages by separating pedestrians from vehicular traffic. Some cities use skywalks for efficient use of the available area by creating additional spaces above the streets. As shown in A city may find skywalks desirable for a number of reasons. A general list of motivational factors is given below:

- Connect nearby business facilities
- Elevate pedestrians to a location away from moving vehicular traffic
- Expand businesses
- Improve comfort level for pedestrians and workers
- Maximize the use of space in downtowns
- Improve property values
- Make a city feels more urban and up to date
- Provide protection against poor weather and harsh climate conditions.

Table 4-1, Bangkok, Hong Kong, and Mumbai have the highest population densities and uses skywalks to reduce street level crowding.

As cities grow, businesses within them tend to grow as well. Skywalks are used for expanding the spaces owned by the same business by bridging adjacent buildings. As part of the Milwaukee's Skywalk System, Northwestern Mutual connected neighboring buildings to expand the space that they owned. Due to convenience and comfort offered by skywalks, building owners charge higher rates for skyway-connected properties (Roper 2012).

A city may find skywalks desirable for a number of reasons. A general list of motivational factors is given below:

- Connect nearby business facilities
- Elevate pedestrians to a location away from moving vehicular traffic
- Expand businesses
- Improve comfort level for pedestrians and workers
- Maximize the use of space in downtowns
- Improve property values
- Make a city feels more urban and up to date
- Provide protection against poor weather and harsh climate conditions.

Table 4-1. Facts about Skywalk Bearing Cities

Cities	Weather Conditions		City Scale			
	Average Annual Snowfall (in)	Avg. Snowfall (days/year)	Population (2010 Census)	Area (mi^2)	Density (People per mi^2)	Per Capita Income ($)
Mumbai, India	-	-	12,478,447	232.9	53,603	1,858
Hong Kong	-	-	7,024,200	426.00	16,488	31,420
Bangkok, Thailand	-	-	8,280,925	606.00	13,665	13,623
Toronto, Ontario	48.8	40.9	2,615,060	243.3	10,749	55,923
Hartford, Connecticut	41.2	20.1	124,775	18	6,952	16,448
Baltimore, Maryland	20.6	9.6	620,961	92.3	6,729	24,155
Minneapolis, Minnesota	54.9	37.3	382,578	58.5	6,548	30,734
Milwaukee, Wisconsin	47.7	35.3	594,833	96.8	6,147	19,199
Rochester, New York	101.1	65.9	210,565	37.2	5,675	18,757
Detroit, Michigan	43.4	36.4	713,777	142.9	4,997	14,861
Grand Rapids, Michigan	76.1	52.1	188,040	45.3	4,155	20,147
Cincinnati, Ohio	4	28.4	296,943	79.6	3,733	24,538
Winnipeg, Manitoba	45.5	53	663,615	179.3	3,704	31,942
Spokane, Washington	45.6	34.4	208,916	60.1	3,481	24,034
Calgary, Alberta	21.7	129	1,096,833	318.6	3,443	43,637
Atlanta, Georgia	3	2.1	420,003	132.4	3,173	35,719
Kalamazoo, Michigan	59.1	44.6	74,262	25.2	2,958	18,402
Des Moines, Iowa	35.5	26.2	203,433	82.6	2464	23,914
Charlotte, North Carolina	4.4	1.9	731,424	297.7	2458	31,653
Indianapolis, Indiana	26.4	23.5	820,445	372	2207	24,340
Sioux City, Iowa	35.4	25.5	82,684	58.9	1404	21,742
Morristown, Tennessee	8.8	4.2	29,137	20.9	1397	17,718
Duluth, Minnesota	87.5	60.6	86,265	87.5	987	24,480
Oklahoma City, Oklahoma	8	5.6	579,999	620.00	935	24,629
Kansas City, Kansas	13.6	8.3	145,786	319	456	18,771

4.3 REVIEW OF EXISTING SYSTEMS

4.3.1 Skywalk System in Des Moines, Iowa

Des Moines, with a population of approximately 200,000 people, has one of the most extensive skywalk systems in the country. Originally covering 12 blocks, the system now encompasses about 60 blocks with over three miles of indoor climate controlled walkways. Construction began in 1969 with a majority of the skywalks being implemented in the 1980's. A map of the current skywalk system is available in a mobile phone application (Figure 4-2). The map shows sidewalk access points (also locating handicap accessible points) and provide detours for temporarily closed skywalk segments.



Figure 4-2. Skywalk map on the app (Source: SkywalkDSM 2016)

The primary objective for developing a skywalk system was to inspire economic development in Des Moines by attracting new businesses to the downtown area while maintaining existing businesses. The existing skywalk system helps making the downtown area more compact as the city continues to evolve and become more populated. The skywalk system is not entirely a public property. In general, the city of Des Moines provides funds for construction of skywalks crossing the street (when right-of-way for construction is required) and building owners pay for private skywalks within their premises.

The city of Des Moines is working on better integrating their sidewalk and skywalk systems. As investment in improving the quality of the pedestrian experience continues, early returns are observed. Favorable responses to the investments are observed in terms of increased private investments, thriving retail businesses, and increased pedestrian activity. Investment in the quality of the pedestrian experience includes additional signage as well as updating out-of-date signage. It also includes having additional, and more identifiable, vertical connections from the sidewalk to the skywalk. The city also wants to work on adding "beauty", as continually requested by citizens at public meetings (Crownie et al. 2008). This not only includes the beauty of the skywalk itself but the view the skywalk offers from an elevated position in comparison to the

sidewalk. Figure 4-3 shows an inside view of a skywalk segment crossing a street within downtown Des Moines.

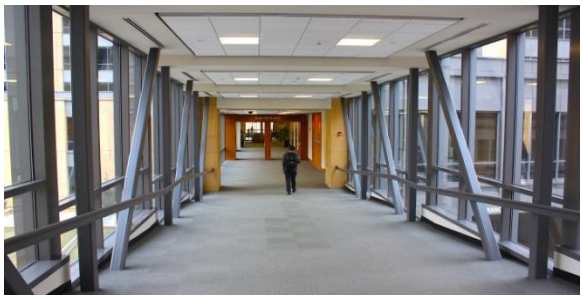


Figure 4-3. An inside view of a skywalk segment in Des Moines (Source: Carole 2013)

The city is planning for additional connections between existing skywalks as well as extending the skywalk to growing downtown locales. The future expansions will encompass the west side of the Des Moines River, the Methodist Hospital and related medical campuses, popular transit stops, and parking structures. It is noted that most of the large employers that have office buildings in downtown do have connections to nearby parking structures. However, those structures are primarily used by the people working in that particular building and need to be expanded to connect with the rest of the systems to better serve the pedestrians traversing the city.

Challenges of expanding existing systems or developing new systems are in general related to city's existing infrastructure. For example, many existing structures need evaluation, repair/retrofits, or in some cases even replacement in order to incorporate skywalks. The skywalk infrastructure require routine inspection and maintenance. The private and public relationship that builds the skywalk system makes it difficult to manage. Another challenge for a city is to make vertical access points more abundant and identifiable. This has become a problem for the skywalk system because many of the vertical access points are located within private business properties. Another consideration for developing or expanding skywalk systems is the impact on city's landscape and aesthetics.

4.3.1.1 The Facilities Connected through the Des Moines Skywalk System

A Partial list of major facilities connected to the skywalk system is given below:

- Wells Fargo Arena- A 16,980-seat multi-purpose arena
- Community Choice Credit Union Convention Center (Iowa Events Center) - Features 29 meeting rooms and a 28,730 square feet ballroom
- Hy-Vee Hall- Contains over 150,000 square feet of space for events, meetings, etc.

- Wellmark YMCA- Community-focused nonprofit offering recreational programs
- Renaissance Des Moines Savery Hotel- 11-story hotel with conference rooms and over 12,000 square feet of space
- Des Moines Performing Arts (Civic Center) - Performing art center, features two theaters and a park
- Des Moines Information Center- City government information and referral center
- Hyatt Place Des Moines Downtown- 12-story hotel with 1,050 ft^2 of meeting spaces
- Des Moines Marriott Downtown - 33-story hotel featuring 417 rooms and suites
- Des Lux Hotel- 5-story upscale hotel with 51 rooms.

4.3.2 Skyway System in Cincinnati, Ohio

Cincinnati had the idea to build a skywalk in their city back in the 1960's. The idea came to life in the 1970's, as the first link of the skywalk connected Fountain Square to the Convention Center in 1971. Construction was completed in 1998. The entire 1.3-mile skywalk is mostly enclosed. The total cost is little over $16M (Alltucker 2003).

Some cities saw skywalks as a way of modernizing their pedestrian experience. The goal is to make pedestrians feel cleaner and safer being elevated off the streets (Healy 2005). Cincinnati's skywalks are no different, and were an attempt of modernizing their city and meant to be an asset to the downtown area. However, the skywalk made the streets feel deserted and lifeless.

Between general maintenance and safety, the skywalks had their fair share of problems. When the skywalk was built, the city had made approximately 40 different arrangements with private business owners. These arrangements were meant to act as a contract to take care of regular maintenance of a designated section of the skywalk. These arrangements were not well detailed for the business owners to understand their responsibilities. The businesses often tend to disregard the general maintenance. This led to problems such as unfixed broken windows, drainage issues, leaky roofs, rust, etc. Due to lack of maintenance, the open-climate skywalk segment was torn down in 2012.

4.3.2.1 The Facilities Connected through the System

Layout of the skywalk network in Cincinnati is shown in Figure 4-4. This walkway provides access to many facilities in the downtown area. A partial list of the major facilities is given below:

- Duke Energy Convention Center - Over 750,000 ft^2 of area including a ballroom
- Saks Fifth Avenue. – A two-story, designer department store
- Carew Tower - An observation deck for Cincinnati standing 49 stories high. Carew Tower incorporates a total of 25 different shops, restaurants, and offices.
- Tower Place Mall - A closed mall in the same block district as Carew Tower
- Fountain Place Lazarus - A three-story department store with 814,000 ft^2
- Westin Hotel - Historic hotel made in 1897 with 188 rooms spanning the 4^{th} to 17^{th} floor
- Fountain Square District - Includes many shops and acts as a town square above ground.
- Fifth Third Bank Center - Headquarters of Fifth Third Bank, 30 stories high
- 580 Walnut Offices - Office buildings that are currently closed.
- Federal Courthouse - Courthouse and Federal Building.
- John Weld Peck Federal Building - Federal Government Office.
- 250 E. Fifth St. (Chiquita Building) – Building with 29 floors that hold offices. Currently looking to rent out top 6 floors.
- PNC Center - Building with 27 floors that are used for offices and commercial use.

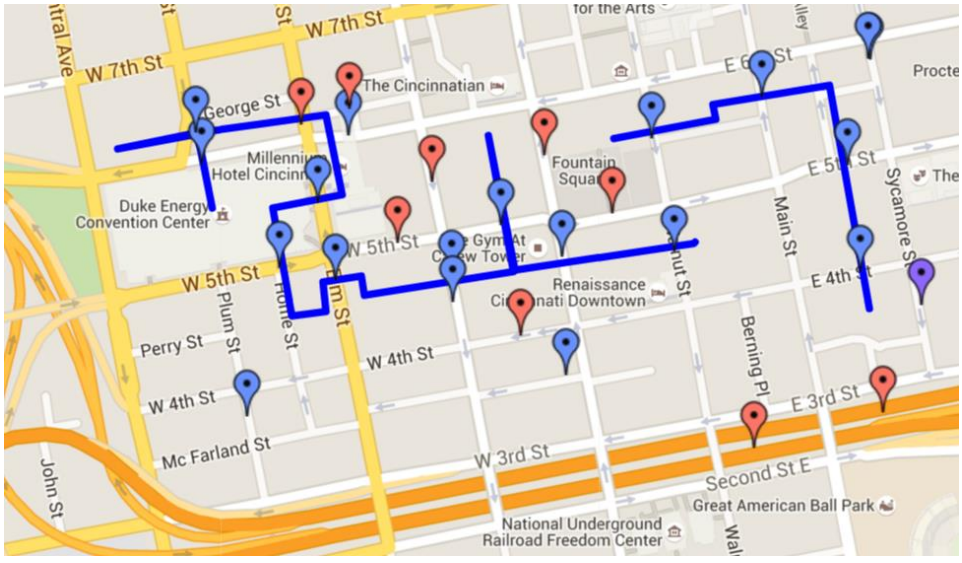


Figure 4-4. Skywalk network in downtown Cincinnati (Source: Google)

4.3.3 Skywalk System in Milwaukee, Wisconsin

Figure 4-5 shows the network layout. The total length of the skywalk system is 1.75 miles. It is used to connect adjacent buildings, either across the street or on the same side of the street. There are two skywalks that act as foot bridges across the Milwaukee River. The entire system is privately owned and maintained. It is open from Monday through Friday from 7:30 am to 5:30 pm, but certain sections that are controlled by business owners are closed during certain hours (Milwaukee Downtown 2016).



Figure 4-5. Downtown Milwaukee skywalk network (Source: Milwaukee Downtown 2016)

The system connects over 10,000 parking spots located in parking structures and allows thousands of people to move directly from their parking spots to work or to a department store for shopping. Skywalks helps businesses expanding their office space and working area. In the case of Northwestern Mutual Fund, the company purchased a building across the street of their existing address and planned on moving employees to this new location. The new building is used as an extra storage with additional office spaces (Ryan 2012). The company used a skywalk to connect the buildings and bring unity back to the offices. Many other skywalks throughout Milwaukee offer a synergistic vibe to the businesses. For example, connecting a strip mall to a hotel can offer

a lot of persuasion to where someone may venture out to go shopping or eat, potentially increasing sales for nearby businesses.

Businesses that have attached skywalks will pay for leasing the air space. Northwestern Mutual was permitted the lease the air space above the street to construct a skywalk connecting two office buildings. Northwestern Mutual pays $5,000 annually as the rental fees for the air space (Daykin 2014).

In the past, Milwaukee skywalks were used to retain large business in the area. In 1996, Milwaukee City officials agreed to pay $600,000 on a $1.2M bill for adding a skywalk connecting Firstar Center and the Lewis Center spanning across Van Buren St. The city stated the decision was made as part of an economic development. The skywalk helps retain Firstar Center in Milwaukee to pays a large amount of taxes to the city (Daykin 1996).

4.3.3.1 The Facilities Connected through the System

An overview of the system and major establishments connected through the system are listed below. In addition, Table 4-2 listed the facilities as hotels, parking garages, etc. General information about the skywalk system:

- 1.75-mile skywalk system
- 18 coffee shops
- 2,497 beds in hotels
- 10,399 parking spots within 13 parking structures
- 6 fitness centers
- 11 banks and ATMs
- 28 eateries, ranging from steakhouses to quick stop and goes
- Connects over the Milwaukee River in two different locations

Buildings connected through the system:

- Faison Building – 430,865 ft^2 of Class A office space in a 35-story tower
- The Riverside Theater – Historic theater with 1,339 seating
- Wisconsin Center District - Convention and entertainment center
- Hyatt Regency Milwaukee – A hotel with 481 guestrooms
- Hilton Milwaukee City Center – a four diamond hotel with 729 rooms and suites

- Spring Hill Suites – six-story hotel opened in June, 2016
- The Blue – Office space with 20,000 square feet ground retail space
- Shops of Grand Avenue - Urban shopping plaza spanning a total of three blocks
- Courtyard Milwaukee - six-story hotel with 169 rooms and suites
- Residence Inn – seven-story hotel with a business center and three meeting rooms
- Chase Tower – a 22-story skyscraper with 480,000 square feet of office space
- 250 E. Wisconsin Avenue. – a 20-story office building with 200,039 square feet.

Table 4-2. Major Skywalk Connections in Milwaukee

Hotels	Parking Garages	Offices	Banks	Other
Hilton Milwaukee City Center	310 W. Wisconsin	Faison Building	Chase Tower	Wisconsin Center District Convention Center
Hyatt Regency Milwaukee	Isaacs Family Limited	The Blue		Riverside Theater
Spring Hill Suites	The Shops of Grand Avenue Parking	250 E. Wisconsin Ave.		The Shops of Grand Avenue
Residence Inn by Marriott	Central Parking			
Courtyard Milwaukee by Marriott				

4.4 FUNDING SOURCES

In certain cities, the private sector invested in skywalks based on their needs. With others, the city completely or partially financed the construction. Cincinnati is an example of a city where the public sector provided funding to implement a skywalk network. Cincinnati implemented a 1.3-mile skywalk over the course of 17 years with a net cost of approximately $16 million. Cincinnati public money also paid for the removal of specific, unwanted segments.

In Milwaukee, funding was provided by private businesses. The businesses have to go through an approval process to receive a permit for adding a skywalk segment. In Milwaukee, the public sector makes money from private sector investments because the city does not pay for the construction but charges the business for leasing the air space above the street. Due to the private business involvement in the construction of these skywalks, funding amounts are not available in the public domain and might require contacting city officials for records.

Des Moines funding mechanism differs from both Cincinnati and Milwaukee. In Des Moines, the city will pay for the construction of skywalks passing over the street, when right-of-way is required. However, Des Moines does not pay for the private segments within a business

entity. Due to the private business involvement in the construction of these skywalks, funding amounts are not available in the public domain and might require contacting city officials for records.

4.5 LESSONS LEARNED

Funding and implementing a skywalk network by public sector is risky business. It is risky because the people that are supposed to utilize the network may not appreciate it. The skywalk may become underappreciated due to aesthetic reasons, or perhaps the location is not quite right for it to be used by most people. It is potentially more expensive than just the cost of construction as there can be added costs due to maintenance and climate control. When a city implements the skywalk, the city must decide who is responsible for maintenance as well. In Cincinnati's case, the city made agreements with the businesses that were directly attached to the skywalks to make them responsible for general maintenance. When the skywalks are abandoned by their designated businesses, they become grungy and uncomfortable for pedestrians to use. The people that are supposed to use them now avoid them like a dark alley. With public skywalks, they are open all the time, just like the roads. This can attract disorderly teenagers to hangout in the segments with dead ends or similar areas.

A great benefit of the skywalks being privatized is that it almost guarantees it will get well utilized. The only reason a company is going to pay for a skywalk to be connected to their place of business is if it will provide a valuable function. Whether it is for a business opportunity to have more people walk past your store or to connect two offices, the skywalk will be put to good use under private funding. Furthermore, the skywalk will not be abandoned into disrepair by its business that it connects to. A major drawback of having private entities funding and operating skywalks is the controlled hours of operation. The skywalk may only be open for a limited number of hours a day making it inconvenient to public. However, this becomes a challenge only if the closed section becomes a bottleneck for the operation of the rest of the network.

With skywalk networks, there is a decrease in street level activity. This can be seen as a benefit, if attracting people to an elevated position (and away from vehicular traffic) is the goal. It can have a negative impact as it may reduce business to the retailers at the ground level.

A list of general lessons learned is given below:

- Publicly funded skywalks can be a burden to the tax payers

- Skywalks that incorporate both private and public funding can be more difficult to manage unless clear maintenance instructions and guidelines are presented.
- Appropriate signage and directions are necessary within a skywalk.
- Skywalks are better accepted when they are aesthetically pleasing.
- Presence of adequate number of easily identifiable vertical access points are important to make a system attractive.
- Skywalks are useful and appreciated in colder climates

5 TECHNOLOGY FOR IMPROVING SUSTAINABILITY AND RESILIENCE

5.1 OVERVIEW

Pedestrian lighting systems and snow melting systems are described in this chapter. Also, planning tools for identifying optimum locations for installing renewable power sources such as wind and solar are discussed. In addition, implementation case studies and challenges and lessons learned are presented.

5.2 PEDESTRIAN LIGHTING

Pedestrians must be able to safely navigate through streets and walkways. Lighting systems must be properly installed and maintained to ensure pedestrian safety; thus, rationally developed guidelines are needed. Also, use of energy efficient luminaries are needed to reduce operational costs. This section synthesizes types of luminaries and performance (in terms of efficiency), a commonly used tool for designing lighting configurations, and cost of implementation.

5.2.1 Luminaire

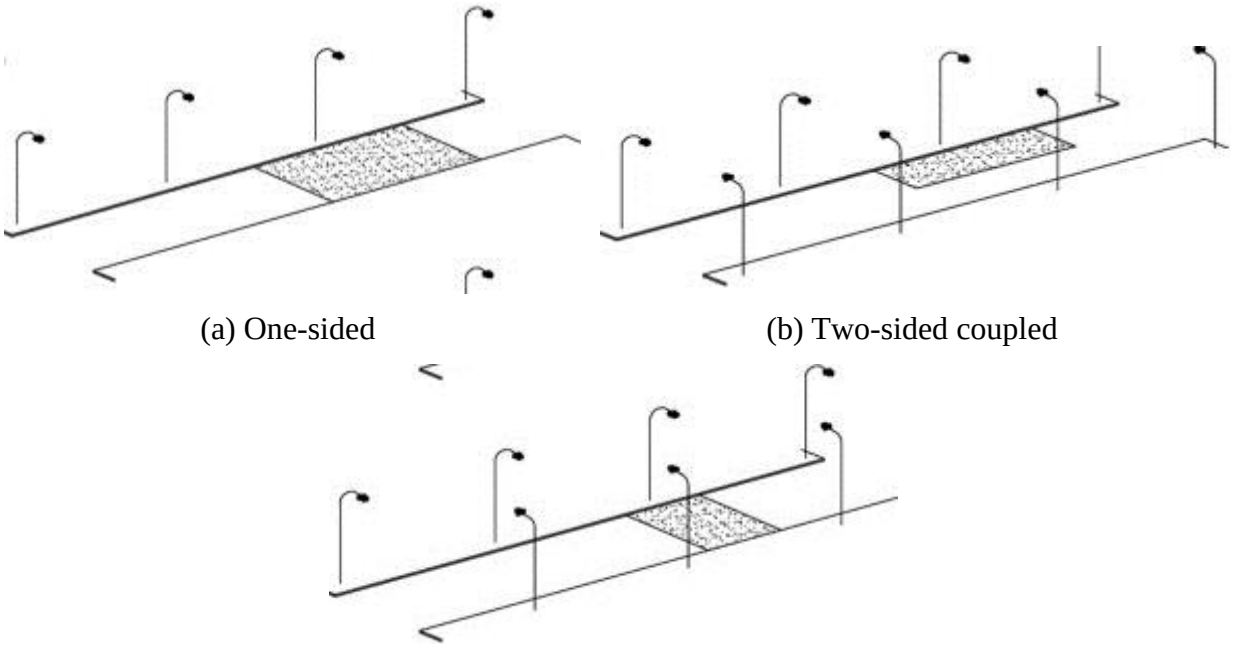
5.2.1.1 Types of Luminaires

There are three major luminaire types used in street lighting systems: high intensity discharge (HID), fluorescent, and incandescent. Among these, HID lamps are the most common type. The most common HID lamps are mercury vapor (MV), metal halide (MH), and high pressure sodium (HPS). Of these three types, HPS and MH are predominant. MH lamps offer superior color quality with a bright white light output, while most HPS lamps offer greater efficiency at the expense of color rendering by producing an amber light (Pipattanasomporn et al 2014). More recently, Light Emitting Diodes – LED are considered by many agencies due to its lower power consumption; thus, lower operational costs (Relume 2016; Gibbons et al. 2015).

5.2.1.2 Typical Arrangement

Lighting systems follow set requirements and arranged in various configurations (BS 5489 2013). The three common configurations are one-sided, two-sided staggered, and two-sided coupled. Figure 5-1 illustrates these 3 arrangements. The one-sided arrangement utilizes the luminaires on one side of a road. The two-sided coupled arrangement is most commonly seen on

highways, interstates, and most streets because of its functionality and expansive coverage for pedestrians. The staggered arrangement involves each luminaire being placed, alternating from one side to the other. This arrangement overlaps the coverage of each luminaire and increases the glare towards likely pedestrians. The hatched area shown with each configuration is the theoretical area illuminated by each individual luminaire assumed for design calculations.



(a) One-sided (b) Two-sided coupled

(c) Two-sided staggered

Figure 5-1. Lighting configurations (Rabaza et al 2013)

Rabaza et al. (2016) presented typical guidelines used by lighting designers for selecting a lighting configuration (Table 5-1). However, the guidelines do not include a criterion to determine spacing of luminaries for each configuration.

Table 5-1. Lighting Configuration and Width/Height Ratio (Rabaza et al. 2016)

Configuration	(Street width, ω)/(Mounting Height, H)
One-sided	B/H < 1
Two-sided staggered	1 ⩽ B/H < 1.5
Two-sided coupled	1.5 ⩽ B/H

5.2.1.3 Luminaire Efficiency

Rabaza et al. (2013) conducted a study evaluating the efficiency of luminaries following 2008 Street Lighting Energy Efficiency Criterion (SLEEC) and International Commission on Illumination (CIE) standards. An efficiency of a luminaire system is evaluated using Eq.1 while

an efficiency of a single luminaire is evaluated using Eq. 2. In these equation, A_T is the total surface area illuminated by luminaries; E_{av} is the average illuminance; P_T is the total electrical power consumed by the entire system; A is the surface area for a single luminaire that is determined based on the lighting arrangements shown in Figure 5-1; and P is the electrical power consumed by one luminaire that includes light sources and electrical auxiliary devices/systems.

$$\varepsilon = A_T \times E_{av}/P_T \quad (1)$$

$$\varepsilon = A \times E_{av}/P \quad (2)$$

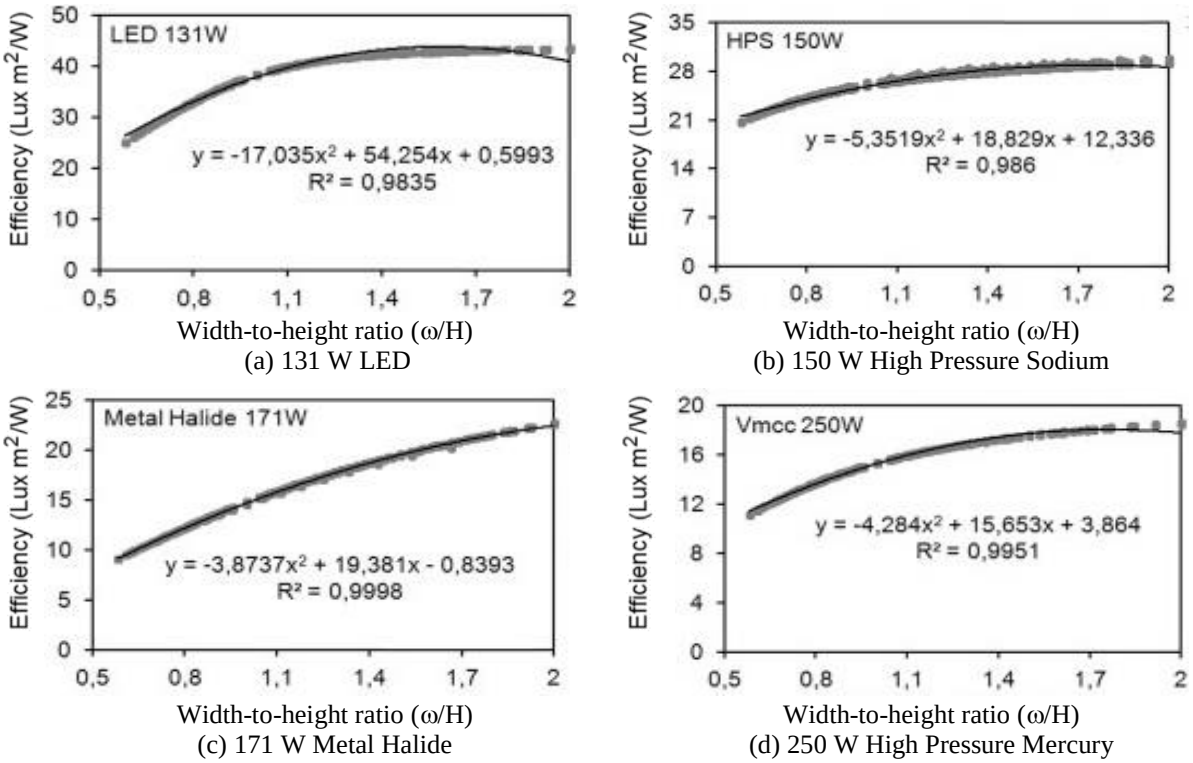
As an example, Rabaza et al. (2016) evaluated energy efficiency variation of LED, HPS, MH, and High Pressure Mercury (HPM) luminaires against ω/H ratio (i.e., the ratio of street width-to-height of luminaries). As shown in Figure 5-2, the LED luminaire exhibited the highest efficiency (~ 40 Lux m²/W) with a ω/H ratio of about 1.4. Efficiency of HPS luminaire exhibits a constant increase until ω/H = 1.7, and remains constant at 28 Lux m²/W up to ω/H = 2. The HPM luminaire exhibited the same trend as LED and HPS but the efficiency of HPM was significantly lower. Efficiency of MH and HPM luminaries are at or below 50% of the average LED efficiency even with a ω/H ratio of 2. Of the four luminaires used in the energy efficiency analysis, the LED was found to be the luminaire with the highest efficiency. Even though the initial implementation cost is high, higher efficiency makes life-cycle cost of LED much lower (Relume 2016). Hence, LED is used to replace other luminaire types.

Based on the data from the analysis shown in Figure 5-2, which complies with CIE and SLEEC recommendations, more advanced polynomial models were constructed by Rabaza et al (2016) displaying the energy efficiency of each luminaire type as a function of ω/H ratio. Eq. 3 is a quadratic polynomial representing efficiency variation of a luminaire.

$$\varepsilon = a_0 + a_1 \times (\omega/H) + a_2 \times (\omega/H)^2 \quad (3)$$

where a_i represents polynomial coefficients specific to each luminaire type. As an example, Figure 5-2a shows variation of LED 131W luminaire efficiency against ω/H ratio and the polynomial derived through curve fitting. According to the polynomial, $a_0 = 17.035$, $a_1 = 54.254$, and $a_2 = 0.5993$. Hence, the efficiency of the specific LED 131W luminaire system is represented by Eq. 4. For other luminaire types, manufacturers are expected to present all the system components in a lighting system and the efficiency variation for designers to use.

$$\varepsilon = 17.035 + 54.254\ (\omega/H) + 0.5993\ (\omega/H)^2 \quad (4)$$



(a) 131 W LED (b) 150 W High Pressure Sodium

(c) 171 W Metal Halide (d) 250 W High Pressure Mercury

Figure 5-2. Energy efficiency variation against width/height ratio (Rabaza et al. 2016)

The EU standard EN13201-5 defines Streetlight Energy Efficiency Criterion (SLEEC). As shown in Eq. 5, an efficiency parameter is calculated based on illuminance based lighting design (SE) or luminance based design (SL). Table 5-2 shows energy efficiency classification based on SE or SL values. As an example, if SE calculated for a specific luminaire falls within the range of 0 to 0.014 W/ (lux. m^2), that luminaire belongs to the highest energy efficient class – A. The efficiency parameter provides an opportunity to select the most energy efficient luminaire type from a group of luminaries considered for a specific application.

$$\text{SE or SL} = 1/\varepsilon \quad (5)$$

Table 5-2. Energy Efficiency Classification of Luminaire (Rabaza et al. 2016)

Energy Class	SE W/(lux·m^2)	SL W/(cd/m^2)/m^2
A	0.000–0.014	0.00–0.21
B	0.015–0.024	0.22–0.36
C	0.025–0.034	0.37–0.51
D	0.035–0.044	0.52–0.66
E	0.045–0.054	0.67–0.81
F	0.055–0.064	0.82–0.96
G	0.065–0.074	0.97–1.11

5.2.1.4 Lighting Series Classes

Table 5-3 presents lighting series classes based on roadway or pedestrian/cyclist pathway traffic exposure conditions (such as conflict areas, low speed areas, and high speed areas). In addition, the table provides an average minimum illuminance and luminance levels for each class and the minimum uniformity requirement. Uniformity (U_0) is defined as the ratio of minimum to average illuminance (E_{min}/E_{ave}). The P series is relevant to pedestrians and cyclists on road areas lying separately along a traffic area (BS 5489 2013). For P series, the minimum average illuminance ranges from 2 to 15 lux. The CE series is also applicable to pedestrians and cyclists. For CE series, the minimum average illuminance ranges from 7.5 to 50 lux. Selection of an appropriate lighting class depends on many factors such as ambient luminance condition, roadway type and uses, and amount of traffic (Table 5-4 and Table 5-5). Once a lighting class is selected, average minimum illuminance or luminance as well as the uniformity can be selected.

Table 5-3. Lighting Series Classes and Corresponding Average Minimum Illuminance and Luminance, and Uniformity (CIE 2013)

	Lighting Series Class									**U_0**
Low speed areas	P6	P5	P4	P3	P2	P1				≥ 0.2
Conflict areas				CE5	CE4	CE3	CE2	CE1	CE0	≥ 0.4
High speed areas			ME6	ME5	ME4	ME3	ME2	ME1		≥ 0.4
Average Minimum Illuminance (lux)	2	3	5	7.5	10	15	20	30	50	
Average Minimum Luminance (cd/m^2)			0.3	0.5	0.75	1	1.5	2		

Table 5-4. Lighting Classes for Subsidiary Roads with Mainly Slow-Moving Vehicles, Cyclists, and Pedestrians (BS 5489 2013)

Traffic Flow	Ambient Luminance	
	Very low (E1) or low (E2)	Moderate (E3) or high (E4)
Busy	P4	P4
Normal	P5	P5
Quiet	P6	P6

Table 5-5. Lighting Classes for City and Town Centres (BS 5489 2013)

Type of traffic	Lighting class			
	Normal traffic flow		High traffic flow	
	E3	E4	E3	E4
Pedestrian thoroughfare	P2	P1	P2	P1
Pedestrian only	CE4	CE3	CE3	CE2
Mixed vehicle and pedestrian with separate footways	CE3	CE2	CE2	CE1
Mixed vehicle and pedestrian on same surface	CE2	CE1	CE1	CE1

5.2.2 Tools for Designing Lighting Configurations

DIALux, is a program used to calculate E_{ave} and U_0 parameters. **DIALux** utilizes different luminaire types available in an online catalog linked to the luminaire section of the software. Luminaire types are selected and other parameters such as pole spacing, pole height, light overhang, maintenance standard, and luminaire arrangement (which includes height (H), spacing (S), width (ω), and configuration) are defined. The program output include the minimum E_{ave} and U_0 values for the defined configuration. These values are then compared to the minimum and average standard values (set by both the CIE and the BS EN standards). As an example, lighting class can be selected from Table 5-4 or Table 5-5 and the minimum E_{ave} and U_0 values are determined from Table 5-3 to check against the software output. When the requirements are not satisfied, either luminaire type, spacing, arrangement, or a combination thereof is changed until satisfactory results are obtained. Rabaza et al. (2016) demonstrate application of **DIALux** software for evaluating various lighting configurations and luminaire types.

5.2.3 Case Studies

5.2.3.1 LED Implementation

LED is emerging as the most energy efficient technology for lighting applications. Most of the existing applications focus on replacing existing street lighting units with more energy

efficient LEDs. Examples include roadway lighting in Philadelphia, walkway lighting in New York City, roadway lighting on Golden Gate Bridge, and roadway lighting in Portland, OR (DOE 2012 and 2013). Findings from these projects indicate that the potential for energy savings of energy efficient LED-based systems is as much as 50% compared with that of the traditional high pressure sodium (HPS) lamps. One interesting feature of LEDs is the ability to reduce their illumination level based on the ambient conditions and needs. As a result, some of the LED demonstration projects explored dimmable features of LEDs with occupancy sensors, mainly for parking garages. At present, LED lighting systems have become more commonly accepted and selected municipalities have already upgraded their street lighting systems to LED.

The systems are designed such that the LEDs are activated after sunset and their intensity is reduced using dimmable feature to save energy costs. A sensor network can be installed to monitor pedestrian activity, so that traffic activates the LEDs to their full intensity. As an example, a LED lighting system was implemented to replace 8 existing HPS luminaires in a lighting system at the US Navy Research Center in Maryland (Pipattanasomporn et al. 2014). Figure 5-3 shows the locations of light poles, traffic sensors, and the building. Table 5-6 shows the components used for this implementation, number of units, and the installation locations. Results indicated a significant reduction in energy usage with about 74% electricity savings after the implementation of LED luminaires instead of HPS luminaires. The annual electricity savings due to LED when compared to HPS is 11,060 kWh. This resulted in 7294 kg of lower CO_2 than their HPS counterparts. This data demonstrates that the implementation of state-of-the-art technology into existing pedestrian systems can make the systems more efficient and user-friendly.

Table 5-6. Technology Components and Installation Locations (Pipattanasomporn et al. 2014)

Technology component	No. of Units	Installation Locations
LED light fixtures	8	On top of eight light poles to replace existing HPS luminaires
Streetlight controllers	8	At the base of each light pole
Traffic sensors	4	One at the 1st light pole One at the 8th light pole One at each of the two entrances of Building A
Smart server	1	Inside Building A

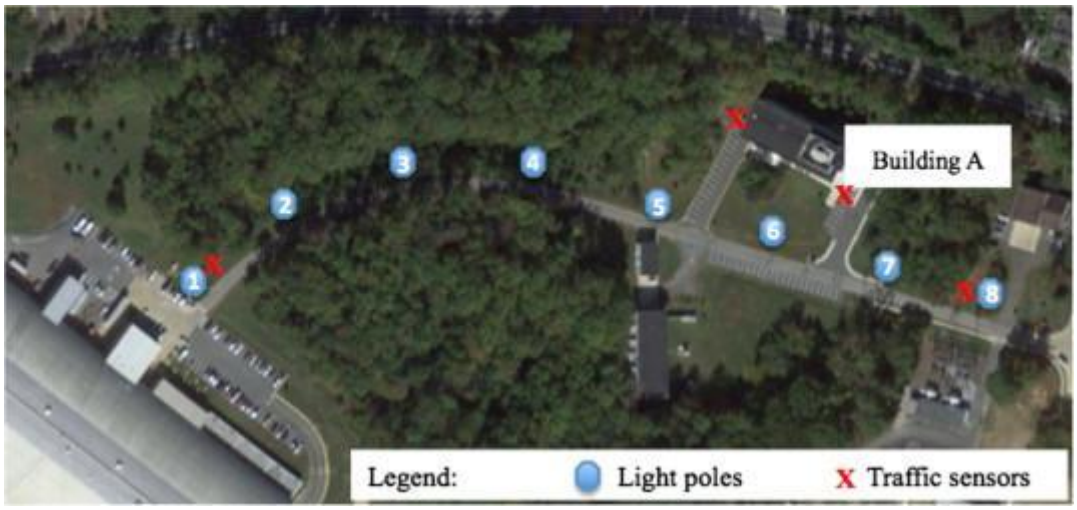


Figure 5-3. Light poles and traffic sensor arrangement (Pipattanasomporn et al. 2014)

5.2.3.2 Implementation Cost Comparison – City of Ann Arbor

The city of Ann Arbor was one of the first few cities to replace existing street and pedestrian lights with LEDs. In addition to the total cost savings, LED implementation received a positive response on the performance. Less light trespass has been observed and the blue/white light was easy on the eyes. The globe fixtures used in this project are 10 ft tall and consisted of four panels that faced down toward the street. Each fixture draws 56 watts with an expected life span of 10 years making them cost effective when compared with the previous HPS of 120 watts and 2-year life span. Even though LED purchasing cost is significantly higher than the HPS systems, significance in savings during service life is more than enough to justify higher installation costs. Further, due to extended service life, LED luminaires do not require the maintenance hours needed for HPS systems; thus, maintenance costs are significantly reduced. Table 5-7 and Table 5-8 provide a cost comparison. Accordingly, replacing one light with LED saves $1,111 during a 10-year period. It is estimated that the city of Ann Arbor implementation payback period to be 3.3 years (Relume 2011). Other technologies such as motion sensors and dimmable features can be integrated to yield additional benefits.

Table 5-7. Total Cost for Using Existing Luminaires for Next 10 Years (Relume 2011)

Description	Number	Unit Cost ($)	Total Cost ($)
Replacement cost of luminaire with 2-year service life	5	35	175
Labor and equipment for replacement	5	268	1,341
Ballast (10 yr. life)	1	59	59
Igniter (10 yr. life)	1	35	35
Energy cost (4,380 kWh)			325
		Total Cost	**$1,935**

Table 5-8. Total Cost for Using LED Luminaire for Next 10 Years (Relume 2011)

Description	Number	Unit Cost ($)	Total Cost ($)
Replacement cost of LED with 10-year service life	1	400	400
Labor and equipment for replacement	1	268	268
Energy cost (2,100 kWh)			156
		Total cost	**$824**

5.2.4 Summary and Conclusions

Pedestrians must be able to safely navigate through streets and walkways. Current trend is to use LEDs to illuminate streets and walkways. Even though the implementation cost is high, data has shown a potential for achieving about 50% cost reduction when LEDs with 10-year service life are installed instead of HPS with 2-year service life. Further, publish data indicate a potential payoff of the implementation cost in about 4 years. LED technology is new and a lot of municipalities and cities are considering adopting the technology. However, being a new technology field performance of LEDs needs to be monitored to collect adequate data to justify future implementations. **DIALux** is a software commonly used for lighting design. As a feasibility study, this software can be used to evaluate suitable luminaire types and configurations for implementation. There are a large number of parameters that need to be considered for selecting and implementing a lighting system. Hence, getting the service of lighting professionals is advised.

5.3 PLANNING TOOLS FOR LOCATING WIND AND SOLAR SYSTEM

Solar and wind are two environment-friendly natural resources that can be used to generate electrical power to operate bike-share kiosk, pedestrian lighting, etc. Solar panels are commonly used to power bike-share kiosks (Fogelberg 2014). Two such examples are discussed in section

2.7.1 and 2.7.2 of this report. During this study, bike-share programs in two Michigan cities (Ann Arbor and Battle Creek) were reviewed and the successes and lessons learned were documented. Solar powered kiosks are used in both cities (Figure 5-4).



(a) A bike-share station in Ann Arbor
(Source: semichiganstartup 2016)



(b) A bike-share station in Battle Creek
(Source: Lewis 2013)

Figure 5-4. Solar powered bike-share stations

One of the major challenges with solar powered kiosks is the maintenance of a reliable power supply. As reported in section 2.7.2, batteries needed to be replaced to maintain system power. This is primarily due to poor planning and design. Use of average solar insolation data for planning purposes is not adequate. Spatial distribution needs to be carefully analyzed for an area to identify suitable locations for solar infrastructure. Also, the entire solar power system design needs to be carefully analyzed for the need.

5.3.1 Solar Power System

A typical power system includes a solar array, a charge controller, and a battery bank. Solar arrays or photovoltaic (PV) systems are devices that use sunlight to generate electricity (Ramchandra and Boucar 2011). Sunlight provides energy in the form of radiation. The amount of solar irradiance directly corresponds to the amount of energy that can be produced from a solar panel, and is the single largest factor effecting the production of electricity. Solar irradiance is the term used to denote the amount of solar radiation that reaches a surface or an area over a certain period of time, and it is often expressed in units of Langley (Ly) or kilowatts per square meter per day ($kW/m^2/day$). Due to the extreme importance of solar insolation in the production of reliable power, it is important to determine the solar insolation instead of the number of sunshine hours. This is because the sunshine hours provide only the number of hours that sunlight is available at a

site, but not the intensity of sunlight (Shirahata et al. 2014). Solar insolation data can be obtained from the *Atmospheric Science Data Center* at the *NASA Langley Research Center* (NASA 2014).

In addition to solar insolation, exposure conditions and type of solar photovoltaic affect the solar power system performance. Cloud cover, temperature, humidity, wind, and dust affect the production of solar power from a panel. Cloud cover affects energy production by way of reducing the amount of solar irradiance that comes into contact with the panel. Similarly, dust particles and shadows from nearby structures or trees can have a large impact on the electricity generation. Higher temperature also reduces the amount of energy being produced by a solar panel. In addition, humidity levels in excess of 75% can lead to a decrease in solar panel efficiency (Ettah et al. 2012; Kazem et al. 2012). Kazem et al. (2012) studied the effect of humidity on the performance of three types of solar photovoltaic: Monocrystalline, Polycrystalline and Amorphous silicon. Results show that the reduction in relative humidity increases the voltage, current and efficiency. Further, the Monocrystalline panel has the highest efficiency when relative humidity is decreased with respect to other technologies.

An advanced charge controller can manage the entire solar power system. It has the ability to manage the power to equipment, and to protect the battery bank from overcharging and over-discharging and the solar array from reverse current (Hee and Isa 2009). Where needed, inverters can be used to convert direct current (DC) power into alternating current (AC) power. However, additional losses due to an inverter need to be considered when sizing the solar array and the storage. Certain charge controllers have load control options for the purpose of setting up timers as well as advanced programming to improve charging efficiency. One such example is the Maximum Power Point Tracking (MPPT) charge controller. The MPPT charge controller uses DC to DC conversion to convert the array's operational voltage to the battery charging voltage. The conversion works on the principle that power into the MPPT is equal to the power out of the MPPT (i.e. Volts In × Amps In = Volts Out × Amps Out). The efficiency of the power conversion ranges from 92% to 95% (Sunsaver 2014). With the power conversion algorithm used in the MPPT controller, the charge (amperage) supplied to the battery can be increased by about 10% to 35% (Sunsaver 2014). The advantage of using an MPPT charge controller is that it allows the solar array to operate at its maximum power point voltage (V_{mp}); whereas, a typical charge controller supplies a charge to the battery in proportion to the power produced by the array.

The battery provides needed energy storage. Deep discharge lead-acid batteries are good for storing solar energy that can later be delivered with minimal damage to the battery cells. Battery storage or capacity is often expressed in amp-hours. The capacity stated on the battery is the total amount of energy that can be withdrawn from the battery before complete discharge. However, the total capacity of a battery can be affected by the rate of discharge and operating environment conditions (e.g., battery capacity drops to about 60% under below freezing temperatures). This effect on the battery's capacity can be determined by using Peukert's equation or through C-rate tables available on most battery datasheets from the manufacturer of the battery. Inefficiency also exists in the process of discharging and recharging a battery; for a typical lead-acid battery, this loss can be in the range of 10%-30% (Shirahata et al. 2014). Batteries have a cycle life, or an estimated number of times that they can be discharged and recharged before the battery begins to lose its ability to maintain a charge. A cycle is the period over which the battery is discharged and recharged once; thus in a solar system a cycle would occur every day. The depth of discharge (DoD) is a term that refers to the amount of energy discharged from a battery, before it begins a new cycle. The DoD can affect the life of a battery, the majority of battery manufacturers recommend not exceeding 50%-60% discharge.

When a solar power system is installed without proper evaluation of site conditions and the solar power system (array, controller, battery bank, and the load), assuring a reliable performance is a challenge. Also, a routine inspection plan and an inventory are needed for managing such infrastructure to assure system reliability.

5.3.2 Wind-Solar Hybrid System

In order to overcome solar powered system limitations, wind-solar hybrid systems are developed and used to power LED street lighting systems (Yildiz 2014). Figure 5-5 depicts the components of a wind-solar hybrid street light system. It consists of a solar panel, a small wind turbine, deep cycle batteries, a controller, and a street light (HYE 2015). A few examples or concepts of such a hybrid system are shown in Figure 5-6. A properly designed system for a specific site could be very effective to operate pedestrian lighting and similar low powered infrastructure by harvesting energy during day time (through sun light and wind) and night time (through wind) of a day (Selvam 2014). Also, power can be generated throughout the year (including winter and summer seasons). However, a challenge in operating such small wind

turbines during winter is the potential for ice build-up that requires adequate wind power to break the ice and get the turbine operated. Further, depending on the size of the wind turbine, hazardous conditions might arise due to ice buildup. Above all, a reliable system design and implementation require analysis of local level wind flow patterns and solar insolation within the physical urban landscape. Other challenges include the cost of a system and requiring a trained crew for inspection and maintenance (Quing 2014).

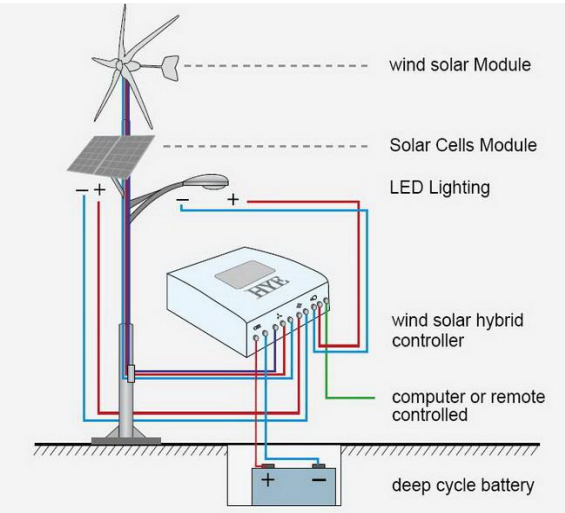


Figure 5-5. Components of a wind-solar hybrid street lighting system (GHY 2015)



Figure 5-6. Wind-solar hybrid street lighting systems (Source: Sunning 2015)

To demonstrate advantages of combining solar and wind sources to generate power in winter cities, variation of solar insolation and wind speed and direction are discussed using City of Kalamazoo, Michigan, as an example. The average solar insolation variation for Kalamazoo City represents a bell shaped curve with the highest and lowest values documented during summer and winter seasons, respectively (solarenergylocal 2016) (Figure 5-7). The solar insolation ranges from 2 to 6 kWh/m^2/day. Figure 5-8 shows average wind speed variation across City of

Kalamazoo. As shown in the figure, maximum wind speed is observed during winter months. During summer months, there are periods with almost no winds. Data shown in Figure 5-7 and Figure 5-8, demonstrate the feasibility of combining wind and solar resources to generate power throughout the year. Figure 5-9 and Figure 5-10 show wind direction variation. Dominant wind directions are South (S), Southwest (SW), West (W), and Northwest (NW). For an effective implementation, local site conditions as well as potential of freezing need to be considered. Section 5.3.3 describe models available for solar radiation analysis with shadowing effects. Section 5.3.4 describes models available to analyze wind pattern around structures and other obstacles. The models described in these sections can be used to evaluate sites for optimal locations for implementing wind, solar, or hybrid power systems.

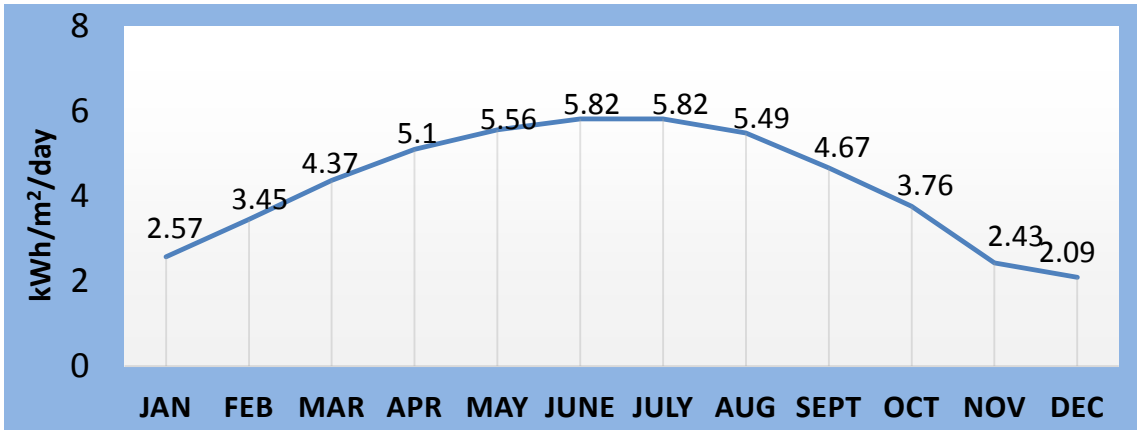


Figure 5-7. Average solar insolation for Kalamazoo City (Source: solarenergylocal 2016)

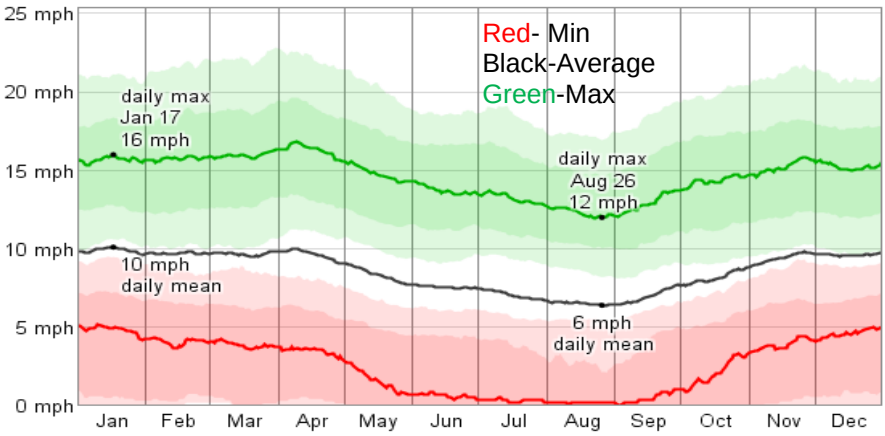


Figure 5-8. Average wind speed across Kalamazoo City (Source: WeatherSpark Beta 2016)

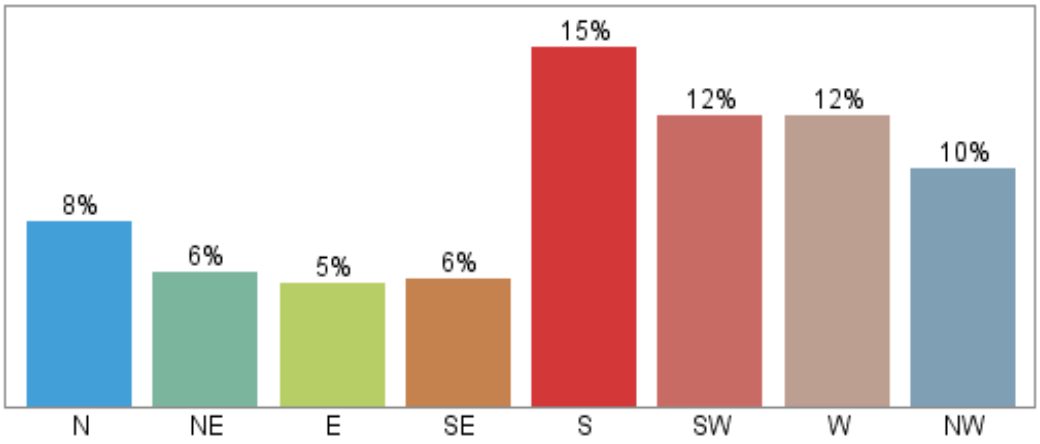


Figure 5-9. Direction of wind across Kalamazoo City (Source: WeatherSpark Beta 2016)

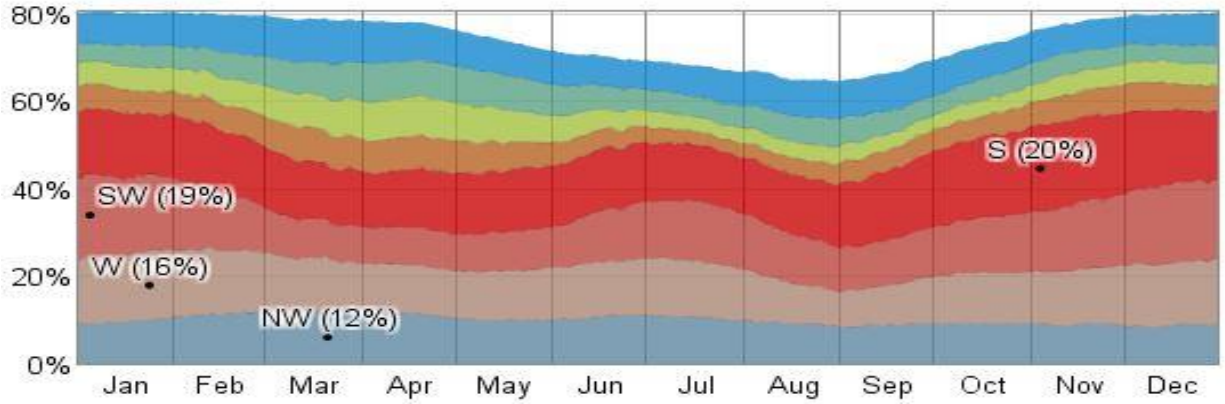


Figure 5-10. Direction of wind across Kalamazoo City (Source: WeatherSpark Beta 2016)

5.3.3 Impact of Shadows and Solar Radiation Analysis

5.3.3.1 Impact of Shadows

Locations for implementing sunlight sensitive infrastructure needs to be identified carefully by analyzing the effect of shadows casted by neighboring buildings and other obstacles. As an example CEQR (2014) describes the work performed for evaluating the impact of shadows casted by a proposed 303 ft tall building in New York City on sunlight sensitive infrastructure. Four particular days representing different seasons (summer and winter) were analyzed. March 21 was selected to represent variation of shadows from vernal equinox. June 21 was selected as summer solstice (to mark the onset of summer and the day with the longest day time). The period from May 6 to August 6 was selected to represent summer. December 21 was selected as winter solstice (the day with the longest night).

Two green color boxes shown in Figure 5-11 represent sunlight sensitive infrastructure. As shown in the figure, shadow of the proposed building covers the sunlight sensitive infrastructure located on northeast side right after the 2:30 pm and remains at least partly covered even after 4:30 pm on March 21. During the period of May 6 to August 6, the shadow had very little effect on the infrastructure (Figure 5-12). On June 21, there was no impact on any of the sunlight sensitive infrastructure (Figure 5-13). Representing winter season, analysis was performed on December 21. Results show that the infrastructure located on northwest side impacted for about an hour in the morning while the infrastructure on northeast had no impact due to shadows (Figure 5-14).

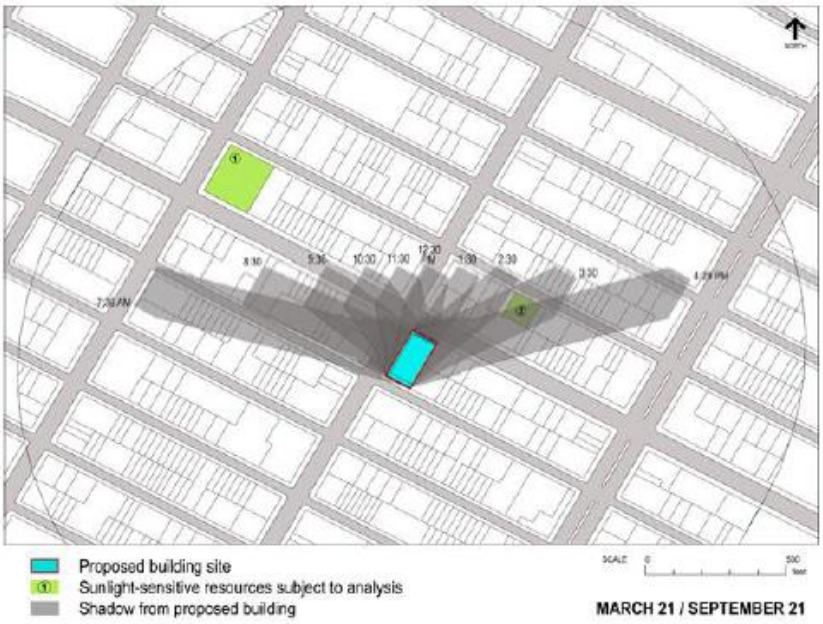


Figure 5-11. Shadow effect on March 21 (Source: CEQR 2014)



Figure 5-12. Shadow effect for the period of May 6 to August 6 (Source: CEQR 2014)

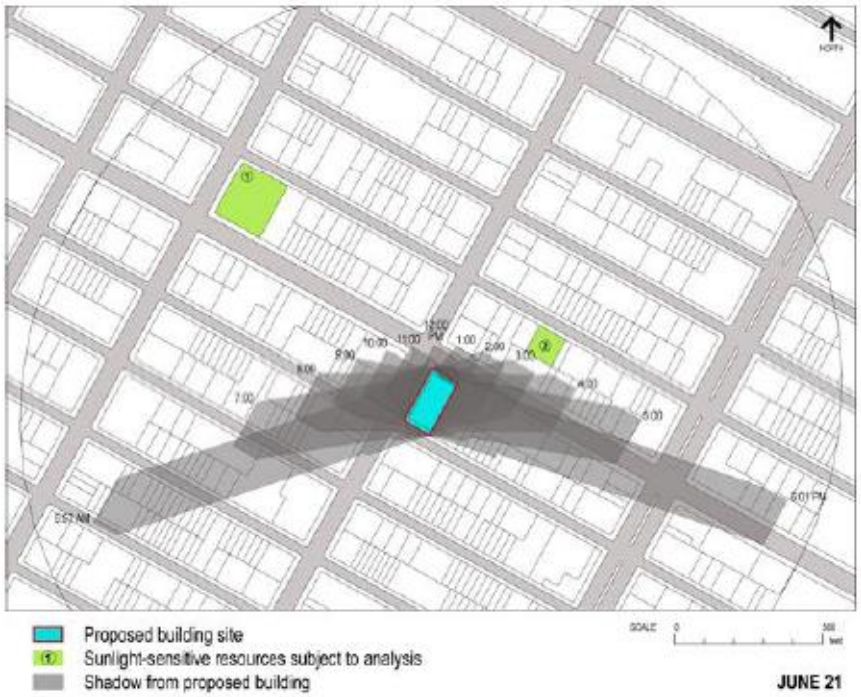


Figure 5-13. Shadow effect on June 21(Source: CEQR 2014)

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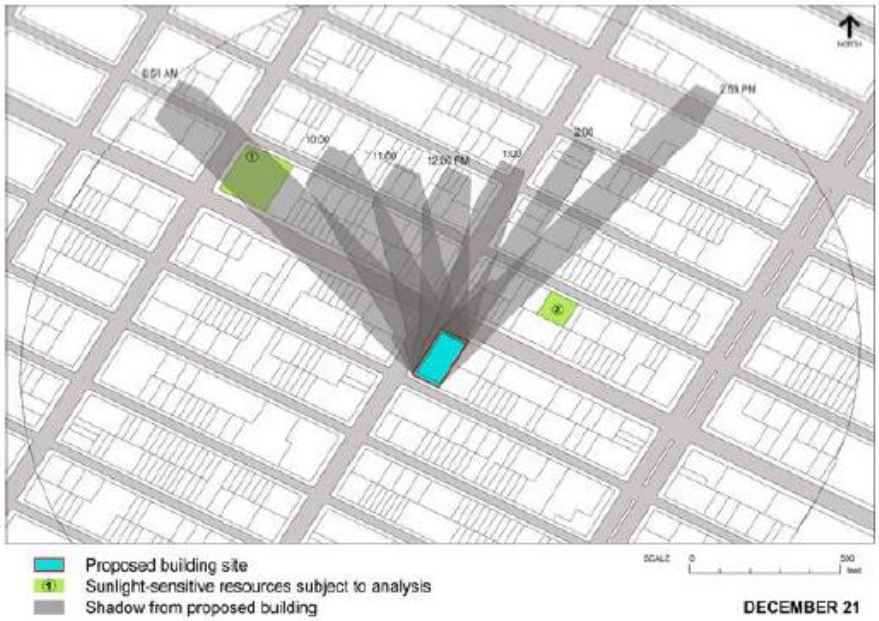


Figure 5-14. Shadow effect on December 21 (Source: CEQR 2014)

Shadow length (s) can be calculated in terms of object height (h) and solar elevation angle (α) as shown in Figure 5-15 and Eq. 6.

$$s=h/\text{Tan}\,(\alpha) \qquad (6)$$

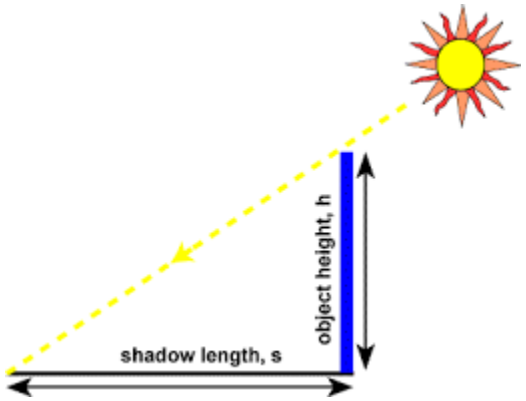


Figure 5-15. Definition of shadow length (Source: PVeducation 2016)

Solar elevation angle (α) is a function of the latitude of the location of interest (φ), solar declination angle (δ), and the hour angle (HA) as shown in Eq. (7). Solar declination angle is calculated using Eq. 8 as a function of the day number (n) where n=1 represents January 1st.

$$\alpha = \sin^{-1}[\sin\delta \sin\varphi + \cos\delta \cos\varphi(HA)] \qquad (7)$$

$$\delta = 23.45 \frac{\pi}{180} \sin[2\pi(\frac{284+n}{36.25})] \quad (8)$$

The hour angle (HA) is the azimuth angle of the sun's rays which is caused by the rotation of earth (Holbert 2007) and calculated using Eq. 9. The apparent solar time (AST) needed for Eq. 9 is calculated using Eq. 10.

$$\text{HA} = \frac{(\text{No.of minutes past midnight,AST}) - 720 \text{ mins}}{4 \text{ min/deg}} \quad (9)$$

$$\text{AST} = LST + \left(\frac{4min}{deg}\right)(LSTM - Long) + ET \quad (10)$$

where,

LST= Local Standard Time or clock time for that time zone (may need to adjust for daylight savings time, DST, that is LST=DST-1 hr)

Long= local longitude at the position of interest

LSTM= local longitude of standard time meridian and calculated using Eq. 11.

ET= equation of time in minutes and calculated using Eq. 12.

$$\text{LSTM} = 15° \times \left(\frac{Long}{15°}\right) \quad (11)$$

$$\text{ET} = 9.87 \, \mathbf{sin}(2D) - 7.53 \, \mathbf{cos} \, D - 1.5 \, \mathbf{sin} \, D \quad (12)$$

$$\text{Where, } D = 360° \times \frac{(N-81)}{365} \quad (13)$$

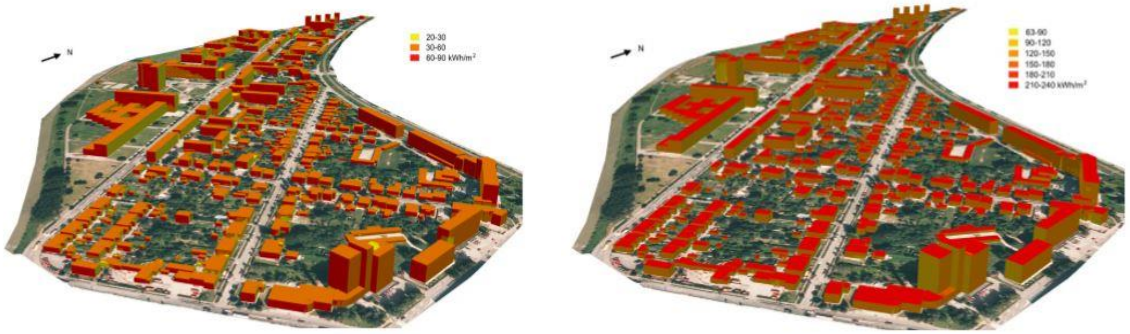
Using the above equations and acquiring necessary parameters (hour angle, solar declination angle, and latitude of interest) the solar elevation angle and be calculated. After that, the shadow length can be calculated to evaluate the impact of shadows from neighboring structures or other obstacles on the planned solar sensitive infrastructure.

5.3.3.2 Solar Radiation Analysis

Various solar radiation analysis models (e.g. *r.sun, Solar Analyst, SolarFlux, SRAD, and Solei-32),* the methodology implemented in such models, and input and output parameters are discussed. The scope and limitations of different models are also described and compared briefly at the end of this section. Most of the models are operated by external working environments incorporated with ArcGIS. These models are capable of calculating overall solar irradiance on the surface with different shadowing effects due to surrounding infrastructure.

The *r.sun* is an updated solar radiation model that can be integrated with open source environment of GRASS GIS. Suri and Hofierka (2004) demonstrated the use of this model by implementing it to develop a solar radiation model for some parts of Eastern and Central Europe. The *r.sun* model can perform analysis under clear-sky and overcast conditions. All of the variables of the data model can be represented in raster format and therefore the *r.sun* model is easily compatible with large scale terrain analysis models. The model can run with two operational modes (clear sky and overcast condition) with temporal variation.

Hofierka and Zlocha (2012) conducted a study to build a sample 3-D city model by applying a new 3-D version of *r.sun* solar radiation model. The study included the vertical surfaces for analyzing the effect of solar radiation in addition to 2-D surfaces like terrain and rooftops. The new 3-D solar radiation model was included with the 3-D vector data that represents the complex environment of overall surfaces by following vector-voxel approach. A unique shadowing algorithm was incorporated in the data model for measuring the effect of shadowing on surrounding structures. The model showed the spatial and temporal variation of solar radiation effects on the complex 3-D urban area (Figure 5-16).



(a) Monthly solar irradiation for January (b) Monthly solar irradiation for July

Figure 5-16. Temporal variation of solar radiation (Source: Hofierka and Zlocha 2012)

Solar Analyst is a data model that is run by ArcGIS for analyzing solar radiation in a landscape or specific location. The model can be performed by two methods based on area or point solar radiation analysis across an entire landscape. Three maps are being used to complete the solar radiation analysis process (Fu and Rich 2000). They are graphic representations of the visible sky (view-shed map), the sun's position in the sky across a period of time (sun-map), and the sectors of the sky that influence the amount of incoming solar radiation (sky-map) (ESRI nd). Four steps are used in processing solar radiation map for a specific area or point location by *Solar*

Analyst model. The first step is to calculate an upward-looking hemispherical view-shed on topography. Then the direct and diffuse radiation is estimated by overlaying of view-shed on a direct sun map and sky map respectively. At last, an insolation map is being produced by repeating the process for every location or point of interest.

Hetrick et al. (1993) developed a GIS-based *SolarFlux* model which is written in Arc Macro Language (AML) and incorporated with the programming environment of ARC/INFO interpreter. The *SolarFlux* model was used to analyze the solar radiation on the Big Creek Reserve in California and La Amistad Biosphere Reserve in Costa Rica based on surface orientation, solar angle, shadowing due to topographic features, and atmospheric attenuation. The input data for the model is based on raster grid cell. The specific latitude and longitude with time interval data is required for the model. A UNIX workstation (SUN SPARCstation 2) incorporated with GIS software is needed to run the model. The model has four categories of modules (interface, conversion, solar position, and numerical integration). The interface module configures the form menu with necessary data for the users. The acceptable format of data is checked in with the conversion module. The sun angle with azimuth and zenith angles are calculated in solar position module. Direct, diffuse, and reflected solar radiation is calculated using the numerical integration module.

The *SRAD* solar radiation model can be integrated with ArcGIS (Ruiz-Arias et al. 2009). Recently, the model was incorporated into ArcGIS9.x geo processing framework on windows platform. The *SRAD* model was designed for measuring both the short-wave and long-wave of solar energy in a particular area or place. Solar radiation calculation of large areas is limited through this model. The overall process is performed with four steps within the calculation of solar radiation. The horizontal extraterrestrial irradiance is computed as the first step of short-wave radiation calculation. After that, the value is obtained for the instantaneous short-wave fluxes for clear-sky. The total fluxes are then integrated to obtain daily total irradiance and adjusted to reduce the effect for cloudiness. As the final step, the average daily value is obtained for a specific period and a specified area.

Miklanek and Meszaros (1993) developed the *Solei-32* solar radiation model for a DOS environment and integrated with GIS IDRISI. The model is usually operated with a Digital Elevation Model (DEM) enabled raster grid cell on ArcGIS. The *Solei-32* model computes the temporal topographic attributes and sunshine duration for every grid cell of a land cover surface.

Direct, diffuse, and reflected irradiance is then measured to calculate the total solar irradiance for a specific time period.

Different tools or software that is used to perform solar radiation analysis are shown in Table 5-9. Table 5-10 shows general input/output parameters related to all the models stated in Table 5-9, data formats, and units of measurements. Specific data needed for the models are listed in Table 5-11 and Table 5-12.

Table 5-9. Solar Radiation Models and Associated Tools or Software

Solar radiation model	Tools/software
r.sun	GRASS GIS
Solar Analyst	ArcGIS Spatial Analyst extension
SolarFlux	UNIX workstation (SUN SPARCstation 2) incorporated with ArcGIS
SRAD	ArcGIS9.x geo-processing framework
Solei-32	GIS IDRISI

Table 5-10. Common Input and Output Parameters for the Solar Radiation Models

Input data		
Data	**Type**	**Unit**
Surface grid cell	Raster	Lengths
Elevation	Raster	Lengths
Aspect	Raster	Decimal degrees
Slope	Raster	Decimal degree
Site latitude	Raster	Decimal degrees
Time interval	Single value	Decimal hours
Atmospheric data	Single value	Dimensionless
Output data		
Total insulation	Raster	W/m^2
Horizon shadowing	Single value	Dimensionless

Source: Suri and Hofierka 2004; Hofierka and Zlocha 2012; Fu and Rich 2000; ESRI nd; Hetrick et al.1993; Ruiz-Arias et al. 2009; Miklanek and Meszaros 1993.

Table 5-11. Specific Data Required for r.*sun* Model to Perform Solar Radiation Analysis

Model	Input data		
r.sun	**Data**	**Type**	**Unit**
	Atmospheric Turbidity	Raster	Dimensionless
	Ground Albedo	Raster	Dimensionless
	Clear-sky index for beam component	Raster	Dimensionless
	Clear-sky index for diffuse component	Raster	Dimensionless
	Day number	Single value	Dimensionless
	Solar declination	Single value	Radians
	Output data		
	Solar incidence angle	Raster	Decimal degrees
	Beam irradiance	Raster	W/m^2
	Diffuse irradiance	Raster	W/m^2
	Ground reflected irradiance	Raster	W/m^2
	Duration of the beam irradiation	Raster	Min.

Source: Suri and Hofierka 2004; Hofierka and Zlocha 2012

Table 5-12. Specific Data Required for *Solar Analyst, SolarFlux, SRAD,* and *Solei-32* Models

Analysis Models	Data	Type	Unit
Solar Analyst	**Input data**		
	Daily and seasonal shifts of the sun angle	Raster	Decimal degrees
	Output data		
	Global irradiance	Raster	W/m^2
	Direct irradiance	Raster	W/m^2
	Diffuse irradiance	Raster	W/m^2
SolarFlux	**Input data**		
	Time increment	Single value	Hours
	Local time meridian	Single value	Dimensionless
	Atmospheric transmittance	Single value	Dimensionless
	Reflectance coefficient	Raster	Dimensionless
	Output data		
	Shadowing of different complex structures	Single value	Dimensionless
SRAD	**Input data**		
	Albedo	Raster	Dimensionless
	Sunshine hours	Single value	Hours
	Cloudiness parameter	Raster	Dimensionless
	Atmospheric transmittance	Raster	Dimensionless
	Circumsolar coefficient	Raster	Dimensionless
	Output data		
	Surface and air temperature	Single value	Decimal degrees
Solei-32	**Input data**		
	Ground albedo	Raster	Dimensionless
	Meteorological data (temperature, wind)	Single value	Different dimensions
	Linke turbidity coefficient	Raster	Dimensionless
	Relative sunshine	Single value	Hours
	Output data		
	Insolation duration	Raster	Minutes
	Sunrise time	Single value	Decimal hours

Source: Fu and Rich 2000; ESRI nd; Hetrick et al.1993; Ruiz-Arias et al. 2009; Miklanek and Meszaros 1993

Solar Analyst, *SolarFlux*, *SRAD*, and *Solei-32* models are mainly used for analysis on 2-D surfaces. The *r,sun* model has already been used to demonstrate solar radiation effects in 3-D city models. The *r.sun*, *Solar Analyst*, *SRAD*, and *Solei-32* models are used in large scale analysis. Since it is the earlier version of solar model for solar radiation analysis in ArcGIS, *SolarFlux* model is limited to use in smaller scale analysis. Yet, the shadowing effect of different complex structures can be explained better with this *SolarFlux* model. *Solar Analyst* model is good to show detail map of different view shed (e.g. buildings, trees etc.), but it is not capable of showing complex shadowing effects on complex infrastructure. When analysis capabilities of available models are compared, the *r.sun* model is an advancement to the other models.

5.3.4 Wind Power Technology and Wind Pattern Analysis Models

Kinetic energy of wind developed due to a given configuration of a wind turbine is expressed in Eq. 9.

$$\text{Kinetic energy of wind} = \tfrac{1}{2}\ \rho A V^3 \qquad (9)$$

Where, ρ is air density, A is swept area, and V is wind velocity. The swept areas is a function of the turbine configuration and typically it is the area of a circle defined by the rotor radius.

Figure 5-17 shows wind pressure distribution around a structure. As shown in the figure, turbulent and vacuum areas are developed around the structure. When an isolated structure is considered, it is easy to identify locations that are not favorable to locate a wind turbine. The situation becomes very complex as wind flows through complex arrangement of urban infrastructure. Nelson and Brown (2013) showed an example of wind flow pattern and wind speed variation in Lower Manhattan by using QUIC-URB wind solver (Figure 5-18).

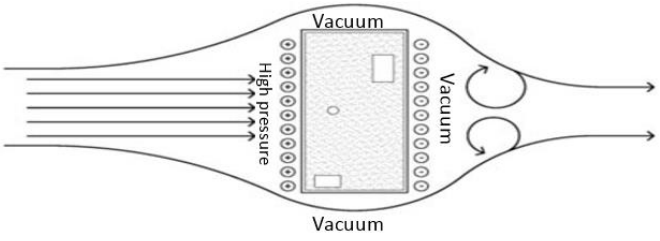


Figure 5-17. Wind pressure distribution around a structure (Source: WindEnergy nd.)

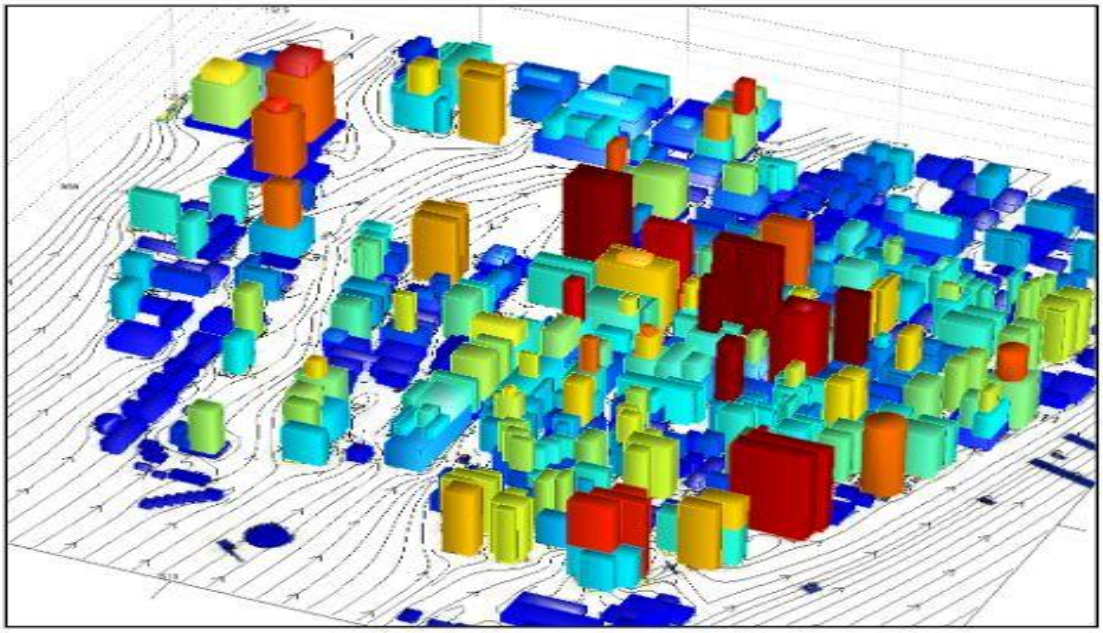


Figure 5-18. Wind flow pattern for Lower Manhattan (Source: Nelson and Brown 2013)

Various real-time simulation programs are used to develop wind patterns in different urban scales. *Computational Fluid Dynamic (CFD) models* have provided satisfactory results to understand wind flow patterns around individual or clusters of urban structures (Gowardhan et al. 2010). In this section, different *CFD* enabled wind pattern models (e.g. *Empirical-diagnostic wind Model, RANS computational fluid dynamics model, LES computational fluid dynamics model, and CFD Enabled Wind model*) are described with respect to methodology and input and output parameters. In addition, *Wind Flow Model* available in WinPRO software is also discussed. The large scale terrain analysis with energy calculations and different wind maps could be obtained by using *Wind Flow Models.*

Empirical-diagnostic wind Model is a fast response wind pattern model to compute the surrounding flow fields of 3-D urban structures. Nelson and Brown (2013) describe the wind flow patterns developed in the Lower Manhattan area. Detailed building dimensions (height, width, and length) and spacing between buildings were considered in the analysis.

Gowardhan et al. (2010) conducted a study to improve the wind-flow runtime by enhancing *RANS computational fluid dynamics model*. The performance of the model was evaluated using wind measurements from the Joint Urban 2003 Oklahoma City field experiment (Figure 5-19). The model was developed by solving 3D Reynolds-Averaged Navier-Stokes (RANS) equations.

A night time intensive operation period (IOPs) was used to conduct the study. The resulting effect by *RANS computational fluid dynamics model* was very satisfactory and it was overlaid with the field measurements. The model predicted the channeling effect between the urban structures and was able to produce optimum velocity around the structures. The reverse flow was calculated for the street canyons and wake regions. The model also overlaid with field measurements for the intersection areas included in the study.

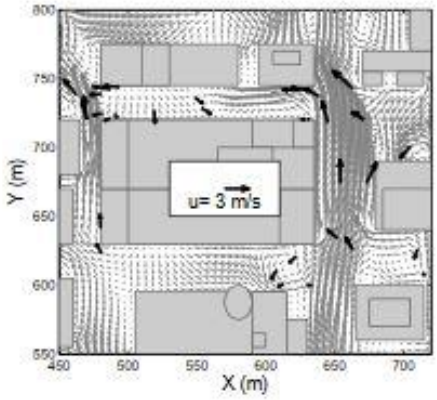


Figure 5-19. Wind flow pattern in Oklahoma City (Source: Gowardan et al. 2010)

Neophytou et al. (2010) enhanced *Large eddy simulation (LES) computational fluid dynamics model* with spatial filtering option to analyze large and small scale wind patterns. The *LES computational fluid dynamics model* explicitly expressed the large air turbulence in addition to complex small scale wind flow patterns between the urban structures. The wind model produces the resolved and sub-grid parts of wind pattern for large turbulence and smaller eddies respectively.

A *computational fluid dynamics (CFD) Enabled Wind model* is developed for the San Francisco area to show variability of the complex wind resources around the city (San Francisco Energy Map 2016). Complex urban 3-D structures were considered in the model and building height was considered as the tallest connected structure for the model. Besides, low-rise buildings were considered as the surface roughness to simplify the wind model. The wind model predicted the higher and lower wind energy potential throughout the bay area and the downtown San Francisco. About eight wind directions were analyzed for the resultant wind flow patterns with a constant wind speed of 10 mph. Northwest and Southeast areas of San Francisco were predicted as upwind and downwind by the data model due to the nature of topography (Figure 5-20).

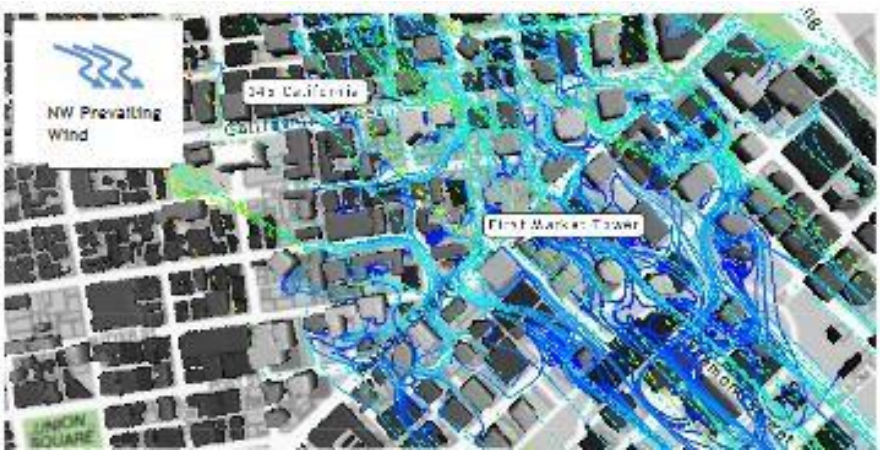


Figure 5-20. Wind flow in San Francisco City (Source: San Francisco Energy Map 2016)

Acker and Chime (2011) analyzed wind follow patterns in Flagstaff, Northern Arizona, to understand wind flow pattern and speed to calculate energy distribution to identify locations and heights for wind turbines. WindPRO software was used for this purpose and WAsP module was used to perform detail terrain analysis for the surrounding area. Detailed energy calculations with predicted wind flow patterns were obtained as the output of the model. Necessary wind resource maps were produced at different vertical layers with 33 ft and 100 ft (10 and 30 m) height for the study area.

Table 5-13 lists wind pattern analysis models documented in literature and the software that has integrated in these models.

Table 5-13. Wind Pattern Analysis Models and Associate Software

Wind pattern analysis models	Software
Empirical-diagnostic wind Model	QUIC-URB wind solver
Reynolds-Averaged Navier-Stokes (RANS) computational fluid dynamics model	QUIC-CFD wind solver
LES computational fluid dynamics model	Large eddy simulation (LES) solver
CFD Enabled Wind model	ANSYS Fluent
Wind Flow Model	WindPRO with WAsP module

General input and output parameters of wind pattern models are shown in Table 5-14.

Table 5-14. Common Input and Output Parameters for the Wind Pattern Models

Data	Type	Unit
Input data		
XY Coordinates	Single Value	Decimal Degrees
Wind Speed	Single Value	mph
Wind Direction	Single Value	Decimal Angles
Surface Roughness Data	Raster	Dimensionless
Height Contour Data	Raster	Meters
Output data		
Energy Calculations	Single Value	W/m^2
Wind Flow Calculations	Single Value	mph
Wind Flow Predictions	Single Value	mph
Wind Resource Maps	Single Value	Dimensionless

Source: Nelson and Brown 2013; Gowardhan et al. 2010; Neophytou et al. 2010; San Francisco Energy Map 2016; Acker and Chime 2011

The software/program specific data required for *Empirical-diagnostic wind Model, RANS computational fluid dynamics model, and CFD Enabled Wind model* are given in Table 5-15.

Table 5-15. Model Specific Data Needs for *Empirical-diagnostic wind Model, RANS computational fluid dynamics model,* and *CFD Enabled Wind model*

Model	Data	Type	Unit
	Input data		
Empirical-diagnostic wind Model	Reference Height for Upwind	Single Value	Meters
	Exponent for Inlet Profile	Single Value	Dimensionless
	Building Input Mode	Single Value	Dimensionless
	Number of Buildings	Single Value	Dimensionless
	Building Dimensions (Height, Width, etc.)	Single Value	Meters
	Output data		
	Wind Flow surrounding the structures	Single Value	W/m^2
RANS computational fluid dynamics model	**Input data**		
	3-D Building Masks	Raster	Dimensionless
	Time Steps	Single Value	Min.
CFD Enabled Wind model	**Input data**		
	Meteorological Data	Single Value	Dimensionless
	3-D Geometric Data	Single Value	Dimensionless
	Output data		
	Higher and Lower energy potential	Single Value	W/m^2

Source: Pardyjak and Brown 2003, Nelson and Brown 2013; Gowardan et al. 2007; San Francisco Energy Map 2016.

Empirical-diagnostic wind Model is the fastest response flow model among other discussed models that computes wind flow around the complex structures. Although *RANS computational*

fluid dynamics model is comparatively slower than *Empirical-diagnostic wind Model,* it produces a more realistic wind pattern. Only *LES computational fluid dynamics model* is enhanced with analyzing for both small and large eddy wind flows among the other wind models. All of the above models can discuss the wind flow between complex urban structures except the *Wind Flow Model.*

5.4 SNOW-MELTING TECHNOLOGIES

5.4.1 Overview

Alternative to using deicing salts, various technologies are used to eliminate snow accumulation and ice build-up on pavements and walkways. The methods that are used for this purpose can be broadly classified as electrical systems, hydronic systems, and infrared heaters. The primary benefits of using such technologies include extend life of walkway and pavement material, increased safety, reduced liability, etc. Snow-melting systems are desired by businesses and residents alike because they discontinue the need for snow removal. Typical systems incorporates temperature and humidity sensors to detect ambient air temperature and moisture. When the temperature and moisture meet the specific requirements, the system turns on and off automatically. With automated systems, the snow removal process is simplified and operating costs are lowered.

This section of the report explains each general method in detail, installation and maintenance costs, and challenges and lessons learned. Hydronic systems used in downtown Kalamazoo and city of Holland are discussed here as two case studies.

5.4.2 Electrical Systems

5.4.2.1 Embedded System

Electricity is used to heat up wires embedded in concrete or asphalt. Surface is heated up due to heat transfer and melt snow. This is known as a radiant heat method because the wires are radiating heat to melt snow. These wires are about $^1/_8$ - to ¼ - inch diameter. The cables lay on top of an insulating later and are positioned closer to the surface of the poured asphalt or concrete. Both ends of the cable meet in an above-ground junction box to provide access to power supply. With a life expectancy of over 30 years, these systems have no moving parts and are maintenance free after initial installation.

Figure 5-21 shows basic components of an electrical snow melting system such as control panel, aerial mounted snow switch, junction box, in-pavement sensor, and heating cables.

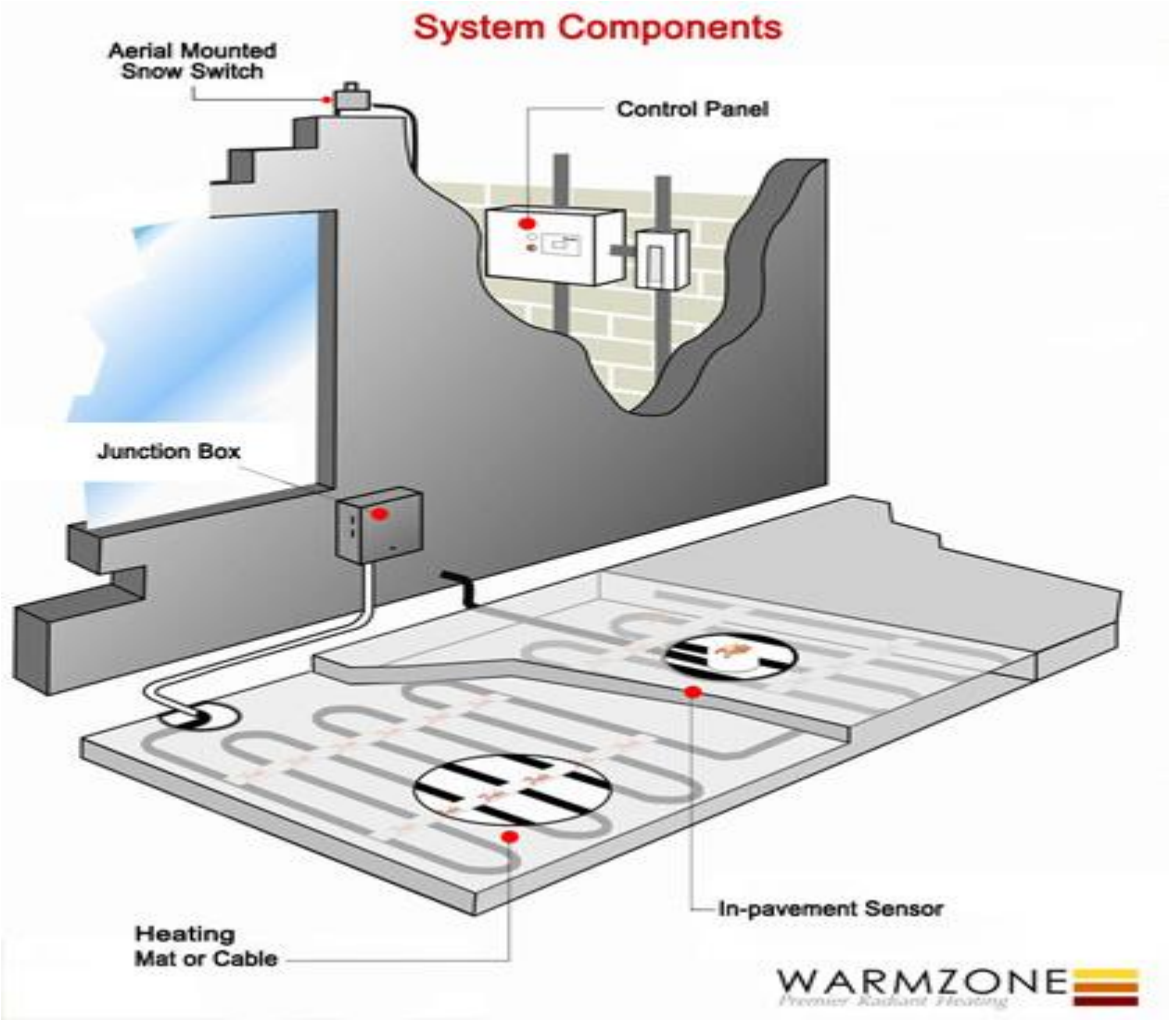


Figure 5-21. Components of an electrical snow melting system (Source: Warmzone 2016)

An electrical snow melting system must be installed carefully as errors will lead to costly repairs and liabilities. Before installation, all the components needs to be checked and tested. An insulation layer is placed above the base to minimize heat losses to ground. Then, an appropriately sized rebar grid is placed above the insulating layer. The wires need to be lifted above the insulating layer and placed two to three inches below the planned surface of the concrete or asphalt. Typically, these cables are tied to the rebar grid in a serpentine pattern throughout the snow melt area. The concrete or asphalt will be poured after the electrical snow melting system is secured in the place. The concrete slab of four to six inches thick is placed, with the cables in the middle or

slightly closer to the surface. Frequent testing needs to be performed throughout the construction process to assure integrity of the system.

Common practice today is to buy a kit that has electric wires prepared and ready for installation. Figure 5-22 shows a *SunTouch* kit that can cover up to 64 square feet for $608.00 (i.e., material cost of $9.50 per square foot). Additional costs include sensors, control kits, paving material, and installation cost. Without labor costs, estimated installation cost ranges from $11 to $16 per square foot depending on size and local conditions (Heatizon 2015b).



Figure 5-22. SunTouch ProMelt mat (Source: SunTouch 2016)

5.4.2.2 Electrical Heat Mat (HeatTrak)

HeatTrak is made from a durable rubber material that can withstand heavy foot traffic (only the industrial mats can be driven on). The *HeatTrak* encompasses heating elements within the rubber to melt snow and ice. This mat acts like a rug for outdoors to be placed and plugged in whenever convenient to melt snow away and clear a path. It is capable of being left outside all winter long and has an average cost of about $1 a day depending on size of the mat and duration of operation. The *HeatTrak* is capable of melting 2-inches of snow per hour and prevents ice buildup on entrances, walkways, handicap ramps, loading docks, stairs, etc., (Figure 5-23).

These mats offer different methods for turning on and off. The first method is to purchase one of the two automatic controllers available in the market. The first controller costs $50 and plugs straight into the outlet. The mat receives power when the sensor reads temperatures below 38˚ F. This controller will continually run once it is powered until temperature reaches 50˚ F or above. The second automatic controller costs $350 and must be installed professionally (probably an additional cost). The device only turns the mat on when it reads temperatures below 38˚ F and senses moisture in the air.



Figure 5-23. *Heat Trak* leading to a hot tub (Source: Heatizon 2016)

5.4.3 Hydronic Systems

Hydronic snow melting systems use an ethylene glycol-water mixture (similar to antifreeze) that runs through a flexible polymer (PEX) tube to transfer heat. A hydronic system requires an average of 100 to 150 BTU/hr/ft^2 to melt snow at an efficient rate (RBA 2014). The operational temperature of the mix ranges from 80 ^{0}F to 140 ^{0}F. A typical system includes the following components:

1) A boiler that uses electricity (from grid or any renewable source such as solar, geothermal, etc.), fossil fuel, or gas.
2) Tubes to get glycol-water mixture flowing through the area to be covered.
3) A pump to move the heated fluid through the tubing.
4) A controlling system to automate the operation.

5.4.3.1 Installation

Installation of tubing must be performed carefully to avoid puncture. An insulation layer is needed to prevent heat loss. When installing a system in concrete, the PEX tubing is laid on top of the insulation. The laid tubing needs to be secured in place approximately two to three inches from concrete surface by tying the tubes to reinforcement layer (Figure 5-24). Figure 5-25 shows a typical cross-section with tubing and insulation.

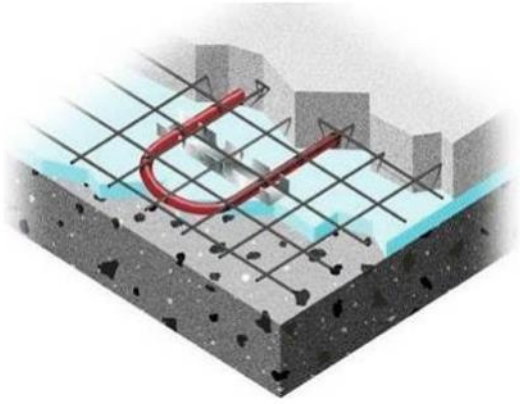


Figure 5-24. Arrangement of tubes, reinforcement, and an insulation (Source: RBA 2014)

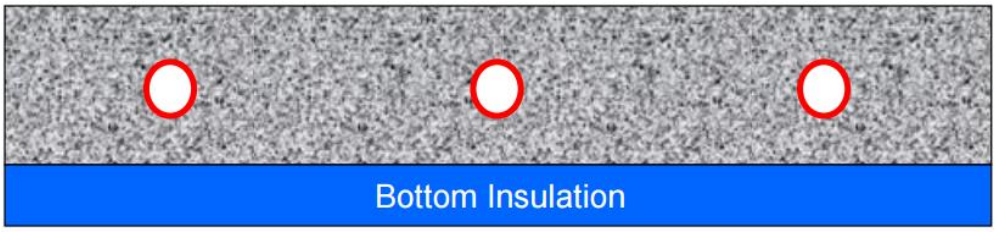


Figure 5-25. Slab cross-section showing insulation layer and tubing (Source: RBA 2014)

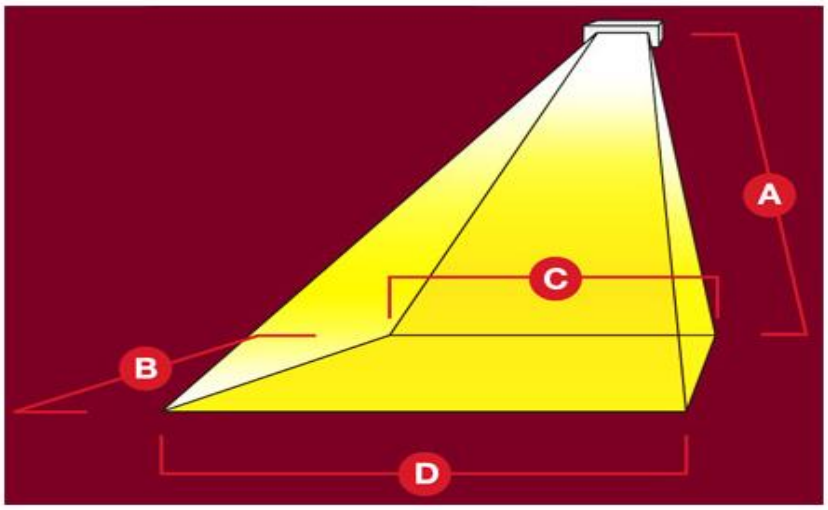
When installing a hydronic snow melt system under asphalt or pavers, the first layer is an insulation layer placed on top of the bare ground. The tubes are connected to the insulation layer and encased within two to three inches of a compacted media. Stone dust or fine sand is used. Crushed stone is not allowed because the sharp edges could damage the tubes. When pavers are used, the pavers are placed on top of the compacted media and compacted normally. If asphalt is used, it is poured as on top of the media and compacted while running cold water through the tubes.

5.4.4 Infrared Heaters

Infrared lamps are used to instantaneously radiate heat and melt snow. They are typically mounted on a pole or a permanent fixture attached to a structure. The infrared lamps provide flexibility in post-construction installation. Retrofitting a lamp is quite simple compared to electrical and hydronic snow melting systems. The infrared lamps are also capable of being automated with sensors. These lamps are typically used at airplane hangars, locker rooms, open air restaurants, parking garage ramps, etc. Figure 5-26 shows information available from

manufacturer data sheets. As shown in the figure, it provides the mounting height, coverage area, and the heat density. The first model listed in Figure 5-26 (SALPHA15120S, 1.5kW, 120V, Silver Heater) costs $368.00 (MEHA 2015b). With a coverage area of 110 ft^2, the heater cost is $3.35 per square foot. However, this does not include installation, maintenance, and operational costs. A typical system consists of the following:

- Infrared lamps
- Automatic controls sensor
- Mounting components (chains, bracket, pole, etc.)



Model	A	B	C	D	Heat Zone*	Heat Density*
SALPHA15120S	8´2˝	10´	10´	12´	110 sq. ft.	13 Watt/sq. ft.
SALPHA15240S	8´2˝	10´	10´	12´	110 sq. ft.	13 Watt/sq. ft.
SALPHA20240S	8´2˝	10´	10´	12´	110 sq. ft.	18 Watt/sq. ft.
SALPHAH2-30240S	10´	11´	13´	16´	160 sq. ft.	19 Watt/sq. ft.
SALPHAH2-40240S	10´	11´	13´	16´	160 sq. ft.	25 Watt/sq. ft.
SALPHAH3-45240S	12´	14´	15´	18´	230 sq. ft.	20 Watt/sq. ft.
SALPHAH3-60240S	12´	14´	15´	18´	230 sq. ft.	26 Watt/sq. ft.
SALPHAH2-40240S X2	12´	14´	15´	17´	200 sq. ft.	34 Watt/sq. ft.
SALPHAH2-45240S X2	15´	20´	15´	22´	370 sq. ft.	24 Watt/sq. ft.
SALPHAH2-60240S X2	15´	20´	15´	22´	370 sq. ft.	32 Watt/sq. ft.

* Heat Zone and actual heat density will vary based on mounting height and angle of heater (Overhead mounted heat zones will be different then this guide). Please use this as a guideline only and contact Solaira for a more detailed specifier guide.

Figure 5-26. Coverage and heat density of a wall mounted lamp (Source: MEHA 2015a)

5.4.4.1 Installation and Maintenance

Figure 5-27 shows common mounting options. Figure 5-28 and Figure 5-29 show implementations at a bus station and an ambulance parking space. In addition to the overhead and wall mount, the infrared lamps can be mounted on poles.

After installation, there are automatic sensors that can used to turn the lamp(s) on and off. Typical lamps are rated for 5000 hours. With an average snowfall duration of 150 hours per year, the bulbs can last 30+ years. Maintenance is as easy as replacing a normal fluorescent light bulb.

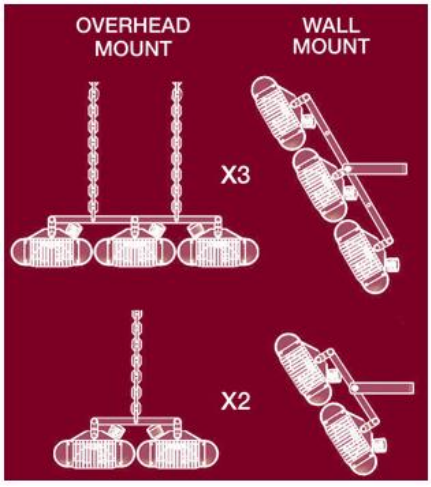


Figure 5-27. Mounting options (Source: MEHA 2015a)



Figure 5-28. Infrared heaters implemented at a bus stop (Source: MEHA 2015a)



Figure 5-29. Infrared heaters implemented at a hospital (Source: MEHA 2015a)

5.4.5 Case-Study

5.4.5.1 Kalamazoo, Michigan

Kalamazoo has a hydronic snow melting system for their downtown mall area. It has been completed in three separate phases. Phase I started in 1998, and the third and last phase was completed in 2005. Figure 5-30 outlines and highlights the segments of sidewalk and roads that are covered by the snowmelt system. The diamond shape located at the lower left corner represents the location of the boiler room. The room is located on a lower level of a parking garage and stores the pumps, heat transfer units, boilers, extra supplies, etc. Just outside the boiler room is the concrete temperature reader. The reader relays information to a computer operated system that controls the system operation and idle times.

Sizable donations and general city funding helped get the snow melting project moving forward for Kalamazoo, with inspirations coming from Grand Rapids and Holland downtown. The major benefit include no snow removal for the Kalamazoo Mall area and lower snow removal costs for the City. Today, business owners, residents, and downtown mall area shoppers all benefit as there is no snow to walk through.



Figure 5-30. Kalamazoo mall snowmelt system coverage area

Construction of Phase I began in 1998 and completed in 1999. The project scope included setting up the boiler room as well as installation of the hydronic system to cover 74,500 ft^2 of roadway and pavement area. Phase I coverage is 70.4% of the planned square footage to be

covered during all three phases of the project. Figure 5-31 outlines the area covered by the system during Phase I - a two block stretch located between East Lovell Street and East Michigan Avenue.



Figure 5-31. Kalamazoo mall stretch covered during Phase I implementation

Phase II construction started in 2002 and completed in 2003. This phase is a one block segment running from West Water Street to East Eleanor Street, representing the northern most segment of the Kalamazoo Mall. Figure 5-32 shows the area covered during phase II construction. The total area covered is 12,100 ft^2 (i.e., 11.4% of the entire area covered by the snowmelt system).



Figure 5-32. Area covered during Phase II construction

Phase III construction started in 2004 and completed in 2005. Figure 5-33 shows the area covered during this phase. This segment wraps around the Radisson Plaza Hotel block and runs from East Michigan Avenue to West Water Street. Phase III covers 19,249 ft^2 (i.e., 18.2% of the entire area covered by the snowmelt system).

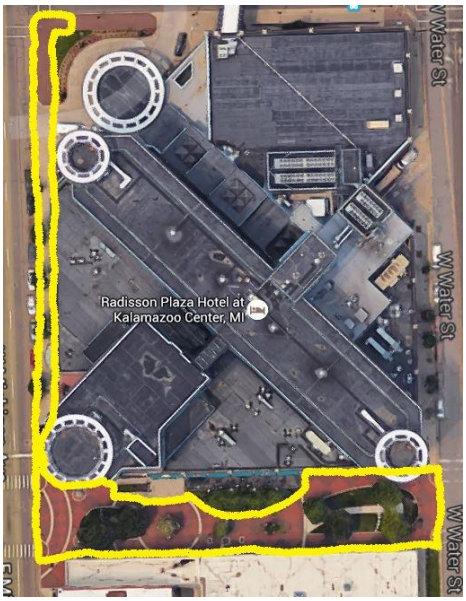


Figure 5-33. Area covered during Phase III construction

Kalamazoo mall installed their snowmelt system using concrete, a flowable fill, sand, and brick pavers. The bottom most layer is a 6 in. thick concrete slab. On top of the concrete slab lays a 2 in. thick layer of flowable fill with the tubing embedded in the middle. Above the flowable fill is a one-inch layer of sand. The brick pavers are placed on top of the sand. Figure 5-34 is a typical cross section of the north end of the Kalamazoo Mall set up in the same manner as described above. Figure 5-35 shows the tubing coming out of the concrete slab and into the flowable fill layer. The tubing is coming from the snowmelt manifold. The concrete slab is boxed out for the tubes to enter the snowmelt surface area from the manifold.

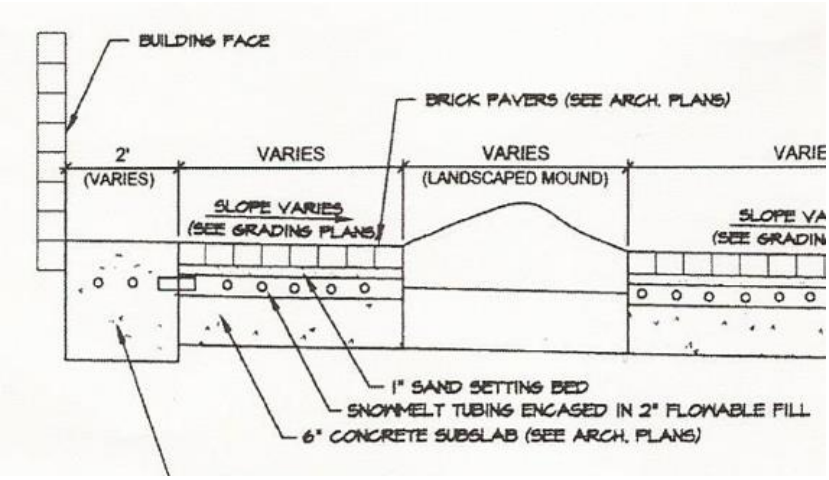


Figure 5-34. A cross-section showing material layers and tube layout

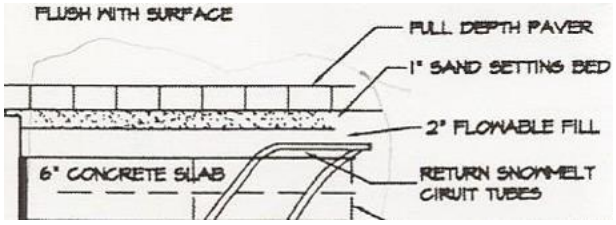


Figure 5-35. Tubes running through a concrete slab

Funding for the snow melt system in Kalamazoo provided from general funding, private donations, downtown development authority (DDA) contributions, and tax assessments for the buildings that directly benefit from the snow melt system. The first two phases of this project cost was $9,388,000, with an average cost of $108.41 per square foot. This includes the entire set up of the boiler room and encompasses 82% of the entire square footage of the system. Donations from a number of private contributors totaled over $5.5 million for the project from 1996 to 2002. General funding totaled $3 million. DDA contributions totaled $1.2 million. This left $448,000 in cumulative cash flow for expansion.

Each year, the city is able to tax building owners who own property that is adjacent to the snow melt system. Building owners pay $15.164 per linear foot (based on the length of a store front), for a total of $43,979.04. These funds are used for general maintenance of the Kalamazoo Mall and the snow melt system that resides within it. The combined annual cost for maintenance and operation of the snow melt system ranges from $160,000 to $200,000 (depending on malfunctions and severity of winters).

The snow melting system covers a total area of 105,849 ft^2. It circulates 19,000 gallons of a glycol-water mixture through 228,267 feet of pipe requiring 14.17 million BTUs to properly operate the system. The mixture of 40% glycol and 60% water is pumped through a filter, two boilers, two heat exchangers, and then out to the street. The mixture being pumped out to the streets leaves the boiler room at approximately 104˚F and 60 psi and return at 32 psi. The pumps flow 1588 gallons of glycol-mixture per minute during operation. The system is operated automatically and on/off function is controlled based on temperature measured at the pavement. Table 5-16 presents the area covered, length of pipes used, and the energy consumption for each phase and the total system.

Table 5-16. The Area Covered, Length of Pipes, and the Energy Consumption

Phase	Area (ft^2)	Pipe (ft.)	Energy (million BTUs)
I	74,500	154,420	9.56
II	12,100	27,865	1.77
III	19,249	45,982	2.84
TOTAL	**105,849**	**228,267**	**14.17**

The most common cause of pipe damages is due to construction activities in the area because the contractors do not contact the city before starting the work. System leaks are usually discovered either by observing liquid at the surface or due to pressure drop in the system. Detecting leaks by observing liquid at the surface is not an effective method because the damage may not always be located directly below the liquid patch. When a leak is located under brick pavers, the liquid usually rises directly to the surface making it much easier to locate the damage. Fixing leaks under brick pavers is easy compared to concrete or asphalt surfaces. When liquid is not observed on the surface or the damage is harder to locate (due to concrete or asphalt), helium can be injected into the system and monitored the gas leaks using detectors to identify the most probable locations of leaks.

The first phase of the project did not use a flowable fill. Construction only included a sand layer on top of the concrete slab. Tubes were embedded in the sand layer. Vehicle movement moved the bricks and settled into the sand layer. Eventually the bricks got in contact with the tubing. As vehicles moved over, the bricks started rubbing the tubes and puncturing them. The problem recurred frequently enough to change the design to include a flowable fill when the pavement is exposed to vehicular traffic. The design with a flowable fill is shown in Figure 5-35. The overall experience with the system led to the following recommendations:

1. Include isolation valves at every block to break the system into smaller grids when needed. This helps identifying leaks much easier.
2. Failure due to age have been seen in the plastic valves as early as 18 years of use. Use of stainless valves for the headers would allow for a longer life span compared to the valves with plastic components.
3. Add tap points at every block to help further expansion easier and less expensive.

5.4.5.2 Holland, Michigan

Holland, Michigan, has the largest public owned snow melt system in the United States. The system was first completed in 1988 and had its first major expansion in 2004. The expansion included a new farmer's market, police station, and court building. The heat source for the system comes from James De Young Power Plant. Excess heat from the plant is captured and used to heat up water. The water is directed to downtown Holland through 168 miles of tubing laid under the sidewalks and roads to melt snow on the surface of 450,000 ft^2. The system can melt snow at a rate of approximately one inch per hour at 15 – 20 ^{0}F (HBPW 2015).

The snowmelt system in Holland was made possible through private-public collaboration. Mr. Edgar Prince donated $250,000. Figure 5-36 shows a walkway condition in Holland, Michigan, during a snow storm.



Figure 5-36. A sidewalk without snow accumulation

Holland uses different layering techniques for the sidewalk and street. This is important because the difference in traffic loads require more protection for the pipes. Figure 5-37 shows a typical cross-section of a sidewalk. The only layers above the pipes are the sand medium and concrete pavers. This layering technique allows easy access to the pipes for a repair. Figure 5-38 is a typical cross-section of a street, including the curb and gutter. The street cross-section has two levels above the embedded pipes, adding more protection to the pipes.

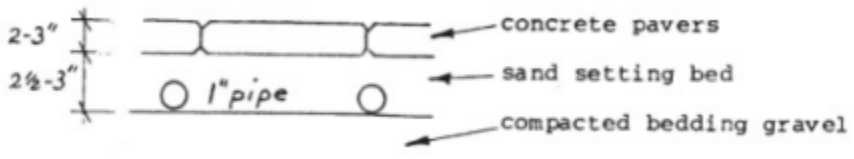


Figure 5-37. Typical cross-section of a sidewalk

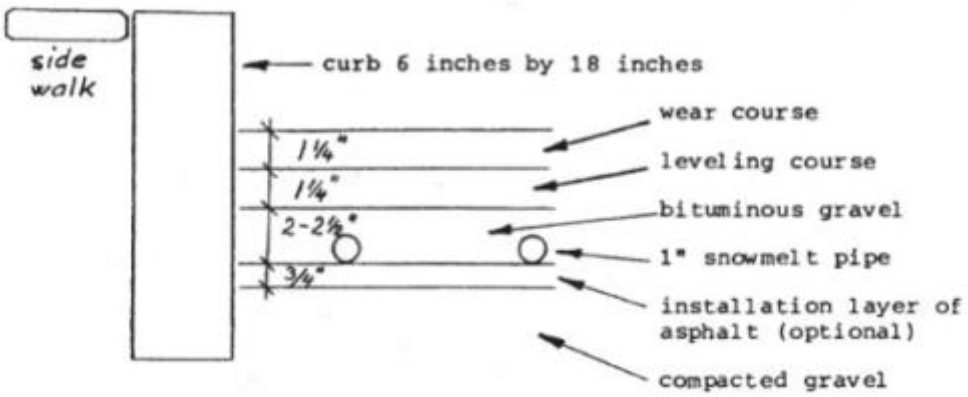


Figure 5-38. Typical cross-section of a street, including curb and gutter

Total capital costs used in 1988 for the first 167,000 ft^2 was $827,183. This cost does not include labor or related materials (such as laying of asphalt, installation of concrete pavers, gravel, etc.) **Error! Reference source not found.**5-17 displays the area covered, length of pipes, and the e nergy consumption of the system as of 2013.

Table 5-17. The Area Covered, Length of Pipes, and the Energy Consumption

Area (ft^2)	Pipe (ft.)	Energy (million BTU/hr)
450,000	887,040	40

As of 2013, the annual operation and maintenance costs are $50,000 and $7,000, respectively. $40,000 of this is collected through special assessments each year. Maintenance activities include (i) an annual flush to eliminate the potential of mud and silt accumulation, (ii) charging the system with city water, and (iii) repairing or replacing areas of poor performance.

The system uses water instead of water-glycol mixture typically used in other systems. The primary reason for using water in the system is that the power plant uses water from the lake Macatawa to cool the system down. The hydronic system in Holland runs this water through the city before discharging it to the lake. Hence, this has been a cost effective way to eliminate snow from walkways and pavements. An advantage of using water is that the snowmelt system is not required to be 100% water tight because there is no risk of getting glycol mix with ground water due to leaks.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY AND CONCLUSIONS

Providing access and mobility for key installations and businesses located in cities become a challenge when there is limited public transport and non-motorized facilities. The challenges are significant in cities that are subjected to severe winter weather conditions. As per published data 62% of millennials prefer to live in urban centers while 56% of millennials and 46% of active boomers prefer to live in walkable, technology-enabled cities where they have affordable and convenient transportation options regardless of the size of the city. In addition to alternative affordable transportation options, 81% of millennials and 76% of active boomers prefer non-motorized modes over cars for their daily activities. Fifty six percent (56%) of millennials want to see improvements to sidewalks and bike lanes to enhance safety. Lack of mobility can significantly affect the small and medium size cities economically due to migration of millennials to larger cities around the country.

This project was initiated to synthesize infrastructure and technology for improving access to non-motorized traffic and mobility within cities while enhancing sustainability. Improving access to sustainable mobility choices is a key aspect of developing livable cities. This project scope is limited to identifying methods and infrastructure to promote walking and cycling in small cities. The following is a list of topics discussed in this report:

- With regards to promoting cycling in cities, bike-share program development and use of location-allocation models as planning tools are presented.
- In many cities with adverse weather conditions, underground and above ground pedestrian systems are provided to encourage walking and cycling. Hence, these two infrastructure options are explored during this study.
- Providing energy efficient lighting systems to make pedestrians and cyclists feel safe to travel within cities is vital to improve mobility. This report provides information on energy efficient lighting systems, cost of implementation, and planning tools.
- In winter cities, providing snow and ice free streets and walkways promote walking and cycling. Technologies used for such endeavors and implementation case studies are presented.

- Electricity needed to operate kiosks at bike-share stations, pedestrian lighting, and snow melting systems can be generated through renewable sources such as solar and wind. However, effective implementation of solar and wind powered systems require identifying the optimal locations for such technologies within the city environment. Hence, this report presents a few tools that can be used for planning purposes.

6.1.1 Bike-sharing

This report presents bike-share program development process from preliminary planning to implementation, program evaluation, and the steps needed to ensure program sustainability. In addition, the report presents the process of using ArcGIS and the available location-allocation models to identify optimum number of bike-share stations and locations for a city. In order to demonstrate the process, a case study for City of Kalamazoo was developed and presented in Appendix B. Also, two existing bike-share programs were reviewed and the successes and lessons learned were used to develop recommendations listed in Section 6.2.

6.1.2 Underground Pedestrian Systems

Underground Pedestrian Systems (UPS) are used in many cities to help public stay away from severe weather conditions. During this study, two cities with UPS were reviewed to lean the funding sources, success, and lessons learned. In general, funding was provided by private business owners. However, once the systems are extended to cover a large portion of a city, maintenance is a challenge. Even though, the exposure conditions in many small cities favor having UPS, implementation and maintenance may not be financially viable. In small cities, streets are not overcrowded to motivate people to use underground structures. Hence, implementation of UPS in small cities needs to be driven by the interest of the business owners to cater their business needs.

6.1.3 Aboveground Pedestrian Systems (AGPSs)

Similar to UPS, aboveground pedestrian systems (AGPSs) or skywalks are primarily funded by the private business owners because of their needs. During this study, skywalk systems in Des Moines (Iowa), Cincinnati (Ohio), and Milwaukee (Wisconsin) were reviewed. Out of the three, the successful ones are privately funded. In small cities, streets are not overcrowded to

motivate people to use aboveground or underground structures. Hence, implementation of skywalks in small cities needs to be driven by the interest of the business owners to cater their business needs. A major drawback of having private entities funding and operating skywalks is the controlled hours of operation. The skywalk may only remain open for a limited number of hours a day, making it inconvenient to the public. However, this becomes a challenge only if the closed section becomes a bottleneck for the operation of the rest of the network.

6.1.4 Pedestrian Lighting

Pedestrians must be able to safely navigate through streets and walkways. Current trend is to use LEDs to illuminate streets and walkways. Even though the implementation cost is high, data has shown a potential for achieving about 50% cost reduction when LEDs with a 10-year service life are installed instead of HPS with 2-year service life. Further, publish data indicate a potential payoff of the implementation cost in about 4 years. LED technology is new and a lot of municipalities and cities are considering adopting the technology. However, being a new technology, field performance of LEDs needs to be monitored to collect adequate data to justify future implementations. **DIALux** is a software commonly used for lighting design. As a feasibility study, this software can be used to evaluate suitable luminaire types and configurations for a specific site. A large number of parameters needs to be considered when selecting and implementing a lighting system; thus, receiving the service of lighting professionals is advised.

6.1.5 Wind and Solar Power Systems

Street lighting to bike-share station kiosks are powered using solar energy. However, reliability of such power sources is a question. As documented during case study reviews, in many cases, batteries at solar powered stations needed to be replaced due to lack of charge. This can be due to two reasons, either the system was not designed for the specific site or it was not located at the right place to have adequate solar exposure. As shown in this report, there is a possibility to combine solar and wind power sources. However, impact of shadows and wind flow patterns need to be evaluated in order to select the optimum location for installation. Primarily, technology is developed adequately to generate power using solar and wind energy. The key is to design a system for site specific conditions and use currently available simulation tools to identify optimal locations for such infrastructure.

6.1.6 Snow-melting Technologies

Electrical systems, hydronic systems, and infrared heaters were reviewed. Hydronic systems have been implemented in several cities and adequate information is available to develop such systems for other cities. Two such systems were reviewed during this study and successes and lessons learned were documented. Infrared heaters are used at many facilities including bus shelters. Snow-melting system operation can be automated using temperature and humidity sensors. Cost-benefit analysis data for infrared heaters was not adequately documented in literature. Also, there was no discussion on health impacts of using infrared heaters.

6.2 RECOMMENDATIONS

- Implement ArcGIS with maximize facilities and minimize facilities models as a decision-support tool to identify the optimal locations for bike-share stations. However, user interaction is extremely important to finalize the list of locations after a careful analysis of the results in the context of the city.
- Evaluate the impact of shadows before installing solar powered infrastructure.
- Evaluate the possibility of combining solar and wind power to enhance the reliability of renewable power sources.
- Implementation of underground and above ground pedestrian facilities in small cities needs to be evaluated against the needs of businesses in the cities.
- LED has shown a good return on investment and needs to be considered for pedestrian and street lighting. **DIALux** software can be used to evaluate lighting configurations and identify the efficient luminaries for a specific application.
- Several cities are successfully in implementing hydronic systems to eliminate snow accumulation on streets and walkways. It is recommended to include isolation valves and tap points at every block to break a system into smaller grids to help with maintenance and future expansion. Further, use of stainless steel valves are recommended over plastic valves for enhanced durability.
- It is recommended to conduct a cost-benefit analysis of using infrared heaters for melting snow at public places such as bus shelters.

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APPENDIX A: ABBREVIATIONS

A

AC	Alternating Current
ACS	American Community Survey
ADA	Americans with Disabilities Act
ALRT	Automated Light Rapid Transit
AML	Arc Macro Language
APS	Aboveground Pedestrian Systems
AST	Apparent Solar Time

B

BTS	Bureau of Transportation Statistics

C

CEC	Clean Energy Coalition
CDC	Centers for Disease Control
CFD	Computational Fluid Dynamic
CIE	Commission on Illumination
CMAQ	Congestion Mitigation and Air Quality Improvement
CTPP	Census Transportation Planning Products

D

DC	Direct Current
DDA	Downtown Development Authority
DPM	Detroit People Mover
DOE	Department of Energy
DOT	Department of Transportation
DoD	Depth of Discharge

E

ET	Equation of Time

F

FHWA	Federal Highway Administration
FTA	Federal Transit Administration

G

GPS	Global Positioning Systems
GIS	Geographic Information System

H

HA	Hour Angle
HHS	Department of Health and Human Services
HID	High Intensity Discharge
HPS	High Pressure Sodium

I

IEA	International Energy Agency
IOPs	Intensive Operation Period

L

LED	Light Emitting Diodes
LES	Large Eddy Simulation
LST	Local Standard Time
LSTM	Local Longitude of Standard Time Meridian
Ly	Langley

M

MN	Minnesota
MPPT	Maximum Power Point Tracking
MV	Mercury Vapor

N

NMP	Non-motorized Transportation Plan

O

OKC	Oklahoma

P

PRT	Personal Rapid Transit
PV	Photovoltaic

R

RANS	Reynolds-Averaged Navier-Stokes
RFID	Radio-Frequency Identification Device

S

SLEEC	Street Lighting Energy Efficiency Criterion

T

TCSP	Transportation, Community and System Preservation Program
TEA	Transportation Enhancement Activities
TIGER	Transportation Investment Generating Economic Recovery
TRC-LC	Transportation Research Center for Livable Communities

U

UGP	Underground Printing
U-M	University of Michigan
UOfM	University of Michigan
UPS	Underground Pedestrian Systems
USDOT	United States Department of Transportation
UTC	University Transportation Centers

V

V_{mp}	Voltage at Maximum Power

APPENDIX B: IMPLEMENTATION EXAMPLE

B.1 BIKE-SHARE PROGRAM IMPLEMENTATION CASE STUDY

B.1.1 Service Area Selection

The size and location of a bike share system is related to the availability of funds and goal of the system. The available funds define the size of the system. One of the most common characteristics found in numerous bike-sharing programs is that dense areas have been used as reference points to identify the areas for an initial bike-share program. The selection of the initial service area is of great importance. The proper selection of the initial service area will result in program success, as these areas attract the most users and sponsorship.

Bike share ridership is influenced by the density and mix of land uses, or in other words, bike-share works best where many people live, work, play, and take transit. These characteristics will help to maximize early success. Downtown Kalamazoo provides a dense, mixed use environment to support an initial bike share launch in Kalamazoo. Launching the system initially in the highest demand areas will accelerate visible success, maximize the chance of the system being profitable and increase the likelihood of future expansion.

Following groups represent the population in Downtown Kalamazoo who can utilize a bike sharing program:

- Students: many students do not have access to a car, and students often face limitations on the ability to maintain and store bicycles.
- Visitors: people visiting the city and colleges may wish to explore multiple areas of the community without the trouble of locating parking facilities, or they may arrive without a vehicle and appreciate the mobility provided by a bike share program.
- Commuters: employees who drive into Downtown Kalamazoo may want to make short trips during the workday to destinations throughout the city or use bike share program for exercise and recreation during lunch or other breaks.
- Residents: bike sharing program can effectively increase the range of destinations accessible without a car to local residents.

The following section defines the demand in Downtown Kalamazoo as population, employment, and locations of interest. These demand criteria will be utilized for the analysis and locating stations.

B.2 DEMAND CRITERIA

B.2.1 Population

As per 2014 Census data, population within Kalamazoo city is 75,922. Downtown Kalamazoo, uncommon among cities of this size, is a true urban center with 600 apartments and at least 1,200 residents. Figure B- 1 shows the distribution of population density in Downtown Kalamazoo (as per the Topologically Integrated Geographic Encoding and Referencing - TIGER system). The TIGER file is a census tract containing information such as boundaries, population counts, housing unit counts, median age, population 16 years and over, population 65 years and over, race, relationship, average household size, and etc. Downtown population density is represented by *Housing Unit Counts*. As shown in Figure B- 1, a majority of housing units are located in the southern side of the city. For this study, number of housing units is used to represent the demand for bike-share station planning. New developments represent future demand and included in demand calculation. Figure B- 2 shows the percentage of households with individuals of 65 years and older. Only about 15 % of households within downtown area has individuals of 65 years or older. Thus, it is safe to say that the downtown population is young. This is an important factor because early adopters of bike-share programs tend to be the young riders.

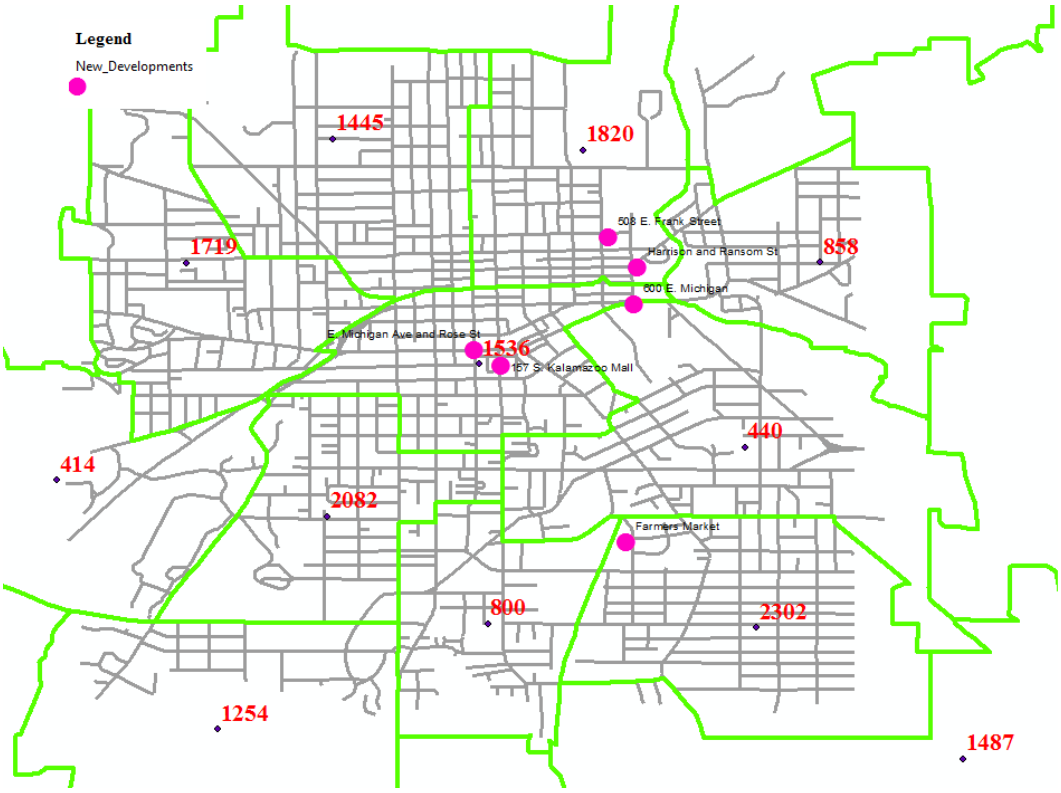


Figure B- 1. Distribution of housing units in downtown Kalamazoo

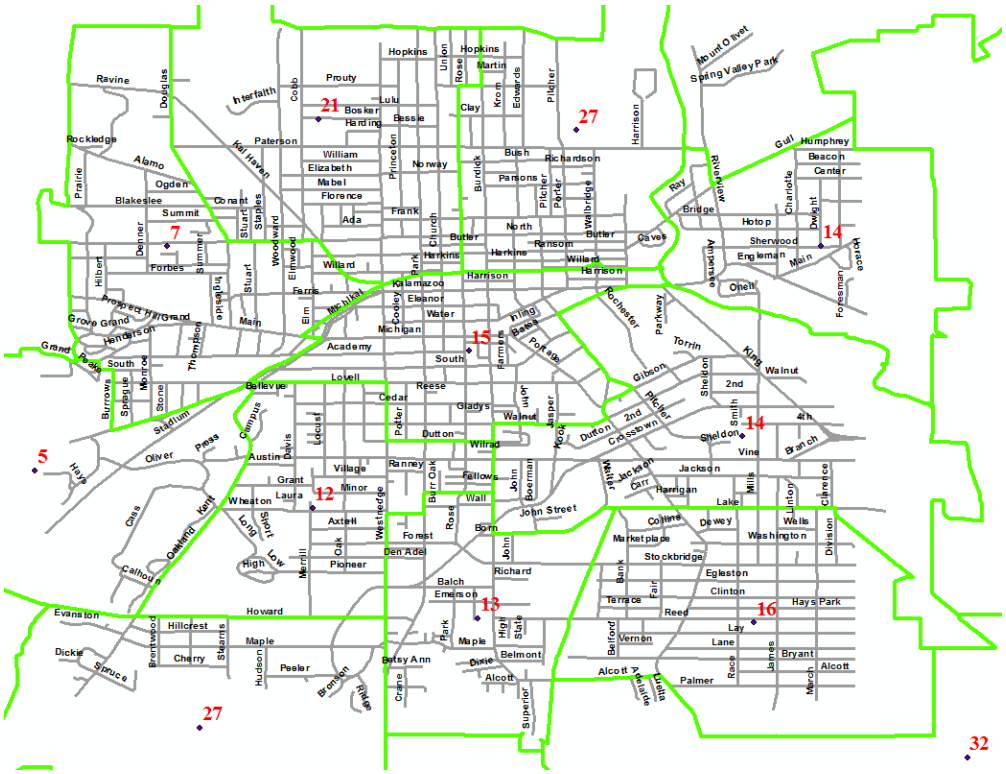


Figure B- 2. Percentages of households with individuals of 65 years and older

B.2.2 Employment

Downtown Kalamazoo has over 1,000 businesses employing nearly 13,000 people (Downtown Kalamazoo 2014) (Figure B- 3). Three colleges located around downtown area have an enrollment over 40,000 students. Furthermore, downtown Kalamazoo hosts over 120,000 visitors every summer. These employers, institutions, and events will serve as important trip generators and attractors for a bike-share program. In addition, these major employers could be possible sponsors or offer corporate membership to promote wellness and/or travel demand management programs. Bike sharing, together with public transit, could significantly increase residents and commuters' access to jobs. Thus it is of great importance to consider these locations during station location planning.

Figure B- 3 shows the distribution of employment density in Downtown Kalamazoo as per the Census Transportation Planning Products (CTPP). The CTPP data is based on 2006-2010 5- year American Community Survey (ACS) data. ACS is an ongoing activity that provides data by giving communities the current information needed to plan investments and services. Therefore this data

is useful for transportation analysts and planners to understand origin and destination of people commuting to downtown and commuting patterns (AASHTO 2016). The data file contains three main categories residence, workplace and flows. The category of interest is workplace. Workplace is further broken down into workers 16 years and over, workers 16 years and over who did not work at home and workers 16 years and over in households. For this analysis, the total worker 16 years and over who did not work at home data was utilized.

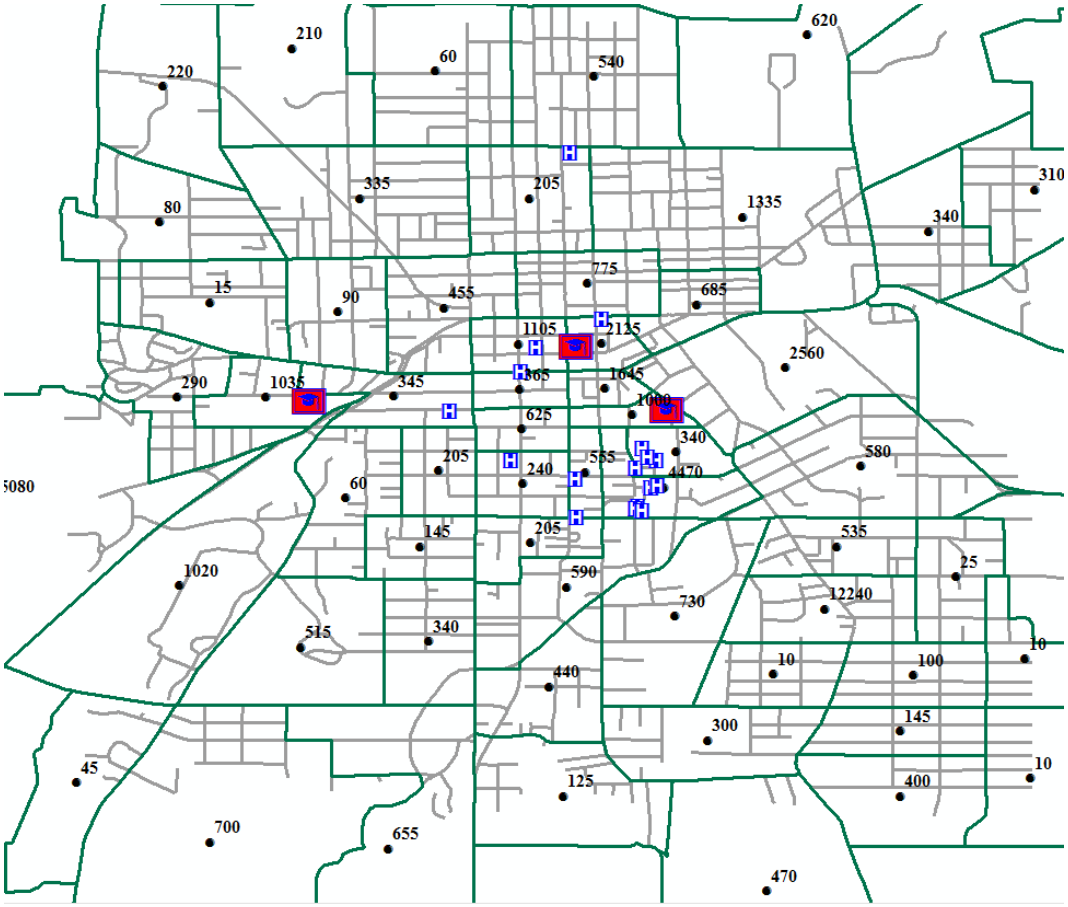


Figure B- 3. Employment distribution

B.2.3 Location of Interest

Retail and commercial areas are often trip attractors for bike share users. Therefore, providing bike-share services in areas of major retail and commercial activity increases the chances of bike share use. As mentioned before, downtown Kalamazoo has more than 1,000 businesses. Downtown Kalamazoo has a 14 screen movie house, 23 live performance stages, a museum, a public library, and many more attractions making it a true urban center people (Downtown

Kalamazoo 2014). Further, downtown continues to grow in the entertainment and restaurant industry. Also, the residential vacancy rate is less than 1.5 %. As shown in Figure B- 4, downtown has a high concentration of retail and commercial areas, making a good location for an initial bike share program. Another locations of interest are the residential areas. Residential areas can, on the other hand, be trip generators. The categories included in the analysis are apartment complexes, banks, bars, churches, clothing stores, college campuses, companies, government institutions, hospitals, pharmacies, parks, parking structures, restaurants, schools, and theaters. All the other businesses that do not belong to the above listed categories are listed under general commercial entities. Altogether, a total of 244 locations of interest are identified within and around the downtown area.

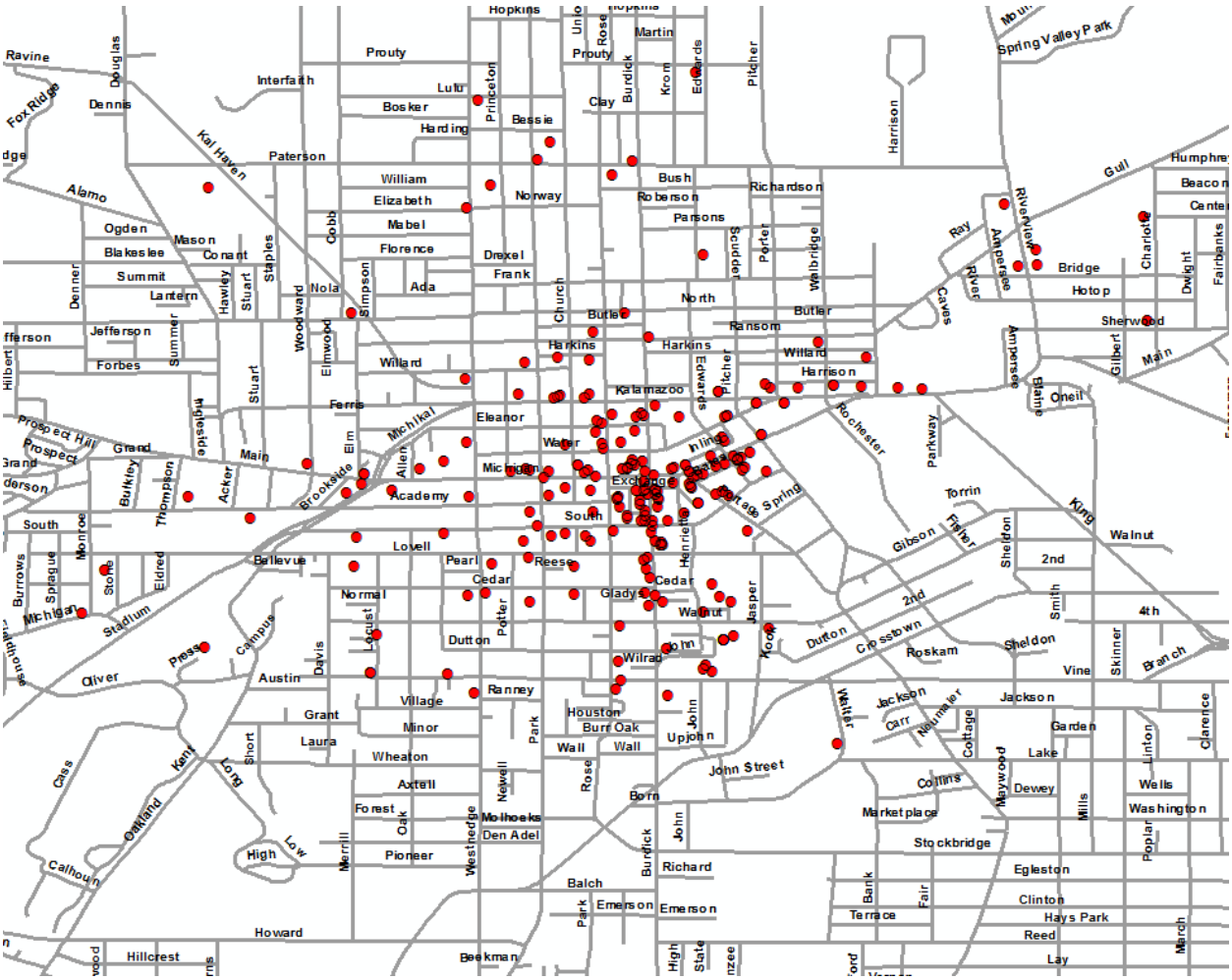


Figure B- 4. Locations of interest within and around downtown Kalamazoo

B.3 CRITERA FOR SELECTING CANDIDATES LOCATIONS FOR STATIONS

B.3.1 Minimum Size of a Program

Effectiveness of a bike sharing program depends on its size. A system with 10 stations spread over at least approximate of 2 square mile (five square kilometers) area is considered as the absolute minimum to provide an effective mix of origin and destination trips, and to justify the cost of operation (Alta Planning and Design Living AB 2012).

The following are key points to be considered when sizing a system:

- The system size is selected to cover an area within which cycling becomes more attractive and convenient than walking.
- The system must offer numerous origins and destinations to promote bicycle use.
- The system should have adequate number of stations to provide reasonable access, minimize walking distance, and discourage driving.

B.3.2 Area of Influence

Many bike share program have used location of influence as a point of reference to locate potential stations. These areas are often called “attractors” and “generators” as these areas are most likely to draw or generate trips. Several of such locations are identified for Kalamazoo downtown area and presented in subsequent sub-sections.

B.3.1.1 *WMU School of Medicine*

The Western Michigan University School of Medicine was established in August 2012 with 54 medical students and 200 residents. It is located on Portage Street, Downtown Kalamazoo (Figure B- 5).



Figure B- 5. WMU School of Medicine

B.3.1.2 Arcadia Common Campus

Arcadia Common Campus is located on Rose Street, Downtown Kalamazoo. It enrolls 3,000 students each semester. The campus includes Anna Whitten Hall (classroom and student services building), the Center for New Media, the Kalamazoo Valley Museum, and parking for all enrolled students (Figure B- 6).

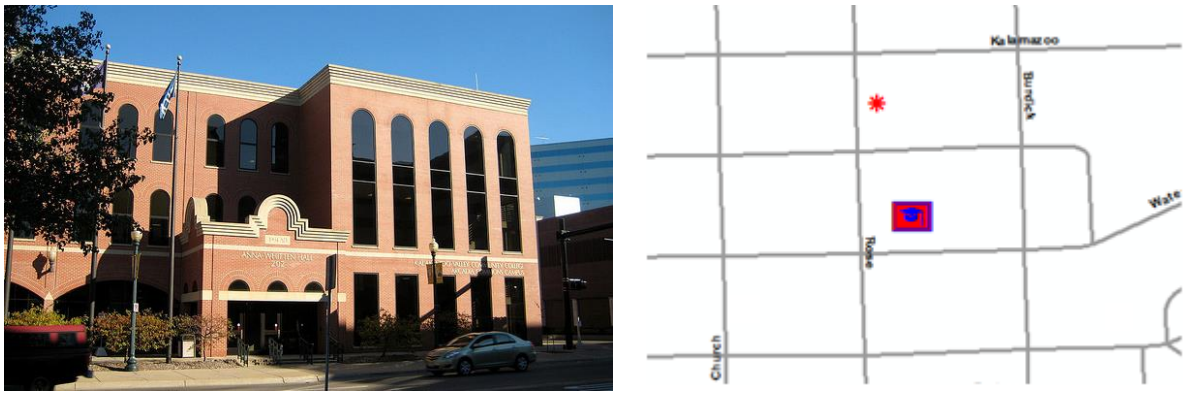


Figure B- 6. KVCC Arcadia Common Campus

B.3.1.3 Bronson Hospital

The Bronson Hospital was founded in 1900 and located on John Street, Downtown Kalamazoo (Figure B- 7). Bronson Hospital has more than 3,500 employees. Also, Bronson has expressed the need to provide alternatives to driving in order to maximize the parking spaces at the hospital premises available to patients. By having a bike share station near the hospital,

employees will be able to utilize bicycles to commute between work and nearby parking structures, as well between work and downtown for shopping and restaurants.

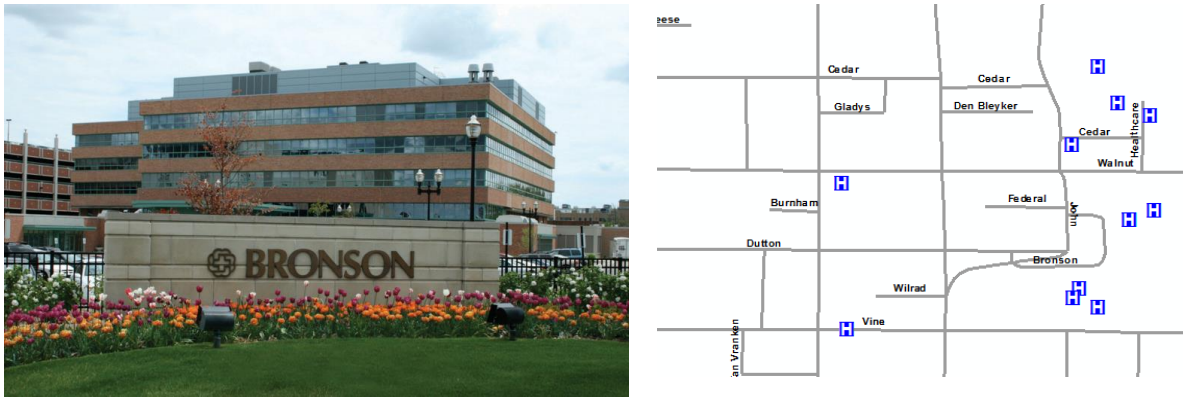


Figure B- 7. Bronson Hospital

B.3.1.4 Radisson Hotel

The Radisson Hotel is a 4-star hotel located on West Michigan Avenue, Downtown Kalamazoo (Figure B- 8). The hotel has 340 hotel rooms, 22 event rooms and ballroom that can accommodate up to 600 guests. Every year, the Radisson Hotel hosts many events and conferences.



Figure B- 8. Radisson Hotel

B.3.3 Non-motorized Facilities

During bike-share program development, it is expected to utilize existing infrastructure to minimize implementation cost. Availability of wide shared-lanes, bike lanes, trails, shared–use

paths, paved shoulders, signage, lighting conditions, and well maintained roads is key to a successful program.

When planning a bike-share program and station locations, it is important to coordinate with planned non-motorized improvements in the area. In 2015, Kalamazoo Non-motorized Transportation Plan (NMP), which was last updated in 1998, was revised after conducting a series of workshops to obtain input from non-motorized users in the city (The City of Kalamazoo 2015). The updated plan included all the existing and future non-motorized facilities as shown in Figure B- 9 and Figure B- 10.

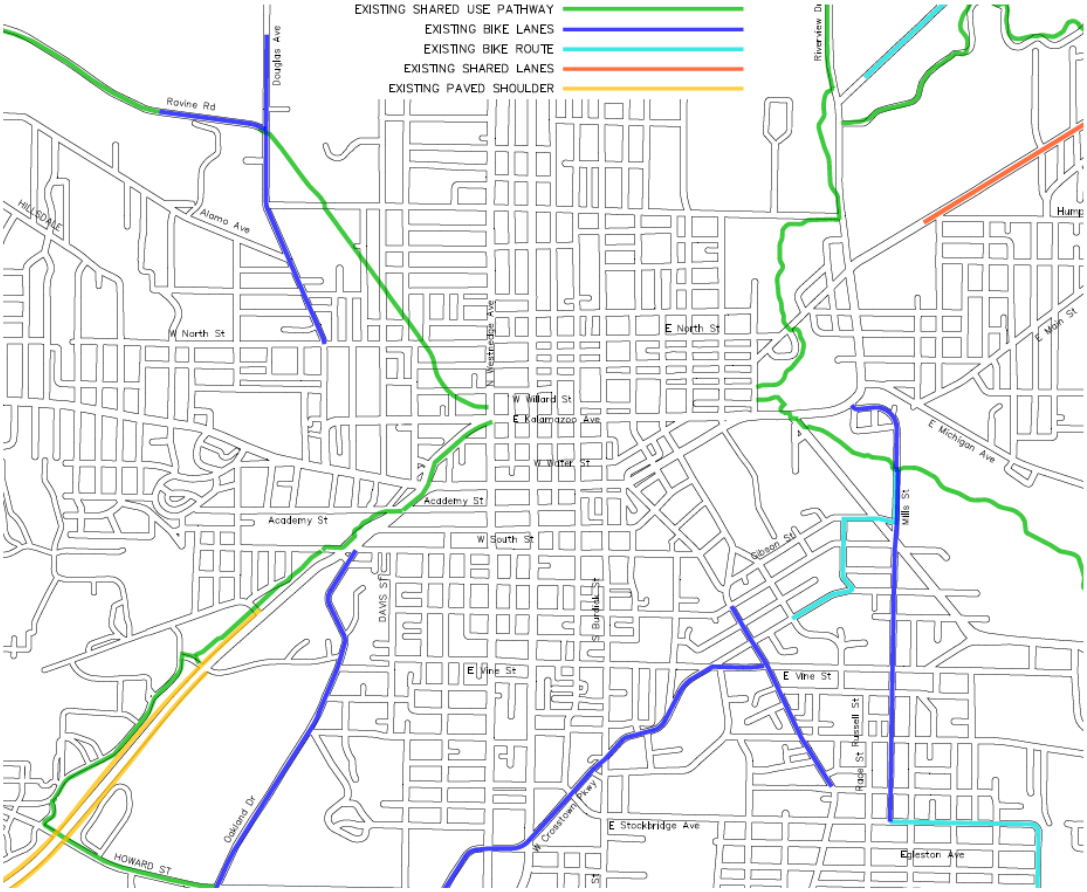


Figure B- 9. Existing non-motorized facilities

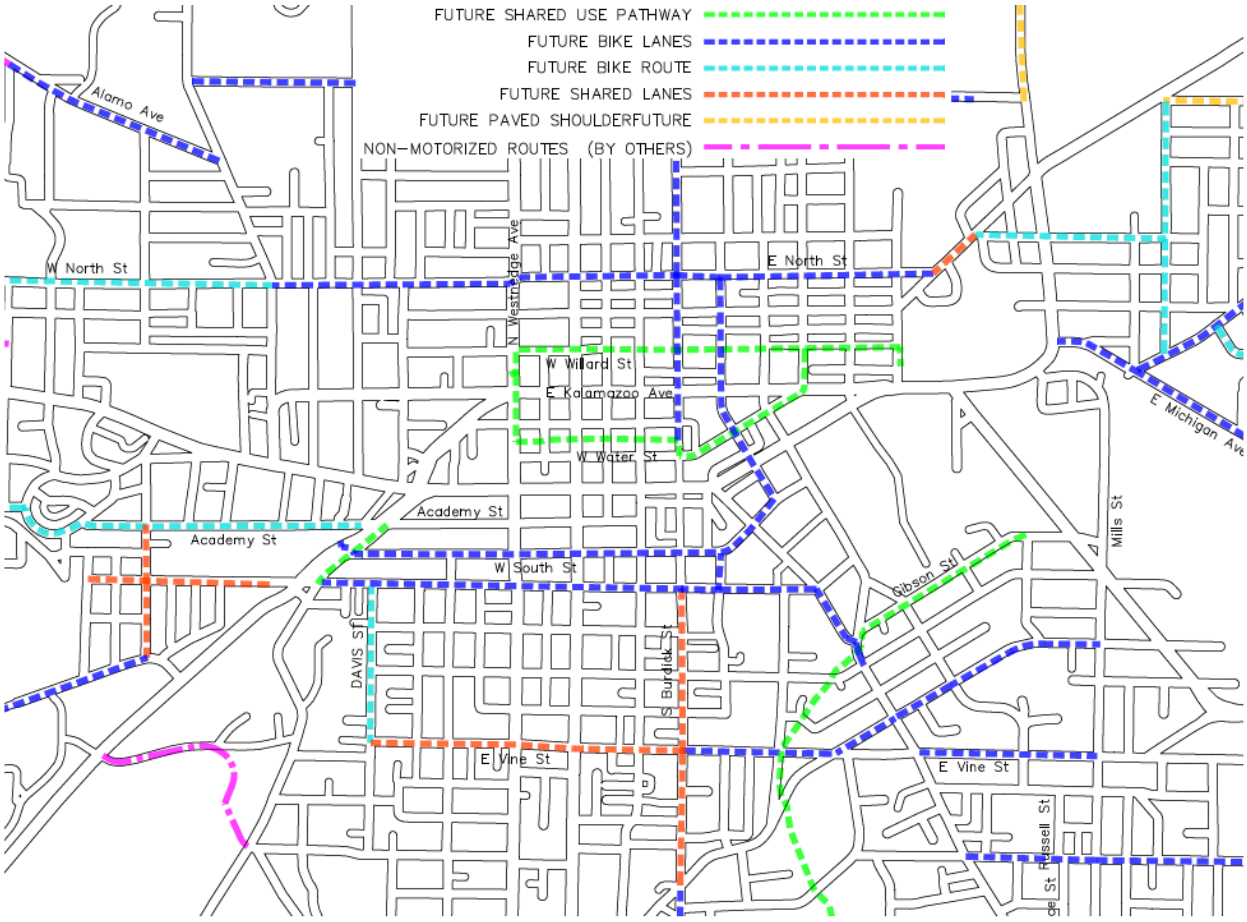


Figure B- 10. Future non-motorized facilities

With the development in downtown area, it is recommended to start placing candidate stations on existing as well as on planned facilities (Figure B- 11).

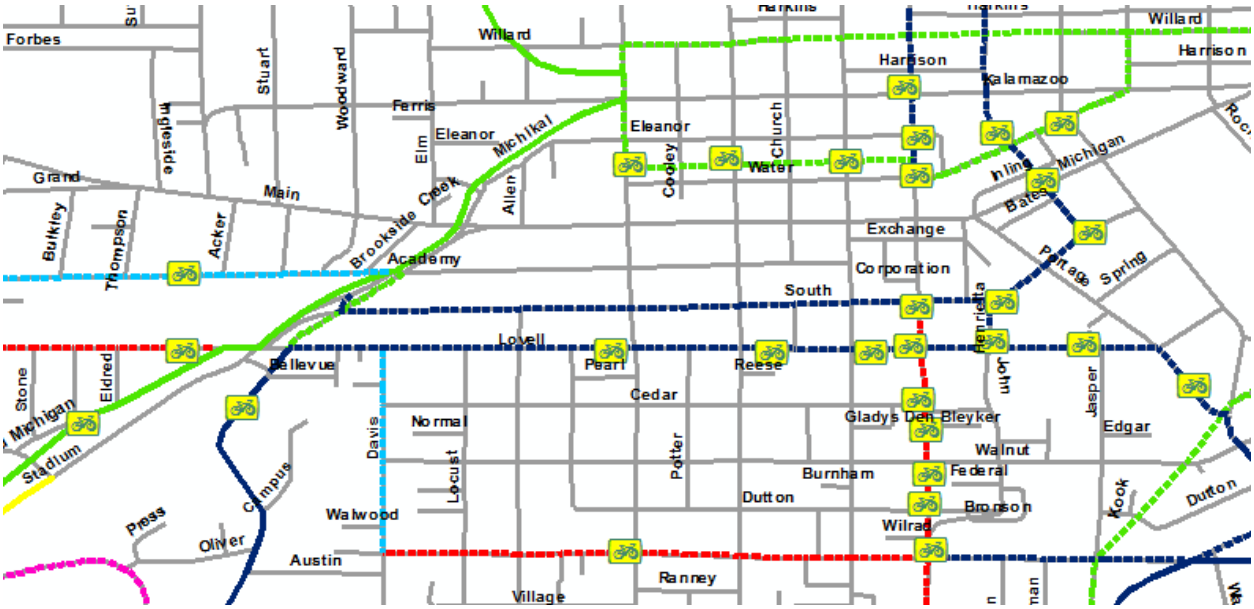


Figure B- 11. Candidate stations located in existing and planned non-motorized facilities

B.3.4 Intermodality Possibility

Accessibility as well as the success of a bike-share program improve when it is integrated with traditional transportation systems. Transit stops are good candidates for bike share stations and allow transit users to extend their trips. Bike share system can be a complement to transit stop as it enables the users to complete their first or last segment of the trips in areas where public transit is not operational. Thus, a bike-share program can provide greater flexibility to commuters through intermodality.

Kalamazoo Metro Transit has 20 regularly scheduled bus routes operating at 15, 30, and 60 minutes intervals depending on the route and the time of day. There are currently 36 buses in the service. According to the available ridership profile data, the transit system users include 16 to 22 years (32%), 23 to 42 years (36%), and 43 to 61 years (24%) (Kalamazoo Metro Transit 2013). The data shows that transit users are mostly young, which is often the dominant age group of bike-share users. Figure B- 12 shows the bus stations located in Downtown Kalamazoo. Efforts should be made to create an intermodality between transit and bike-share system to provide access to users those who live in unserved areas by busses such that the first/last segment of their trips are completed using a bicycle.

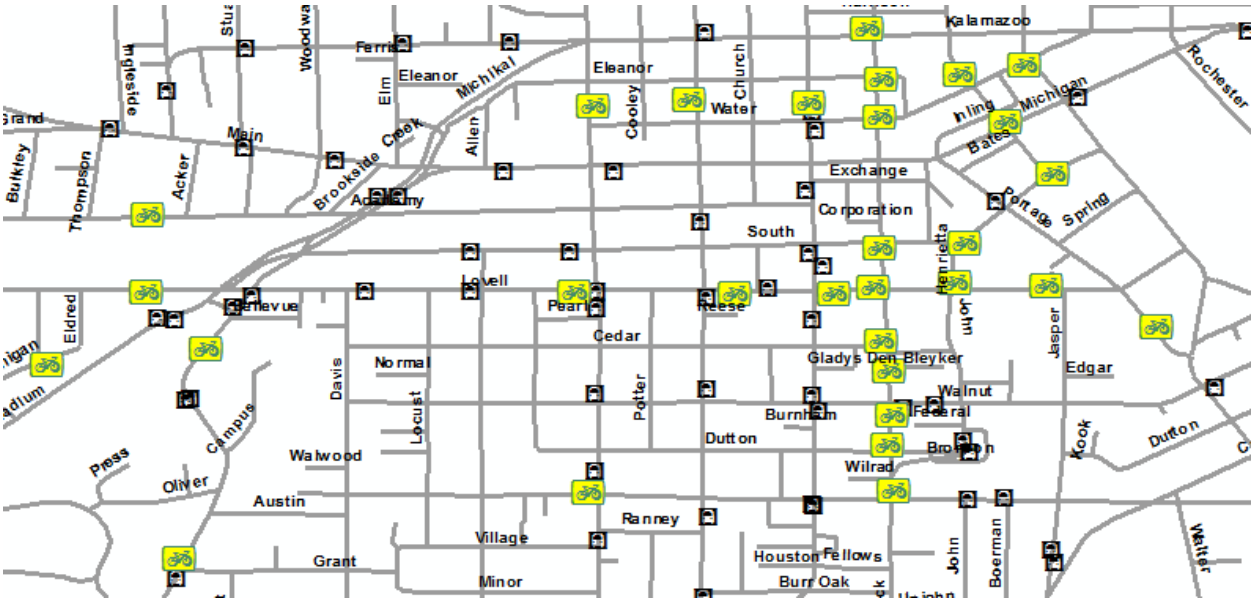


Figure B- 12. Bus stations in Downtown Kalamazoo

B.3.5 Topography

Topography of an area is a crucial decision making factor when locating bike-share stations because users dislike grades more than 4%, and completely evade routes with a grade greater than 8%. Hence, an area with no more than 4% grade along bicycle routes is ideal for implementation of a bike-share program (Midgley 2011). The topography needs to be considered when scheduling bicycle redistribution because the stations downhill will have more bicycles very often. The topography of Downtown Kalamazoo is shown in Figure B- 13. As indicated in green, a majority of the area has a grade less than or equal to 4%. However, a majority of the area located west of downtown has a grade greater than 4%.

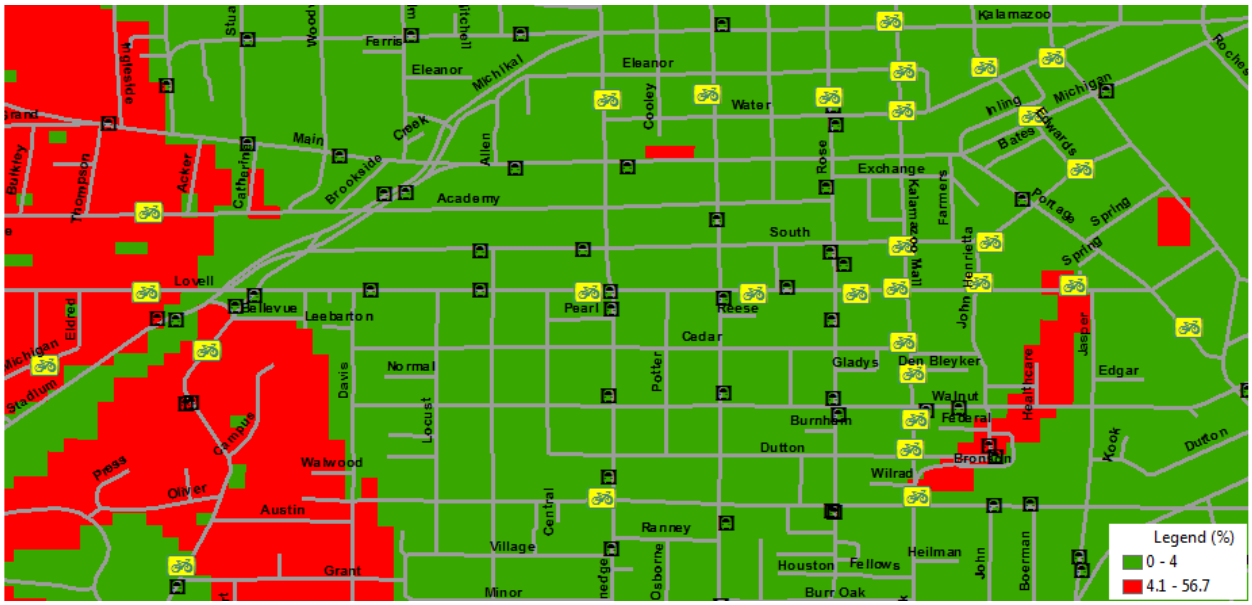


Figure B- 13. Topology of Downtown Kalamazoo

B.3.6 Desired Walking Distance

Desired walking distance is an important parameter for planning bike-share station locations. It is considered as a constraint for analysis. Thus, desired walking distance is used as the impedance cutoff in GIS. According to *State of the Practice and Guide to Implementation* (FHWA 2012) stations should be located no more than ½ mile apart (FHWA 2012). Research shows that a typical walking distance of about ¼ of a mile takes about 5 minutes (Alta Planning and Design Living AB 2013). After evaluating literature on typical walking distances, Schoner et al. (2012) recommended using a ¼-mile walking distance. After evaluating literature recommendations and layout of downtown businesses and establishments, a ¼-mile walking distance to each station was selected for Downtown Kalamazoo. Figure B- 14 shows the area covered by a selected number of bike-share stations with a ¼-mile walking distance.

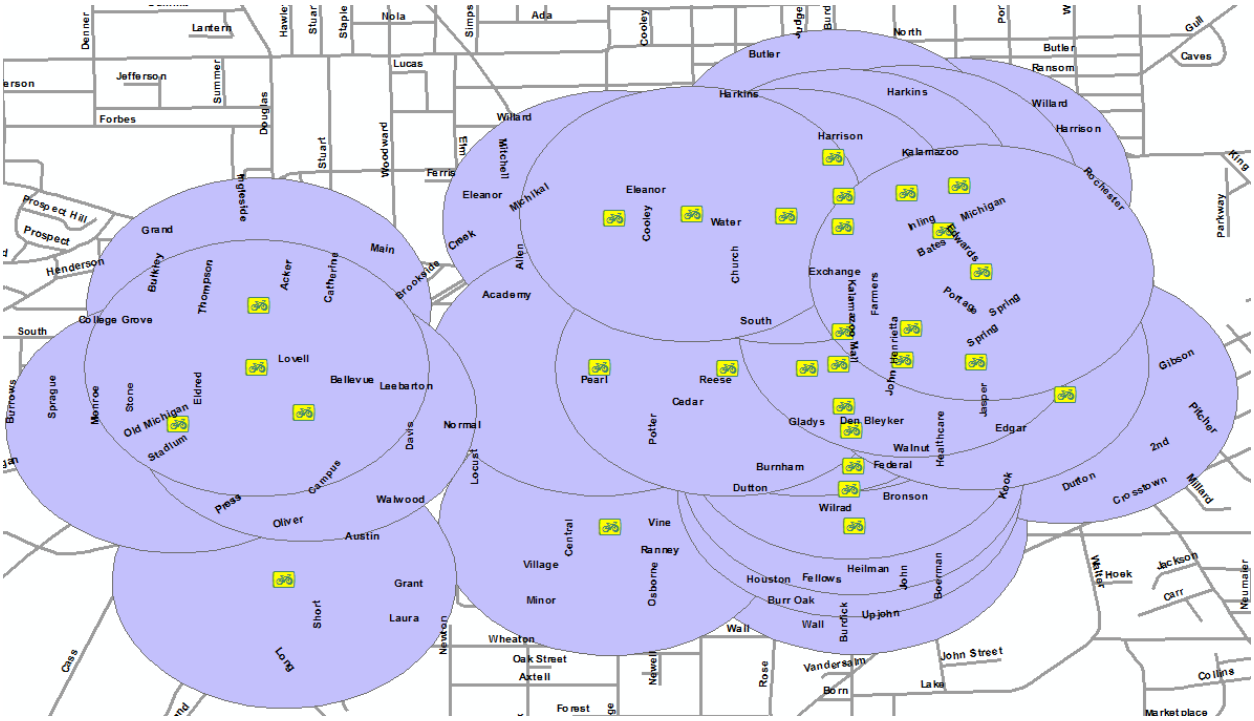


Figure B- 14. Area covered by a selected number of stations with a ¼ -mile walking distance

B.4 ANALYSIS

During the planning process, the number of bike stations is optimized. However, the analysis process requires defining a layout of candidate stations based on the criteria described in section B.3. The purpose of this study is to locate a number of bike- share stations to satisfy the demand within the downtown area as an initial phase of an implementation program. In order to optimize the number of bike-share stations, the demand based on the distribution of population, employment, and locations of interest is considered. However, there is no predefined percentage of demand to be covered. Hence, the intention is to satisfy the demand as much as possible by using a minimum number of bike-share stations starting with the predefined candidates. After considering the parameter applicable for downtown Kalamazoo, thirty (30) stations were selected as the candidates for further analysis (Figure B- 15).

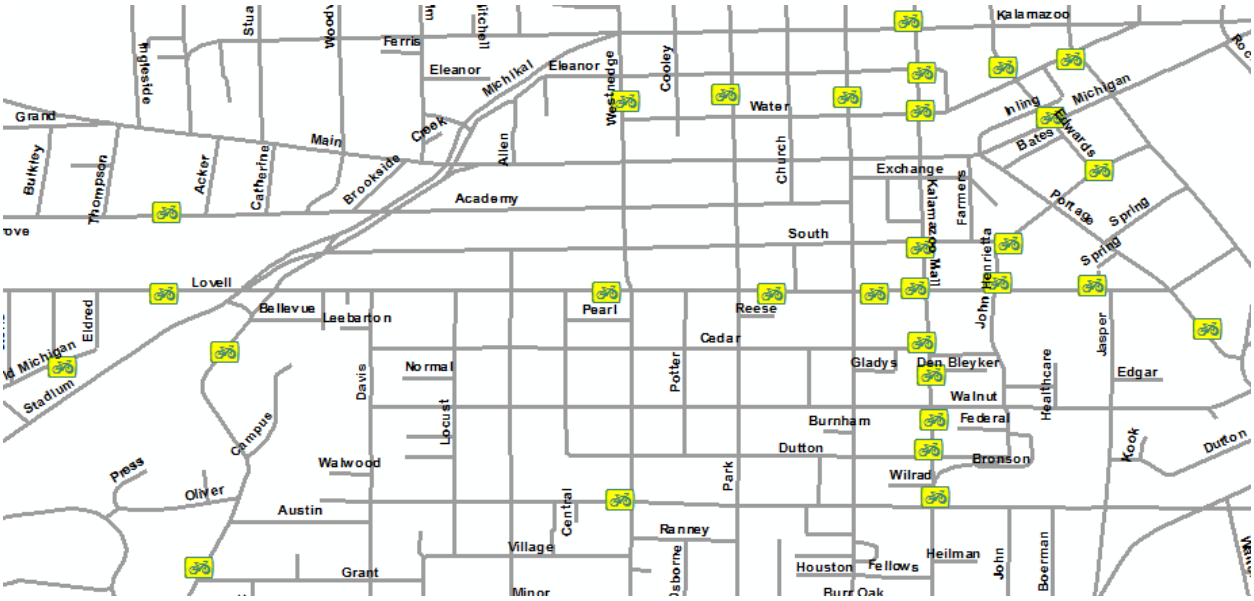
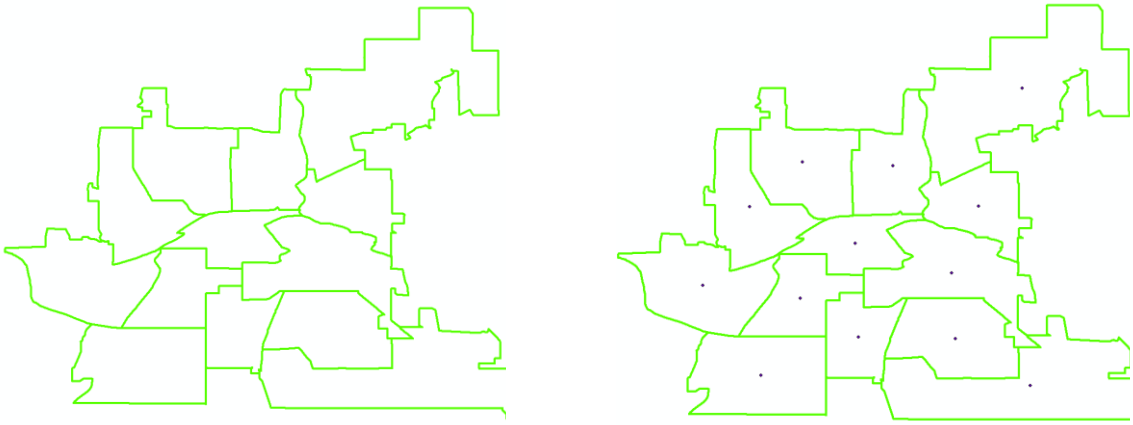


Figure B- 15. Candidate bike stations assigned for preliminary analysis

The population and employment default data files (as presented in sections B.2.1 and B.2.2) are in polygons, where the population and/or employment within a polygon is assumed to be the same. In order to execute location-allocation models in ArcGIS, it is necessary to present demand and facilities data as point files. In ArcGIS, the geoprocessing tool *feature to point* allows user to create points from the representing polygons (Figure B- 16). The point are the centroid of the corresponding polygon. This process is performed to match the framework needed to support location-allocation model on ArcGIS, enduring reliable results. After point data files are developed for each demand type, location of bike-share stations for each demand type is identified using location-allocation models. Once the station locations are identified for each demand type, the stations that are common to all the demand types are selected as the optimum distribution of stations.



a) Default polygon data file

b) Point file

Figure B- 16. Polygon and point data files

B.4.1 Maximize Coverage Analysis

Maximize coverage analysis allows limiting the number of stations to be allocated from a set of candidates. The number of stations is not limited for this study since there is no budgetary constraint defined. Once the analysis is executed with a predefined impedance cutoff, analysis continues by incrementally adding bike-share stations until the maximum number of stations are allocated to cover a specific demand type. In the analysis performed for this study, impedance cutoff is defined as the walking distance limit of a ¼ - mile. The following sections describe the analysis performed for each demand type, and present the number of bike-share stations and station locations.

B.4.1.1 Population Demand

In the default data file format, population density is represented with polygons. One of the challenges of allocating a bike-share station for a demand defined by polygon data file and an impedance cutoff is that if the centroid of the polygon is not within the cutoff limit from a candidate station, the demand is not allocated in the analysis. This is the reason why only one station (closest) was allocated by the model to serve the only demand point that was within the desired walking distance from every candidate station. The bike-share station chosen to serve the population based on maximize coverage model is symbolized with the red-star in Figure B- 17. The total distance between centroid of polygon and bike station is 0.15 mile.

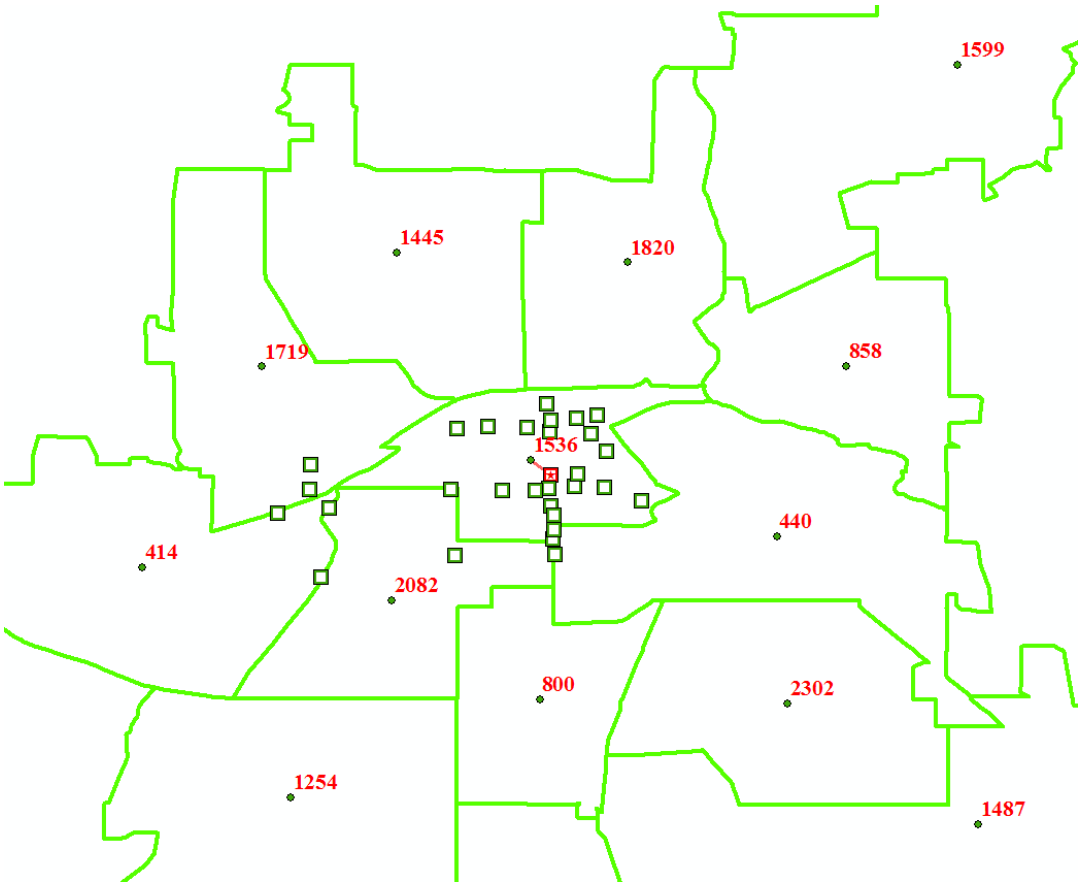


Figure B- 17. Maximize coverage for population demand

B.4.1.2 Employment Demand

In the default data file format, employment density is represented with smaller polygons compared to population data file. Consequently, a more dense distribution of the centroids of the polygons is resulted while the population data file gives a sparse distribution. Because of that, there is a high chance of covering a large percentage of employment demand located within ¼ mile walking distance to a bike share station. Based on maximize coverage, a maximum number of 13 out of 30 stations can be allocated to demand based on the desired walking distance constraint. The stations allocated a total of 16 centroids (Figure B- 18).

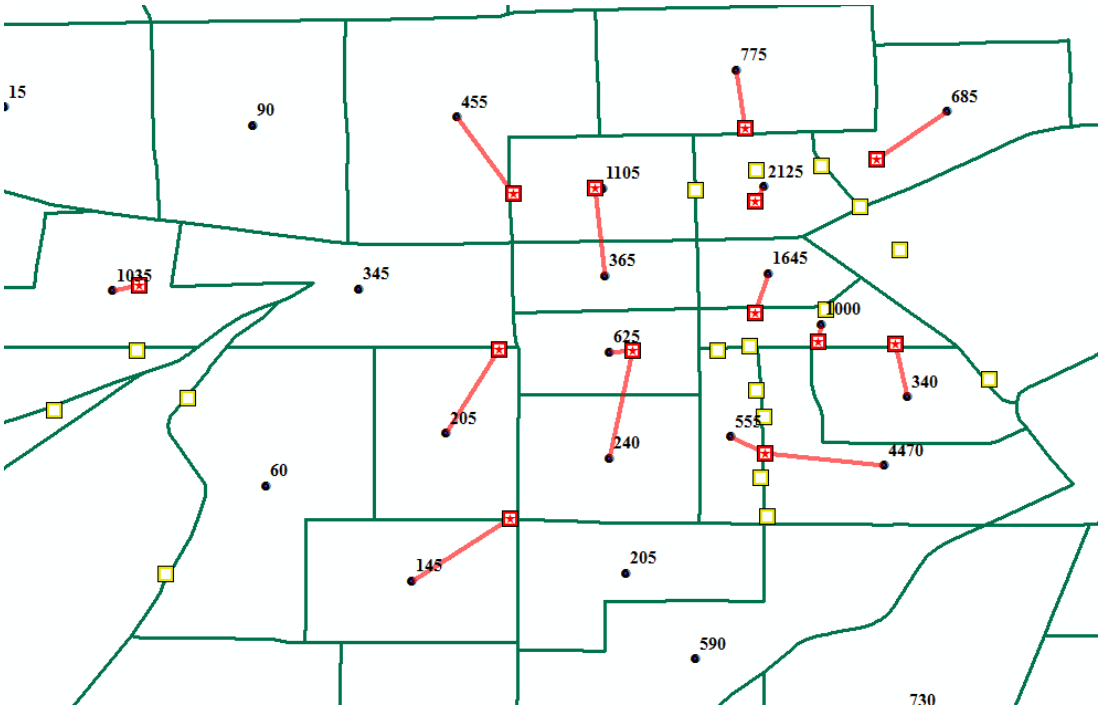


Figure B- 18. Maximize coverage for Employment Demand

B.4.1.3 Location of Interest demand

Downtown Kalamazoo has a high concentration of retail, commercial and residential areas. These was presented in section B.2.3. These locations are presented in point files. The number of location of interest to be allocated is 244. The maximum amount of bike-share station that can allocate, at least, a point of interest is 25 out of 30 (Figure B- 19). The number of locations of interest allocated was 190. This means that 54 locations are outside of the desired walking distance from each bike-share station candidate.

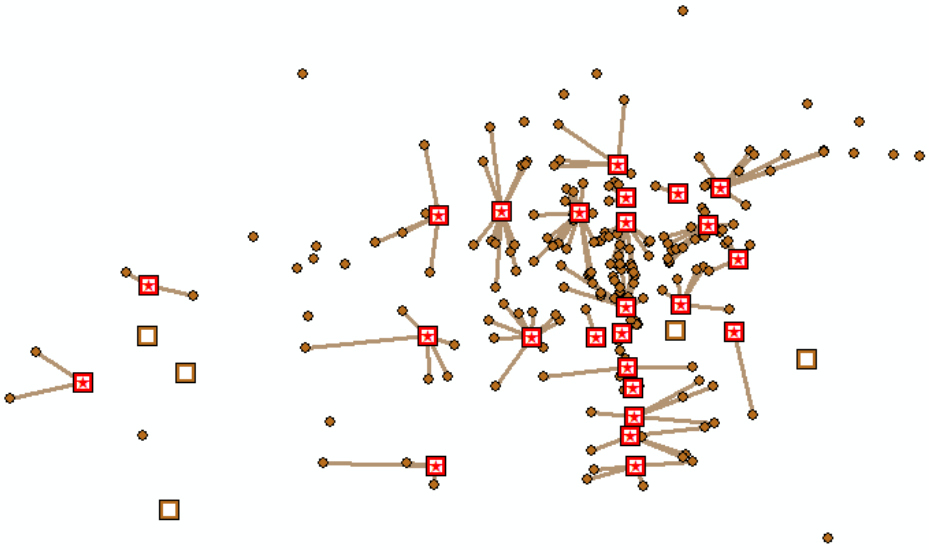


Figure B- 19. Maximize coverage for Location of Interest Demand

B.4.2 Minimize Facilities Analysis

Minimize facilities models provides the minimum number of facilities needed so no demand is left within the desired walking distance specified, thus minimize facility model provides the lower bound of the analysis. For this project, as mentioned before, the desired walking distance to the specific station is defined by the cut-off distance of ¼ of a mile. In contrast to maximize coverage model, minimize facilities does not allow users to specify the number of location to be allocated, therefore the process only consist of providing the demand to be allocated, the candidate bike-share stations and finally the impedance cutoff. The following sections describe the analysis performed for each demand type, and present the number of bike-share stations and station locations.

B.4.2.1 Population Demand

As expected, the same result obtained in maximize coverage analysis model was obtained from minimize facility model. The same challenge is faced due to the fact that the point of allocation is in the centroid of the polygon. Therefore, only one station is found to be feasible to allocate the population demand (Figure B- 20).

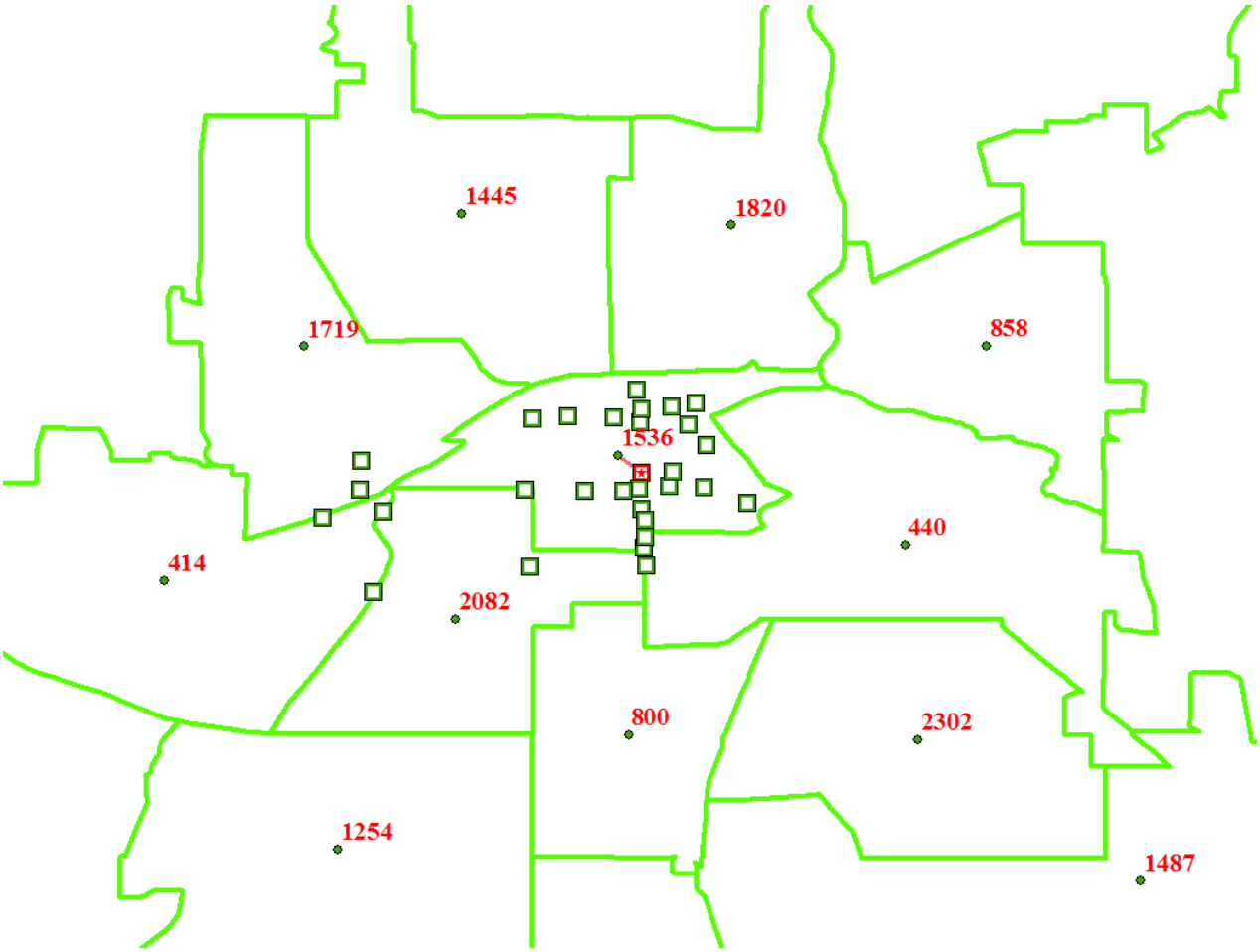


Figure B- 20. Minimize facilities for Population demand

B.4.2.2 Employment Demand

The minimize facilities model for employment demand allocated demand to eight (8) stations. The stations allocated a total of 16 centroids. Meaning that, 16 polygons representing employment densities can be efficiently served with a minimum of 8 stations out of 30 pre-defined candidates (Figure B- 21).

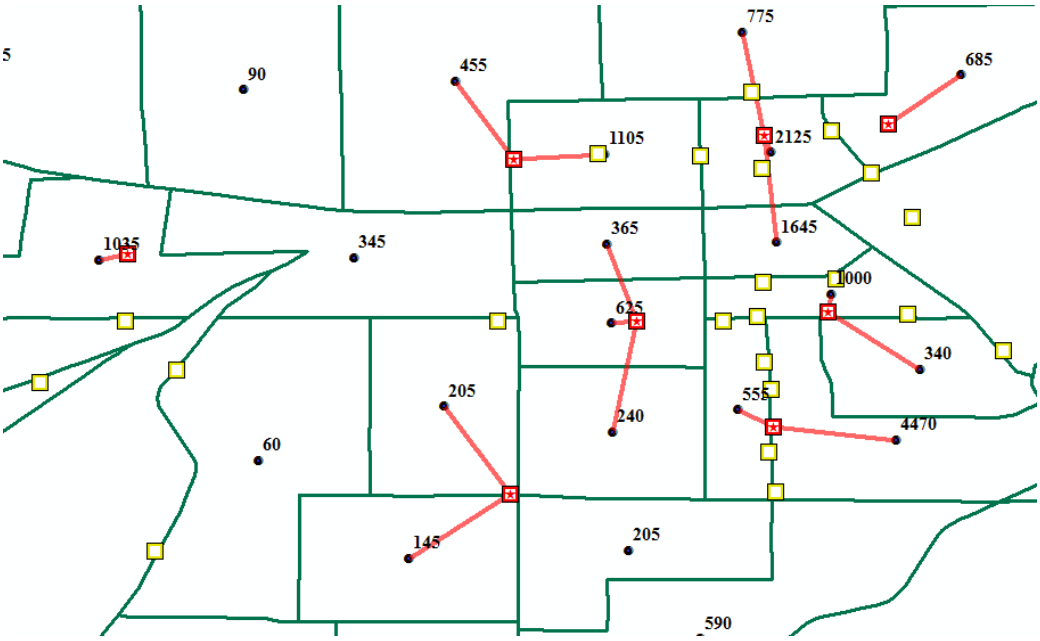


Figure B- 21. Minimize facilities for Employment demand

B.4.2.3 Location of Interest Demand

The minimize facilities model location of interest allocated demand to eleven (11) stations. The stations allocated a total of 190 location of interest. Meaning that, out of the 30 pre-defined bike-share candidates, only 11 stations will be able to allocate demand based on candidates' locations and desired walking distance (Figure B- 22).

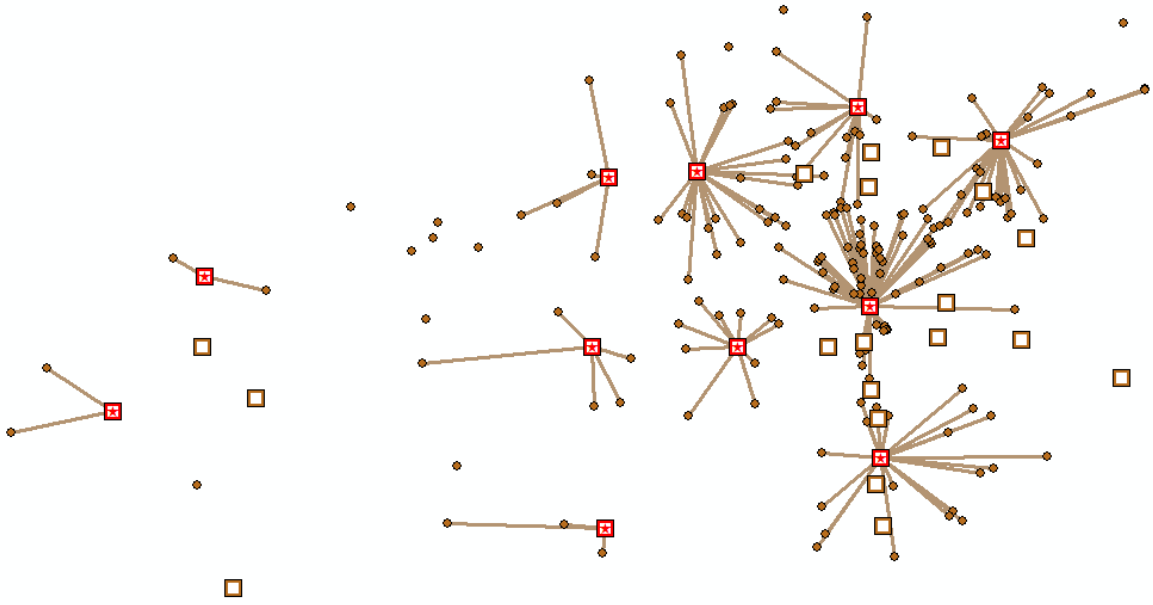


Figure B- 22. Minimize facilities for Location of Interest Demand

B.4.3 Optimal Candidates

The optimal candidates are the candidates that satisfy the population, employment and location of interest demand. As each density demand is obtained from their corresponding default data file, the analysis to determine optimal candidates has to be executed separate. These results in six (6) sets of optimal candidates. Three sets covering each demand using maximize coverage and minimize facilities. Bike-share stations candidates are labeled by numbers as shown in Figure B- 23. Table B- 1 presents the optimal bike station candidates under each demand and model. In order to come up with the set of optimal candidates that serves each demand type, the station that satisfied two (2) or more demand type was selected as optimal for this analysis. For example, in Table B- 1 station 4 satisfies demand for employment and location of interest. Thus, it is selected as optimal candidate.

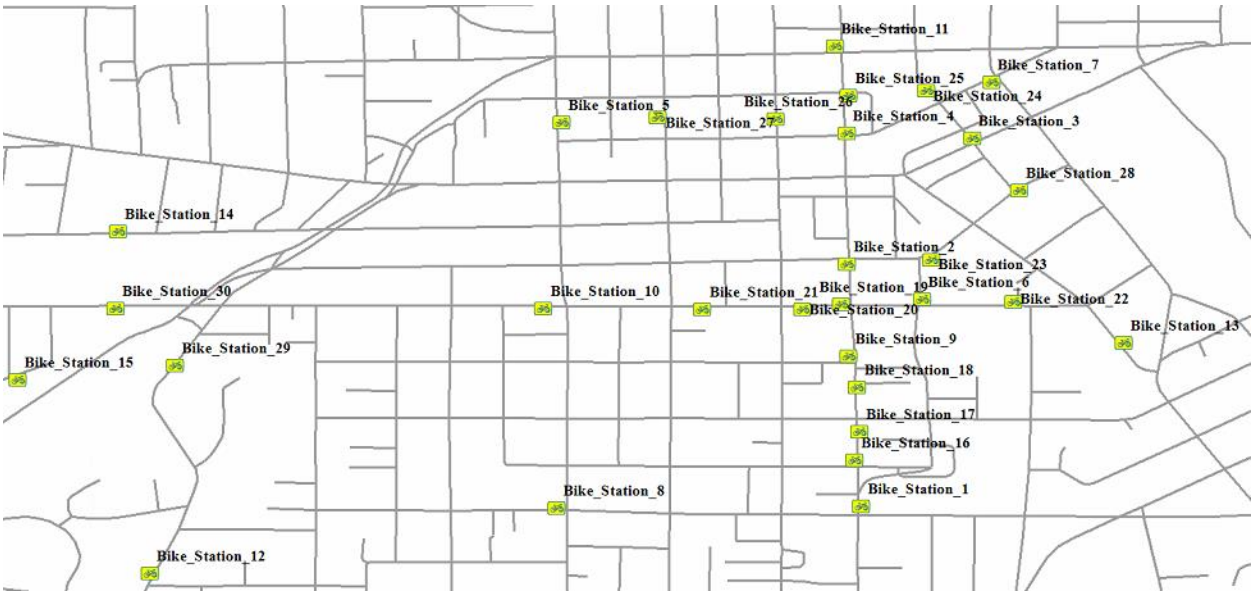


Figure B- 23. Bike-share station candidate labels

Table B- 1. Location-Allocation Model Results

	Population		Employment		Loc. of interest		Optimal candidates
Station	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	
1					√		
2	√	√	√		√	√	√
3							
4			√		√		√
5			√	√	√	√	√
6			√	√			
7			√	√	√	√	√
8			√	√	√	√	√
9					√		
10			√		√	√	√
11			√		√	√	√
12							
13							
14			√	√	√	√	√
15					√	√	
16					√		
17			√	√	√	√	√
18					√		
19					√		
20					√		
21			√	√	√	√	√
22			√		√		√
23					√		
24					√		
25				√	√		
26					√		
27			√		√	√	√
28					√		
29							
30							

After obtaining the set of optimal candidates, their locations are double checked to make sure these chosen stations are located by the areas of influence (attractors/generators) discussed in Section B.3.2, within the desired walking distance of ¼ mile and near bus stations (Figure B- 24 and Figure B- 25). If the set of optimal candidates satisfy the location and distance factors aforementioned, then these candidates become the set of final stations (Table B- 2). Otherwise, the set of optimal candidates are reconsidered and other chosen stations presented in Table B- 1 are evaluated until a set of final stations is found. If no stations are found to meet all location and

distance factors, bike-share candidates can be relocated and re-analyzed until all criteria and analysis factors are met. The final set of optimal stations is presented in Figure B- 26.

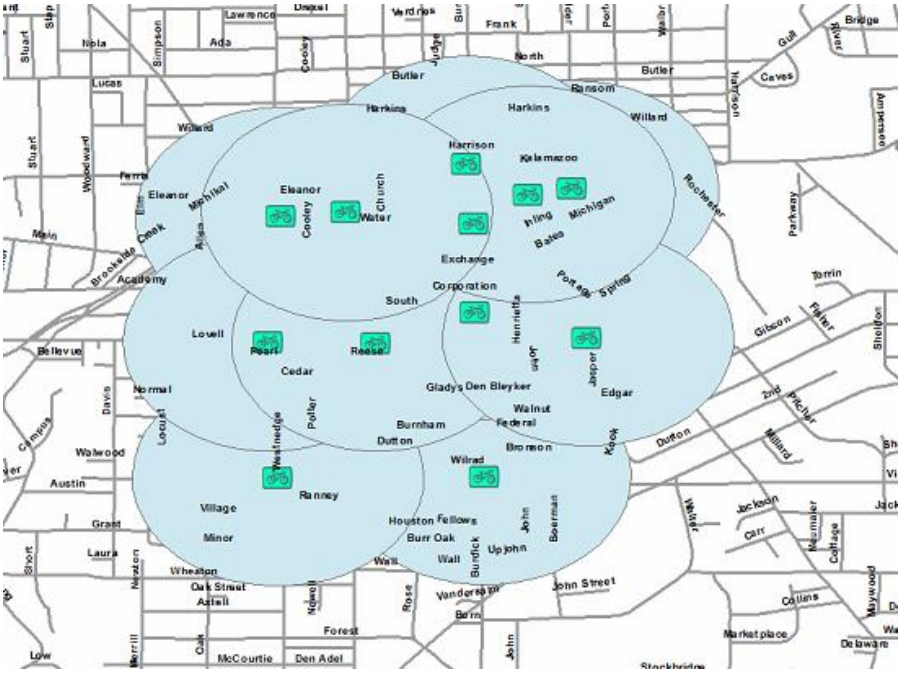


Figure B- 24. ¼ miles buffer from each station

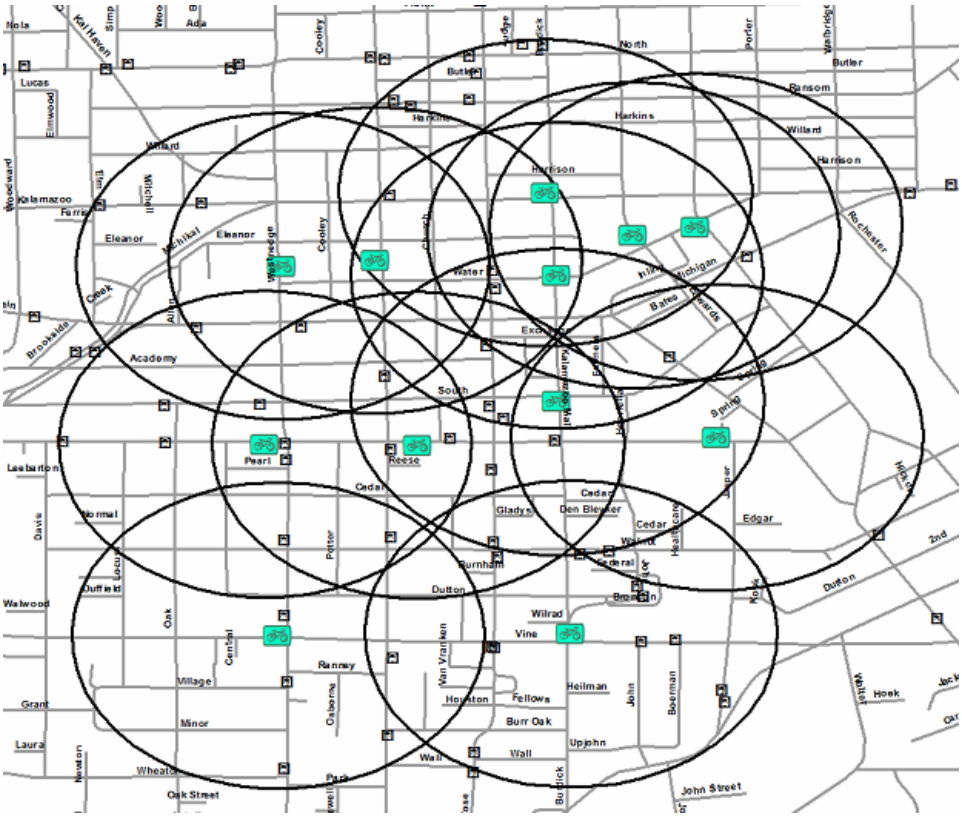


Figure B- 25. ¼ miles buffer from station to nearest bus stop

Table B- 2. Selection of the Optimal Candidates

Optimal station	Accepted/Discarded/inserted	Reason
2	Accepted	-
4	Accepted	-
5	Accepted	-
7	Accepted	-
8	Accepted	-
10	Accepted	-
11	Accepted	-
14	Discarded	Did not meet 1/4 mile buffer from each other
17	Discarded	Switched for Bike Station 1 to serve generator Bronson Hospital
21	Accepted	-
22	Accepted	-
24	Inserted	To serve major attractor/generator Arcadia Creek Festival Place
27	Accepted	-

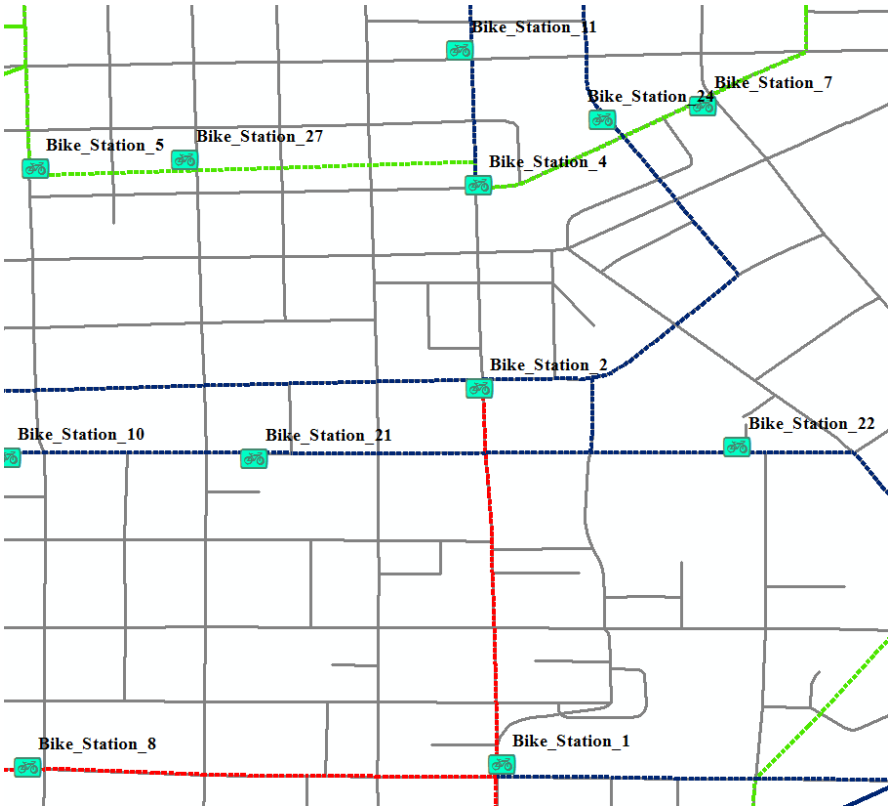


Figure B- 26. The set of final stations

As stated before, the challenge with the Network Analyst, extension of GIS, is that the demand and facilities to be analyzed have to be in point data. This is a major constraint when trying to allocate population and employment demand. Thus, to better show the area being served by each station within the desired walking distance, an extension of GIS called service area was utilized. Service area presents the region that encompassed all accessible streets within a specified impedance. The impedance for service area is the desired walking distance. Figure B- 27, B-28 and B-29 presents the service area covered by the final stations for the population, employment and location of interest demand with a ¼ mile impedance cutoff. Each station covers about 0.1 square mile.

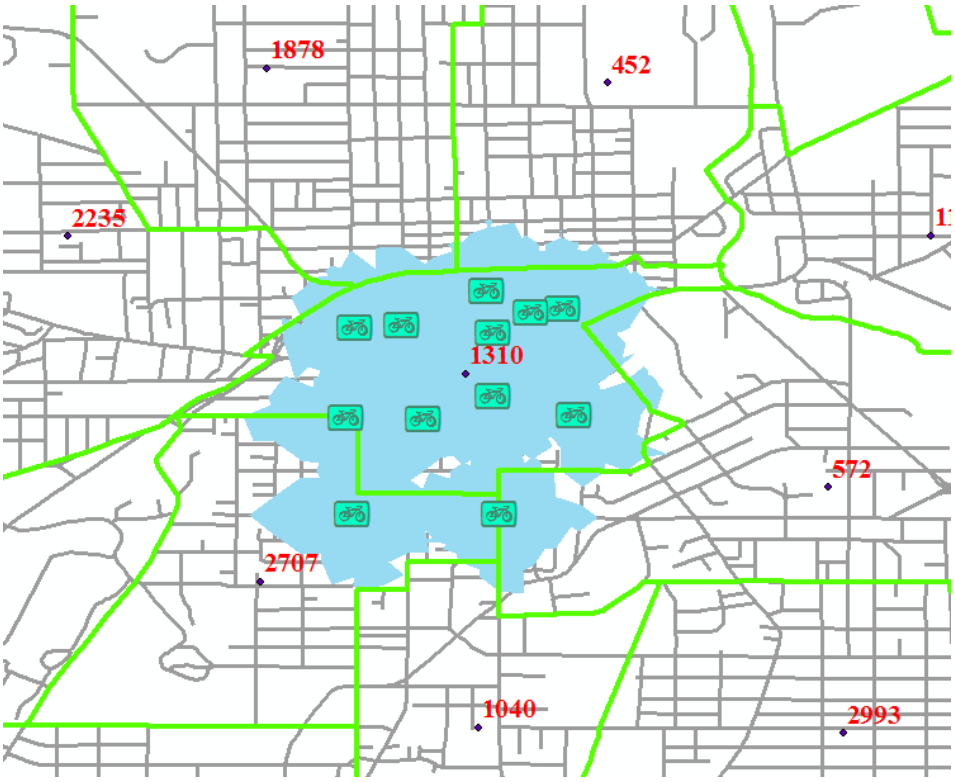


Figure B- 27. Service area for population demand

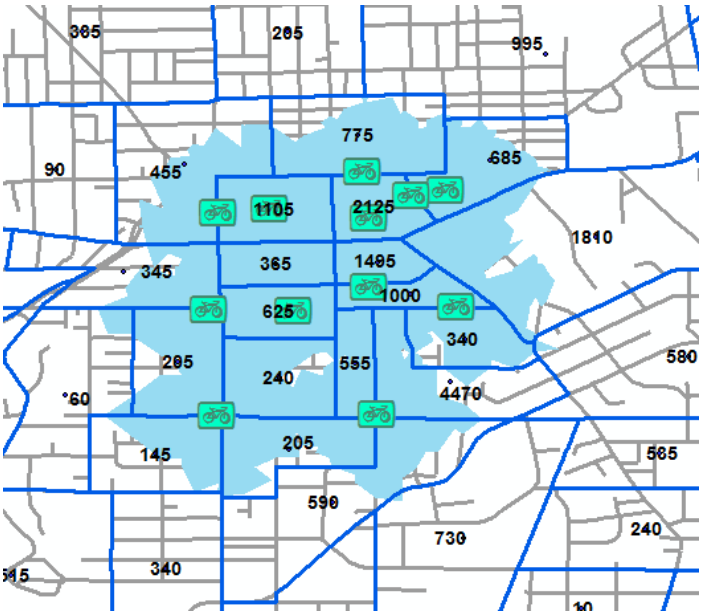


Figure B- 28. Service area for employment demand

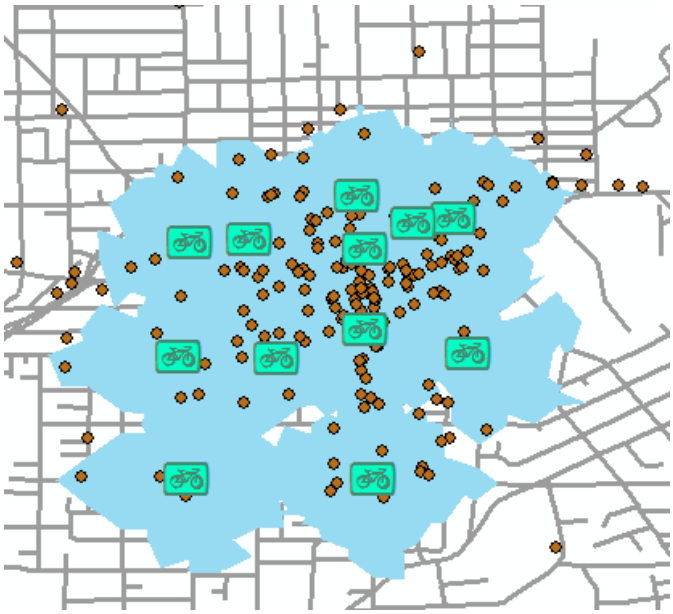


Figure B- 29. Service area for location of interest demand